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TECHNICAL CONSIDERATIONS LEADING TO AN OPTIMUM ALLOCATION OF RADIO FREQUENCIES IN THE BAND 25 TO 60 MC

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IMPORTANT FOREWARD

This Technical Note was originally printed as a restricted NBS Report on March 1, 1955. Many of the technical details have undergone extensive additional study since that time as discussed briefly below, but nevertheless it is considered desirable to reprint this report and make it generally available at this time since some of the general considerations for optimizing the use of the spectrum are as valid today as they were in 1955.

1. Noise predictions more recent than those in reference 7 are available in CCIR Report No. 65 "Report on Revision of Atmospheric Radio Noise Data" (Warsaw 1956, available as a separate document from the International Telecommunication Union, Geneva, or in Vol. I of the Documents of the VIIIth Plenary Assembly of the CCIR, Warsaw, 1956). Data from the current world-wide atmospheric radio noise measurement program are to be published as Technical Notes.

2. The material on tropospheric scatter in reference 23 has now been or will shortly be published:

Kenneth A. Norton, P. L. Rice, and L. E. Vogler, "The Use of Angular Distance in Estimating Transmission Loss and Fading Range for Propagation

Through a Turbulent Atmosphere Over Irregular Terrain," Proc. IRE, 43, 1488, (1955).

Kenneth A. Norton, "System Loss in Radio Wave Propagation," J. Research NBS, 63-D, (Radio Propagation), 53-73, (1959).

P. L. Rice, A. G. Longley, and K. A. Norton, "Prediction of the Cumulative Distribution With Time of Ground Wave and Tropospheric Wave Transmission Loss," to be offered for publication shortly in J. Research NBS, Part D.

3. On page 19, a prediction was made that the next sunspot cycle would have an unusually low maximum. The actual maximum exceeded all previous maxima on record. This points up somewhat further the desirability of recommendation "c" on page 36. It appears desirable that the McNish-Lincoln method should be used for longer range predictions as well as for the shorter range predictions for which it is now used. Further work should be done on prediction at both long and short ranges of ionospheric indices of sunspot activity as well.

4. Recommendation "a" on page 36 has since been acted upon and appropriate maps are now available in Technical Note No. 2, by Donald H. Zacharisen, "World Maps of F2 Critical Frequencies and Maximum Usable Frequency Factors," dated April, 1959.

5. Appendix VII of the original NBS Report on Sporadic E and Ionospheric Forward Scatter has been omitted since much of this material has now been published elsewhere. Some pertinent references are:

R. M. Davis, Jr., E. K. Smith and C. P. Ellyett, "Sporadic E at VHF in the U.S.A.," Proc. IRE, 47, 762-769, (1959) (this paper lists other recent important references).

R. C. Kirby, "VHF Propagation by Ionospheric Scattering - A Survey of Experimental Results," IRE Trans. CS-4, 17-27, (1956).

R. C. Kirby, "1958 Critique of Ionospheric Scatter Communications," IRE-G.W.U. Symposium on Space and Extended Range Communication, Washington, Oct., 1958.

R. M. Davis, Jr., "F2 Interference at VHF,"(to be published).

James Blair, "Frequency Dependence of VHF Ionospheric Scattering," to be published as a Technical Note.

Kenneth A. Norton, "Transmission Loss in Radio Propagation: II," NBS Technical Note No. 12, July, 1959.

TECHNICAL CONSIDERATIONS LEADING TO AN OPTIMUM ALLOCATION OF RADIO FREQUENCIES IN THE BAND 25 to 60 MC

by

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1. INTRODUCTION

The object of this study is to outline very briefly the technical considerations leading to an optimum allocation of radio frequencies in the band 25 to 60 Mc. This report will indicate what technical information is now available and where it may be obtained, as well as what additional information should be obtained in the future.

By optimum allocation I mean one which will best serve the public interest. It is most important to recognize that technical considerations alone will not lead to such an optimum allocation since they do not allow for differences in the social and economic importance of the various uses which may be made of this portion of the radio spectrum. It is only after these social and economic considerations have been superimposed upon the technical considerations that an optimum allocation can be achieved. This portion of the spectrum is used extensively by both government and non-government services. Although there is an agency, the Federal Communications Commission, responsible for allocating frequencies to non-government services in an optimum way, the comparable agency for all allocations - government and non-government - the Interdepartment Radio Advisory Committee, is not organized in such a way as to make it feasible for them to consider the relative social and economic importance of the various uses of the spectrum. 1/ In view of the absence of any

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1/ A good discussion of government organization in the telecommunications field is given in Chapter V of the report "Telecommunications, A Program for Progress," by the President's Communications Policy Board, Washington, March 1951, which is available from the Superintendent of Documents, Government Printing Office, Washington 25, D. C.

regularly constituted government agency with direct responsibility for optimum radio frequency allocations, it will perhaps not be inappropriate if suggestions are made in the course of this report as to how some of these social and economic conflicts should be resolved. Obviously, any suggestions made in this area represent only the personal opinions of the author. These statements may assist in pointing up the problems involved, and it is only with this in mind that these opinions are given.

2. PRESENT OCCUPANCY

First it is desirable to describe the nature of the uses to which this part of the radio spectrum is at present allocated in the United States:

a. Land Mobile
b. Maritime Mobile
c. Fixed Point-to-Point
d. International Broadcasting
e. Television Broadcasting
f. Amateur

The information presently available on the extent and nature of these services is given in Appendix I. In particular an analysis of the statistics in Appendix I indicates that mobile services of one type or another are the principal occupants of this band; in fact 93.26 percent of all transmitters assigned to this band are in the mobile service. On the other hand, only a relatively small number - 4.57 percent - are at present assigned to fixed point-to-point services. The remaining 2.17 percent of the transmitters are assigned to all of the other types of service occupying this band.

3. SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

The use of the concept of transmission loss is first explained as it relates to the problem of determining the mutual interference to be expected between services occupying the same or adjacent portions of the frequency spectrum. It is then shown that services operating on the same radio frequencies inthis particular band are subject at times to severe mutual interference due to (a) transmission by way of the regular F2 layer of the ionosphere or (b) transmission by way of sporadic E ionization of the ionosphere.

It is shown that F2 layer interference is the most severe in terms of its intensity. However, this kind of interference decreases systematically in its duration of occurrence as the radio frequency is increased, and also varies to a substantial degree geographically, diurnally, seasonally, and with the sunspot cycle.

Sporadic E interference may also be quite intense, but the probability of its occurrence (or the percentage of time that it exists) decreases rapidly with increasing intensity of the interfering signals and with increasing frequency. The geographical, diurnal, seasonal, and sunspot cycle variations of this mode of propagation are not as well understood or as predictable as F2 interference.

Other modes of propagation of potential interference are ionospheric and tropospheric forward scatter, but the interference arising from these modes is usually much less intense and can often be avoided by careful planning of the use of this portion of the spectrum in terms of station separations and the use of directive antennas.

It is shown in Appendix VI that the power required to provide a given service may either increase or decrease with increasing frequency, depending largely on the kind of antennas used. Thus, mobile services which normally use non-directional antennas at both ends of the circuit require more power for a given range the higher the frequency. On the other hand, point-to-point services may use large directional arrays at both ends of the circuit and, for a given size, these arrays have an increased gain the higher the radio frequency; thus the point-to-point services may often operate more efficiently at the highest frequencies free from the effects of atmospheric absorption, i. e., above 2000 Mc and below, say, 20,000 Mc.

Based on the above conclusions, the following allocation procedures are recommended:

a. Since the new High Power Fixed Service (RPIS) provides a kind of communication facility which cannot readily be duplicated elsewhere in the entire radio spectrum, it should be favored relative to other services occupying this particular portion of the spectrum.

b. Because of the ease of jamming by means of F2 propagation, all services likely to be jammed should use frequencies sufficiently high so that F2 propagation will not occur during most, if not all, of the time.

c. High Power Fixed Services likely to be jammed should be allocated frequencies sufficiently high so that F2 propagation is not feasible even at sunspot maximum and geographically separated (by, say, 1500 miles or more) from other users of these same frequencies so that other modes of propagation do not cause interference.

d. High Power Fixed Services unlikely to be jammed may be allocated cleared channels anywhere within the 25 to 60 Mc range. Such cleared channels would necessarily have to be negotiated and cleared internationally.

e. Since the Land Mobile Services are evidently able to operate as at present under conditions of fairly severe sporadic interference such as that caused by tropospheric and sporadic E propagation, it seems likely that many more such stations can be allocated to individual channels in this band before the loss in service suffered by those stations already on the channels becomes greater than the additional service provided by the newly allocated stations. Only when such a balance is struck can it truly be said that efficient use is being made of this portion of the spectrum.

f. By the use of higher transmitter-carrier-frequency and receiver-oscillator-frequency stabilities, narrower range modulation schemes and improved receivers, more channels may be made available per megacycle of this valuable spectrum space.

g. Sufficiently high power should be used by all services so that noise does not limit the communications at any time in the case of point-to-point services or at any location within normal operational range in the case of mobile or broadcast services.

h. Many land mobile services can operate satisfactorily in higher frequency portions of the spectrum and, especially if reliable, continuous service is essential, should seek channels in these higher frequency bands.

4. GENERAL TECHNICAL PRINCIPLES FOR RADIO FREQUENCY ALLOCATION

In a recent paper [2] the author outlined the concept of transmission loss and showed how it could be used in radio frequency allocation engineering. It will be convenient to recapitulate some of that theory here. The transmission loss of a radio communication circuit is defined to be the ratio of the power radiated from the transmitting antenna to the resulting signal power available from a loss-free receiving antenna. The transmission loss depends upon the length and geographical location of the transmission path, the time of day, the season of the year, the phase of the sunspot cycle, the radio frequency, and the path antenna gain. The path antenna gain, G_p, expressed in decibels, is approximately equal to, but is in general somewhat less than, the sum of the free space gains of the transmitting and receiving antennas, G_t and G_r :

$$G_p \leq G_t + G_r \tag{1}$$

It is convenient to define a quantity, L_b,* expressed in decibels,

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[2] Kenneth A. Norton, "Transmission Loss in Radio Propagation," NBS Report 2044, Oct. 31, 1952; also Proc. IRE, Vol. 41, No. 1, p. 146, January 1953.

* In this report capital letters are used to denote the ratios, expressed in decibels, of the corresponding quantities designated with lower-case type. The symbol L_b was used to denote the basic transmission loss <u>in free space</u> in reference 2, but is here generalized to apply to the actual transmission path, i.e., the L_b in this report corresponds to the $(L_b + A)$ of reference 2.

which will be called the basic transmission loss, and which is equal to the transmission loss expected for propagation between isotropic transmitting and receiving antennas. If we let L denote the actual measured or calculated transmission loss for the circuit, expressed in decibels, then:

$$L_b \equiv L + G_p \tag{2}$$

If we let P_r denote the power radiated from the transmitting antenna and let P_a denote the power available from the receiving antenna, both expressed in decibels above one watt, then we may write:

$$P_a = P_r - L \leq P_r + G_t + G_r - L_b \tag{3}$$

In the above the approximate expression on the right neglects the difference between G_p and $(G_t + G_r)$, this latter difference being sometimes called the "loss in path antenna gain."

Satisfactory communication over a particular transmission path will be possible only when $P_a \geq P_m$ where P_m denotes the minimum signal power, available from the receiving antenna, which will provide satisfactory reception in the presence of noise and m other undesired signals. The maximum range of a system is determined approximately by the relation $P_a = P_m$.

$$P_m = 10 \log_{10} \left[r f k t b + \sum_{u=1}^{m} r_u p_{au} \right] \tag{4}$$

In the above r denotes the minimum signal-to-noise power ratio which will provide satisfactory reception in the absence of interference other than noise, f is the effective receiver noise figure,[2/]

k is Boltzmann's constant and is equal to 1.3802×10^{-23} joules per degree Kelvin, t is a reference absolute temperature taken to be 288.44 degrees Kelvin so that $10 \log_{10} kt$ is equal to 204 db below one watt per cycle bandwidth, b is the effective receiver noise bandwidth expressed in cycles per second, r_u denotes the minimum signal-to-interference power ratio which will provide satisfactory reception in the presence of the available signal power p_{au} from one of the undesired signals and in the absence of interference from noise or other undesired signals.

The radiated power, P_{rr}, required to just over-ride the noise, in the absence of other forms of interference, may be determined from the relation:

$$P_{rr} = 10 \log_{10}(r f k t b) + L = R + F + B + L - 204 \tag{5}$$

In general F and L will vary with time; in order to ensure service for, say, 99 percent of the time, it is necessary to use a value of P_{rr} which is exceeded only 1 percent of the time, i.e., with a probability, $p = 0.01$. It is shown later in this section that it is often desirable to use a radiated power $P_r = P_{rr} + \Delta P_r$ where ΔP_r is, say 10 db, in order to ensure that optimum use is made of the spectrum. A further discussion of (5) is given in Appendix VI.

As pointed out in reference 2, it is often satisfactory in solving (4) to neglect all except the dominant term in the square brackets. With this approximation, the problem of radio allocation of frequencies is reduced to a consideration of the relative magnitudes of the terms $r f k t b$ and $r_u p_{au}$; thus a reasonably interference-free allocation is achieved when:

$$r_u p_{au} < r f k t b \qquad (u = 1 \text{ to } m) \tag{6}$$

$$\text{or} \quad P_{au} < 10 \log_{10}(r f k t b) - R_u \text{ (decibels)} \tag{7}$$

The above criterion for a reasonably interference-free allocation may be expressed as follows in terms of the transmission losses, L_u, on the m paths between the various undesired service transmitters and the desired service receivers:

$$L_u \equiv (P_{ru} - P_{au}) > L_{mu} \equiv P_{ru} + R_u - 10 \log_{10}(r f k t b) (u = 1 \text{ to } m) \tag{8}$$

The above criterion was developed on the assumption that the desired station uses just the right amount of transmitter power to provide a satisfactory noise-free service. If we let ΔP_r denote the desired station power, expressed in decibels, in excess of that required to provide a satisfactory service in the absence of interference, other than noise, then the interference criterion, I_u, expressed in decibels, may be written:

$$I_u = (L_{mu} - L_u) \tag{9}$$

(for $\Delta P_r \leq 0$; i.e., desired station power less than that required to over-ride noise)

$$I_u = (L_{mu} - L_u - \Delta P_r) \tag{10}$$

(for $\Delta P_r \geq 0$; i.e., desired station power more than that required to over-ride noise)

The desired signals will be reasonably free of interference from the u^{th} undesired transmitter when $I_u \leq 0$; when positive, I_u is a measure, expressed in decibels, of the degree of degradation of the desired service by the u^{th} interfering transmitter.

A necessary condition for the optimum use of the radio spectrum is that ΔP_r be positive, i.e., that somewhat more power be used than is strictly necessary to over-ride the noise. It should be noted that the use by all transmitters of, say 10 db, more power than is strictly necessary (i.e., ΔP_r = 10 db) will not increase the interference from other stations since the desired-signal to undesired-signal ratio will not be modified at any receiving location by such a horizontal increase in power. The only effect of such a horizontal increase in power would be an increase in the desired-signal to noise ratio at all receiving locations and thus an improvement in the service available.

Although the argument presented above contemplated a horizontal increase in transmitter power, studies [3,4,5] of individual

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3/ Kenneth A. Norton and Harry Fine, "A Study of Methods for the Efficient Allocation of Radio Frequencies to Broadcasting Services Operating in the Range above 50 Mc," CRPL Report 4-5, Reference E to the Report of the FCC Ad Hoc Committee for the Evaluation of the Radio Propagation Factors Concerning the Television and Frequency Modulation Broadcasting Services in the Frequency Range between 50 and 250 Mc, Federal Communications Commission Dockets Nos. 8736, 8975 and 9175, August 1, 1949.

4/ Harold Staras, "The Effect on Television Service of Transmitting Antenna Height, Radiated Power, the Use of Off-Set or Synchronized Co-Channel Carriers, and of Correlation among the Radio Fields Received from Several Transmitters," CRPL Report 6-1, Reference K to the Report of the FCC Ad Hoc Committee for the Evaluation of the Radio Propagation Factors Concerning the Television and Frequency Modulation Broadcasting Services in the Frequency Range between 50 and 250 Mc, Federal Communications Commission Dockets Nos. 8736, 8975 and 9175, October 10, 1949.

cases in the television broadcast service have shown that an increase in the power of one station on a channel while another interfering station on the same or adjacent channels maintains the same power, results in a net increase in the total service area provided by both stations since the increase in the service area of the first station is substantially greater than the reduction of the service area of the other station. It seems likely that the advantages accruing from a non-horizontal increase in transmitter power in the broadcast case will apply to other types of service as well, but this question deserves further study.

Unfortunately there are valid technical and economic reasons in some cases why these increases in transmitter power are not feasible. Otherwise it appears that higher transmitter powers should be encouraged for the efficient use of the spectrum in all cases where the power now used does not exceed that required to over-ride the noise by, say 10 db. In this way it is possible to effectively eliminate the influence of the first term in the square brackets of (4).

Several approximations were purposely introduced into the above development of general principles in order to simplify their application. A more accurate treatment is given in Appendix V.

The application of these general principles will be illustrated by an example in the next section.

5. THE ALLOCATION OF HIGH POWER FIXED SERVICES (RPIS) JOINTLY WITH MEDIUM POWER LAND MOBILE SERVICES

This particular example has been chosen since the Land Mobile Services are the principal present users of this portion of the spectrum, while High Power Fixed Services employing ionospheric forward scatter as the mode of propagation are strong new contenders for a portion of this spectrum.

5/ Kenneth A. Norton, "Addendum to Reference E," Working Document of the FCC Ad Hoc Committee for the Evaluation of the Radio Propagation Factors Concerning the Television and Frequency Modulation Broadcasting Services in the Frequency Range between 50 and 250 Mc, November 16, 1950.

The following numerical values may be used to characterize the High Power Fixed Service: P_r = 46 db above one watt; $G_t = G_r$ = 22.5 db; carrier frequency 35 Mc; bandwidth, b = 500 cycles per second, while the following values are typical of the Land Mobile Service: P_r = 30 db above one watt; G_p = 4.3 db;* carrier frequency 35 Mc; bandwidth, b = 20,000 cycles per second.

Consider first whether the Land Mobile Service is likely to interfere with the High Power Fixed Service. It is assumed that the power used for the High Power Fixed Service will be just equal to that required to over-ride the noise ($\Delta P_r = 0$; for technical reasons the use of higher power is probably impracticable at the present time); thus we need only evaluate the maximum value of rfktb in order to have an estimate of the value of the Fixed Service Signal Power available at the receiver which should be protected against interference. It is known, as a result of extensive studies at CRPL, that radio noise of galactic origin determines the minimum signal suitable for reception throughout the band 25 to 60 Mc, except near sunspot maximum when atmospheric noise may be more important in the lower part of this band in some geographical locations. In particular, Cottony and Johler have reported 6/ the levels of galactic noise as received on a horizontal half-wave antenna in the range 25 to 110 Mc, and these may easily be translated into effective antenna noise figures, f_a, 2/ simply by dividing their reported equivalent black body radiation temperatures by 288.44. In this way we find that f_a varies at 35 Mc between 28.8 and 57.2 Since receivers with low noise figures may be constructed readily in this frequency range, and since antenna and transmission line losses are low, we may assume that $f_c f_t f_r$ 2/ is equal to, say 4, and thus we find that the effective receiver noise figure, f, for the maximum galactic noise received on a half-wave horizontal

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* Vertical half-wave dipoles at each end of the path.

6/ H. V. Cottony and J. R. Johler, "Cosmic Radio Noise Intensities in the VHF Band," Proc. IRE, 40, 1053-1060, (1952).

dipole near Sterling, Virginia[7/] should be equal to 60.2.* The receiving antenna used in the High Power Fixed Service is a high-gain rhombic and, for this case, the received galactic noise level, f_a, will be of the order of 3 db higher** than the half-wave antenna value whenever the rhombic is pointing towards the milky way. Thus we may take the effective receiver noise figure, f, to be not greater than 117*** at 35 Mc when reception is on a high-gain rhombic antenna. Consider next the minimum signal-to-noise power ratio, r. Since the desired signal is fading in accordance with a Rayleigh distribution[8/] and since the galactic noise has characteristics similar to random gaussian noise, we may use the theoretical results obtained by Montgomery[9/] for a Frequency-Shift modulation system to determine r. Assuming that one binary error is one hundred may be tolerated during the small number of

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7/ For translating these galactic radio noise levels to other geographical locations, reference may be made to NBS Circular 557 by W. Q. Crichlow, D. F. Smith, R. N. Morton, and W. R. Corliss, entitled "World-Wide Radio Noise Levels Expected in the Frequency Band from 10 Kilocycles to 100 Megacycles," (to be published shortly). These geographical differences are not large and will be neglected in the present discussion. (cf. Foreword, this report).

8/ D. K. Bailey, R. Bateman, and R. C. Kirby, Proc. IRE, 43, 1181, (1955).

9/ G. Franklin Montgomery, "A Comparison of Amplitude and Angle Modulation for Narrow-Band Communication of Binary-Coded Messages in Fluctuation Noise," Proc. IRE, 2, 447-454, (1954).

* $60.2 = (57.2 - 1 + 4)$

** Verbally communicated to the author by Ross Bateman.

*** $117 = (2 \cdot 57.2 - 1 + 4)$

hours that the signal-to-noise ratio is a minimum for the transmission circuit, we obtain R = 16.9 db from Equation (13) in reference 9. Combining the above information we find that average values of the Rayleigh distributed desired signal power as small as 139.2 db* 10/ below one watt should be protected against interference from signals originating from the Land Mobile Service. It is shown in Appendix II that $R_u = 1.3$ db for satisfactory reception of the Frequency Shift telegraph signals in the presence of Land Mobile FM interference, so we find that
$L_{mu} = 30 + 1.3 + 139.2 = 170.5$ db.

In a similar manner we may determine the criteria, L_{mu}, corresponding to the other three possible service-interference combinations, and these are listed in Table I together with the values of R, $10 \log_{10} (r f k t b)$, and R_u required for their determination. The methods used in estimating R and R_u are given in Appendix II; in this connection it was assumed that both the desired and undesired fixed service signals, as well as the undesired mobile service signals, fade in accordance with a Rayleigh distribution, while the desired mobile service signal is assumed to be constant in intensity. The values given for the other two frequencies were obtained by assuming that the galactic noise level, f_a, varies in inverse proportion to the 2.3 power of the radio frequency. 6/

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* $10 \log_{10} (r f k t b) = (16.9 + 10 \log_{10} 117 - 204 + 10 \log_{10} 500) = -139.2$ db

10/ Still weaker signals should be protected from interference when diversity reception is employed. The improvement to be expected with a Rayleigh distiibuted desired signal is given in the paper by G. Franklin Montgomery, "Message Error in Diversity Frequency-Shift Reception," Proc. IRE, Vol. 42, No. 7, pp. 1184-1187, July 1954.

Table I

Parameters, Expressed in Decibels, Leading to the Evaluation of L_{mu}

Service	Source of Interference	R or R_u	$-10 \log_{10}(rfktb)$			P_{ru}	L_{mu}		
			f=25Mc	f=35Mc	f=60Mc		f=25Mc	f=35Mc	f=60Mc
Fixed	Noise	16.9	136.0	139.2	144.3				
Fixed	Mobile	1.3*				30	167.3	170.5	175.6
Fixed	Fixed	16.9				46	198.9	202.1	207.2
Mobile	Noise	3.6	136.5	139.6 11/	144.5				
Mobile	Mobile	6.6				30	173.1	176.2	181.1
Mobile	Fixed	6.6				46	189.1	192.2	197.1

* With the mobile FM modulation off, this would increase to 16.9 db if the mobile FM carrier falls in the fixed service receiver band.

11/ This value is in fair agreement with the value of receiver input power required to over-ride the noise, as reported by C. R. Kraus, W. G. Chaney, and A. T. Steelman, "Radio Transmission of Narrow-Band Mobile Radio Systems at 40 Megacycles," AIEE Communication and Electronics, No. 14, p. 302, September 1954.

Estimates may now be made of the circumstances under which interference may be expected between these two services when they use the same radio frequencies. There are a number of modes of propagation possible in the frequency band 25 to 60 Mc. At short distances the diffracted ground wave may cause interference, but stations will presumably be separated by sufficiently large distances that this source of interference will normally not be important. At intermediate distances, say from 50 to 300 miles, tropospheric forward scatter becomes important. At still greater distances ionospheric modes of propagation are active, and a good summary of the likely importance of the various possible ionospheric modes is given by Morgan.[12/] In this report only four modes of propagation of the interference will be considered, namely, transmission by way of the regular F2 layer of the ionosphere; transmission by way of sporadic E ionization; transmission by way of ionospheric forward scatter; and transmission by way of tropospheric forward scatter. It seems likely that a consideration of only these four modes of propagation of the interference will suffice for a very good first approximation to this allocation problem.

(a) F2 Propagation

Under conditions[13,14,15/] such that the F2 layer will support propagation, it is generally recognized[16,17,18/] that the transmission loss in this frequency range ($f_{Mc} > 25$ Mc) is approximately the same as that expected in free space:[2/]

12/ M. G. Morgan, "A Review of VHF Ionospheric Propagation," Proc. IRE, Vol. 41, No. 5, pp. 582-587, May 1953. See also Report No. 7, "Long Distance Propagation of Waves of 30 to 300 Mc/s by Way of Ionization in the E and F Regions of the Ionosphere," Documents of the VIIth Plenary Assembly, London, 1953, International Radio Consultative Committee, International Telecommunication Union, Geneva, Switzerland.

13/ NBS Circular 465, "Instructions for the Use of Basic Radio Propagation Predictions," 1947, Superintendent of Documents, Government Printing Office, Washington 25, D. C.

$$L_u = 36.58 + 20 \log_{10} f_{Mc} + 20 \log_{10} D - G_{pu} \qquad (11)$$

The above has its maximum possible value for transmission between any two points on the earth when D = 12,500 miles, corresponding to propagation half-way around the earth from a transmitter at the antipode* of the receiver; values of L_u corresponding to this case and for f_{Mc} = 25, 35, and 60 Mc are given in the following table, together with estimates of the path antenna gains, G_{pu}, to be expected on the undesired transmission paths:

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* This neglects the effects of focusing which might occur to some extent near the antipode.

14/ CRPL Series D, "Basic Radio Propagation Predictions - Three Months in Advance," Superintendent of Documents, Government Printing Office, Washington 25, D. C.

15/ Kenneth A. Norton, "Sunspots and Very High Frequency Radio Transmission," CRPL Report 4-3, October 29, 1947; also published in QST, Vol. XXXI, No. 12, pp. 13-17, December 1947.

16/ Kenneth A. Norton, "The Nature of Very High Frequency Ionospheric Wave Propagation," FCC Hearing on Allocation of Radio Frequencies Between 10 kc and 30,000 Mc, Sept. 28, 1944.

17/ E. W. Allen, Jr., "Very-High-Frequency and Ultra-High-Frequency Signal Ranges as Limited by Noise and Co-Channel Interference," Proc. IRE, Vol. 35, No. 2, pp. 128-152, Feb. 1947.

18/ Paul O. Laitinen and George W. Haydon, "Analysis and Prediction of Sky-Wave Field Intensities in the High Frequency Band," Technical Report No. 9, Radio Propagation Unit, Baltimore Signal Depot, Baltimore 20, Maryland, August 1950.

Table II

Maximum Value of Transmission Loss Expected for F2 Propagation

D = 12, 500 Miles

Service	Source of Interference	G_{pu}	L_u f = 25 Mc	f = 35 Mc	f = 60 Mc
Fixed	Mobile	4.3 to 24	122.5* to 142.2	125.4* to 145.1	130* to 149.7
Fixed	Fixed	4.3 to 45	101.5* to 142.2	104.4* to 145.1	109* to 149.7
Mobile	Mobile	4.3	142.2	145.1	149.7
Mobile	Fixed	4.3 to 24	122.5* to 142.2	125.9* to 145.1	130* to 149.7

* These minimum values of L_u correspond to the maximum values of G_{pu} and apply only for interference from stations in those directions such that the fixed service transmitting antenna or receiving antenna, or both, are directed in such a way as to maximize the interference.

Using the values in the above table we may now compute the corresponding minimum value of the interference criterion, I_{mu}, assuming that $\Delta P_r = 0$. At other distances $I_u = I_{mu} + (81.94 - 20 \log_{10} D)$.

Table III

Minimum Value, I_{mu}, of the Interference Criterion Expected for F2 Propagation from the Antipode of the Receiver

($\Delta P_r = 0$; D = 12,500 miles; at other distances $I_u = I_{mu} + (81.94 - 20 \log_{10} D)$)

Service	Source of Interference	I_{mu}		
		f = 25 Mc	f = 35 Mc	f = 60 Mc
Fixed	Mobile	25.1 to 44.8*	25.4 to 45.1*	25.9 to 45.6*
Fixed	Fixed	56.7 to 97.4*	57.0 to 97.7*	57.5 to 98.2*
Mobile	Mobile	30.9	31.1	31.4
Mobile	Fixed	46.9 to 66.6*	47.1 to 66.8*	47.4 to 67.1*

* These maximum values of I_{mu} correspond to the maximum values of G_{pu} and apply only for interference from stations in those directions such that the fixed service transmitting antenna or receiving antenna, or both, are directed in such a way as to maximize the interference. Note that the free space gains will probably be realized in F2 propagation, i.e., $G_{pu} = G_t + G_r$. The minimum values of I_{mu} correspond to G_{pu} = 4.3 db, and thus do not allow for possible nulls in the high gain rhombics. It seems to the author of this report that reliance on these nulls for protection from interference might not be practicable; this question deserves further experimental study.

It is clear from the above table that a fixed service will be most seriously degraded - in fact interrupted - during the entire time that F2 propagation is possible between the fixed service receiving location and any other mobile or fixed transmitting station in the world. The mobile service will have its maximum reliable range greatly reduced during periods of F2 propagation between its receivers and any other mobile or fixed transmitting stations anywhere in the world; the amount of the reduction in range during these periods will be the same as if the desired mobile station reduced its power by I_u decibels.

It will be useful now to consider in somewhat greater detail the conditions under which the F2 layer will support propagation. Reference 13, 14, 15/ has already been made to general methods for solving this problem; in general F2 propagation is much less prevalent at these high frequencies at high latitudes and at sunspot minimum and, near Washington, D. C., is much less prevalent in the summer months.

There are regions within which a negligible amount of propagation via the F2 layer is to be expected. Fig. 1 illustrates how such regions may be determined using the "NBS Basic Radio Propagation Predictions." 13, 14/ Fig. 1 applies to stations within the geographical W Zone 13/ and corresponds to a winter month at sunspot number 130 (although 25 percent of the maxima of past sunspot cycles exceeded 130, this sunspot number was exceeded for only 1.7 percent of the months during the period November 1833 to January 1944, inclusive); thus Fig. 1 corresponds to conditions which are most favorable to F2 propagation. Under these favorable conditions the two solid contours on Fig. 1 enclose regions, defined in terms of both time and geographical area, outside of which the 4000 kilometer MUF is less than 35 Mc. If we now determine the locus of points 2000 kilometers outside of these contours, then the resulting dashed contour encloses a region outside of which a station receiving on frequencies above 35 Mc should be free from interference propagated via the F2 layer from transmitters anywhere in the world for at least 50 percent of the days of this worst month. Fig. 2 gives similar information for other frequencies and sunspot numbers.

It is of interest to note that the present indications are that the next sunspot cycle will have a comparatively low maximum. Thus, in an unpublished paper the author has a method of making an estimate even at this early time as to the next maximum. According to this method, which depends on an observed correlation between the following maximum and preceding minimum, the next smoothed maximum sunspot number will exceed 56 with a probability 0.9, will exceed 92 with a probability 0. 5, and will exceed 129 with a probability 0. 1. The expected maximum value is thus 92, and the expected time of the next maximum (obtained from other correlations) is July 1959. Using other results in the same paper it should be possible, in about two years time, to make a somewhat better estimate of the next maximum and its time of occurrence. If, in fact, this next maximum of sunspot activity is lower than usual, this will have the effect of alleviating the F2 interference in this frequency band until the next following maximum which should not occur for the next 10 to 20 years. Thus, if a chart similar to Fig. 2 were prepared for sunspot number 92 and for the month and geographical zone corresponding to the highest maximum usable frequencies, it would be possible to determine a frequency above which F2 propagation would not be expected anywhere in the world for more than 50 percent of the days of one month during the next 10 to 20 years; for sunspot number 92 this frequency is 54 Mc.

Fig. 2 shows clearly that stations operating in the lower part of this frequency band, say below 35 Mc, at all except extremely high latitudes will be subject to F2 propagated interference during several hours of the day near noon. If such interference can be tolerated, allocations of such frequencies to more than one transmitter on a given channel will be practicable. In such a situation it will be desirable to examine the extent of the expected interference in greater detail. Examples of such studies for particular propagation paths between specific geographical locations are given in recent reports by Klapper and Rieth 19/ and by Gautier and Sargent. 20/ It would appear to be desirable, whenever a new service is allocated a channel in this frequency band, to prepare a comprehensive

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19/ Eric Klapper and Edna Shultz Rieth, Private Communication, May, 1953.

20/ T. N. Gautier, Jr., and C. J. Sargent, "Prediction of the Likelihood of Interference at Frequencies of 30 to 42 Megacycles in Alaska," Journal of Research of the National Bureau of Standards, Vol. 52, No. 1, pp. 21-31, Jan. 1954.

EXAMPLE ILLUSTRATING DETERMINATION OF AREAS FREE FROM F2 PROPAGATION.

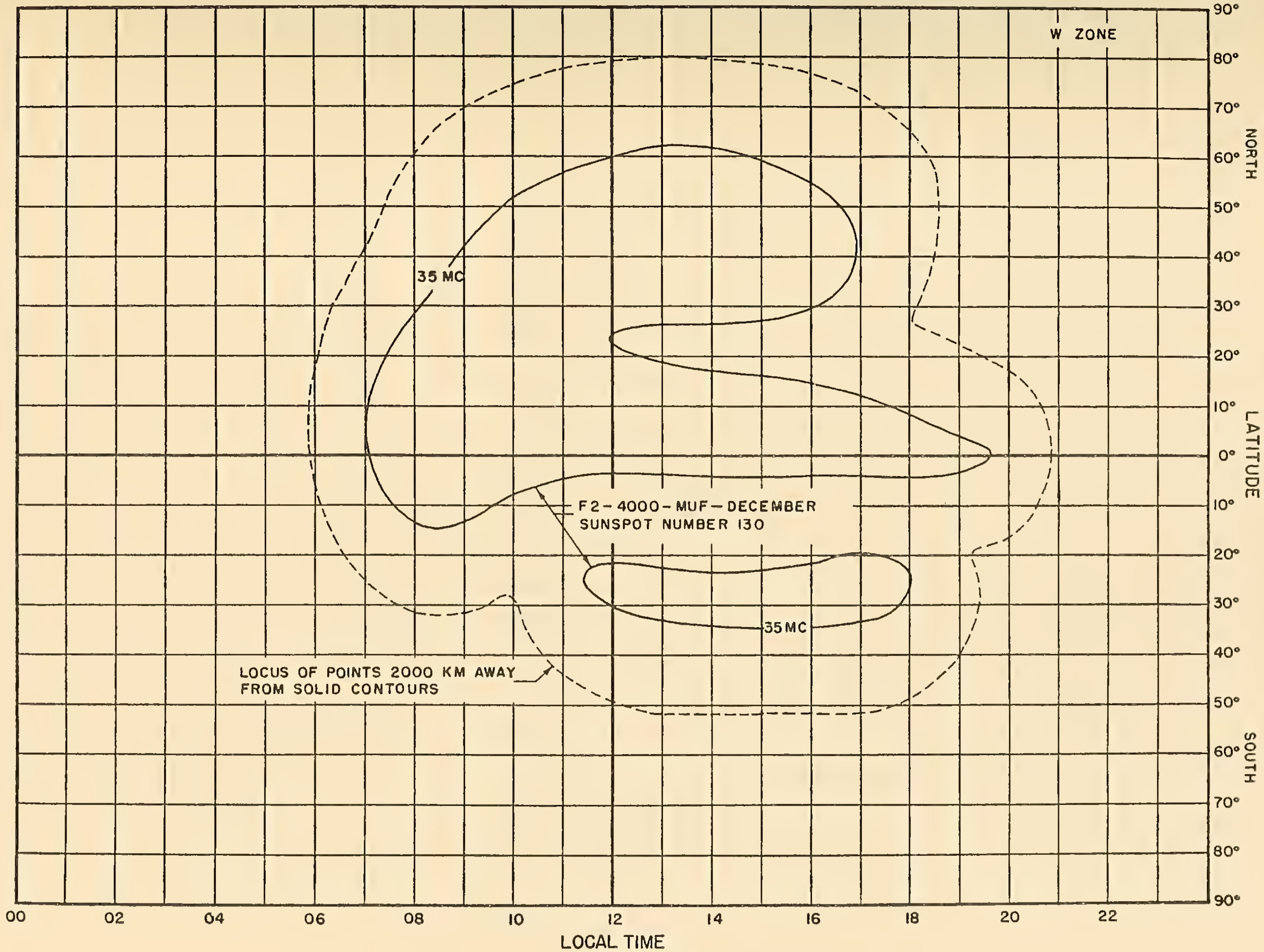


FIGURE 1

RECEIVING STATIONS OUTSIDE OF THE SEVERAL CONTOURS WILL BE UNABLE TO RECEIVE VIA F2 PROPAGATION ON FREQUENCIES ABOVE THOSE INDICATED FOR MORE THAN 50% OF THE DAYS IN DECEMBER.

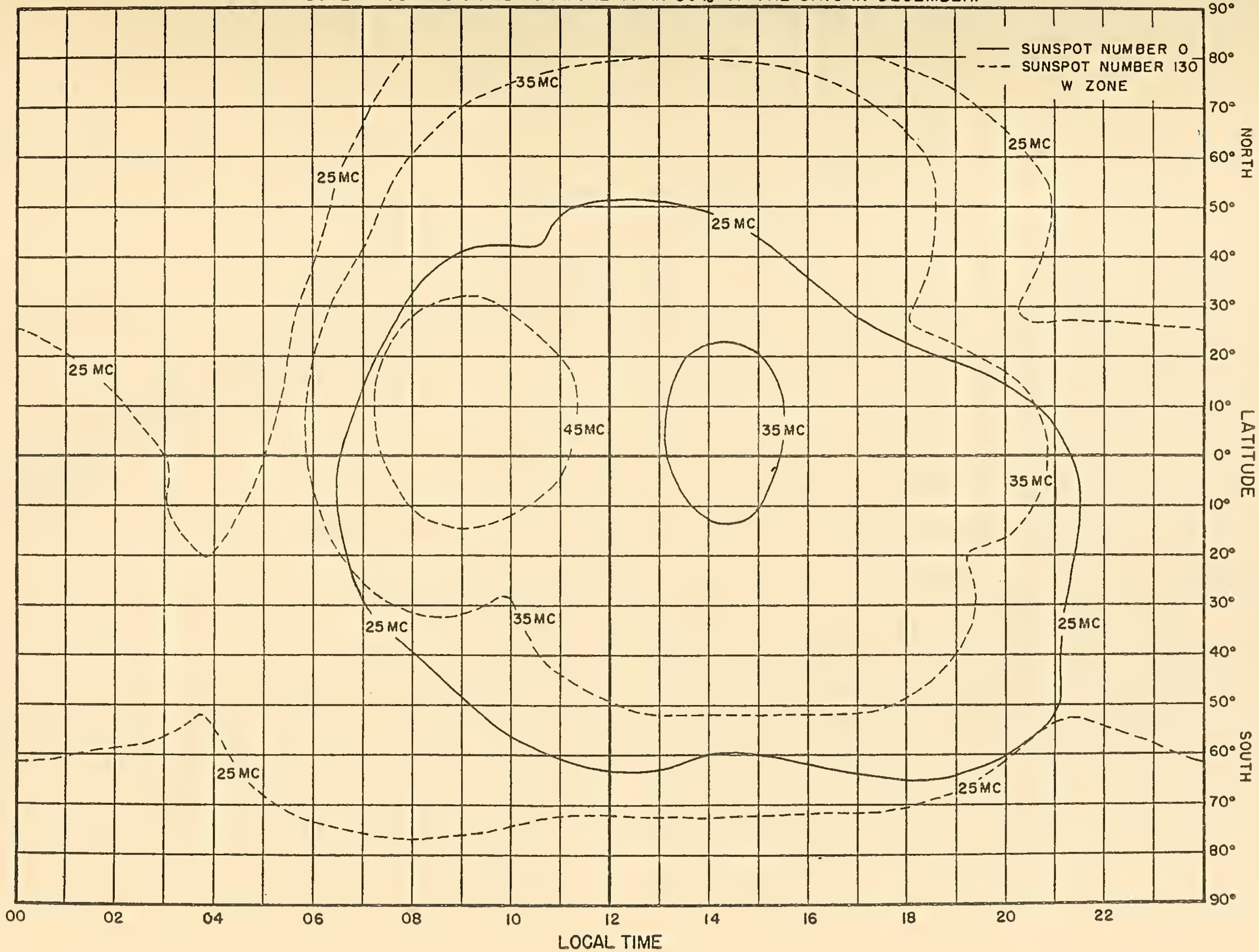


FIGURE 2

BASIC TRANSMISSION LOSS VERSUS DISTANCE AT 25 MC

The Labels on the Curves Refer to the Probability, p,
During a Period of One Year that the Observed
Basic Transmission Loss will be Less than the Indicated Values

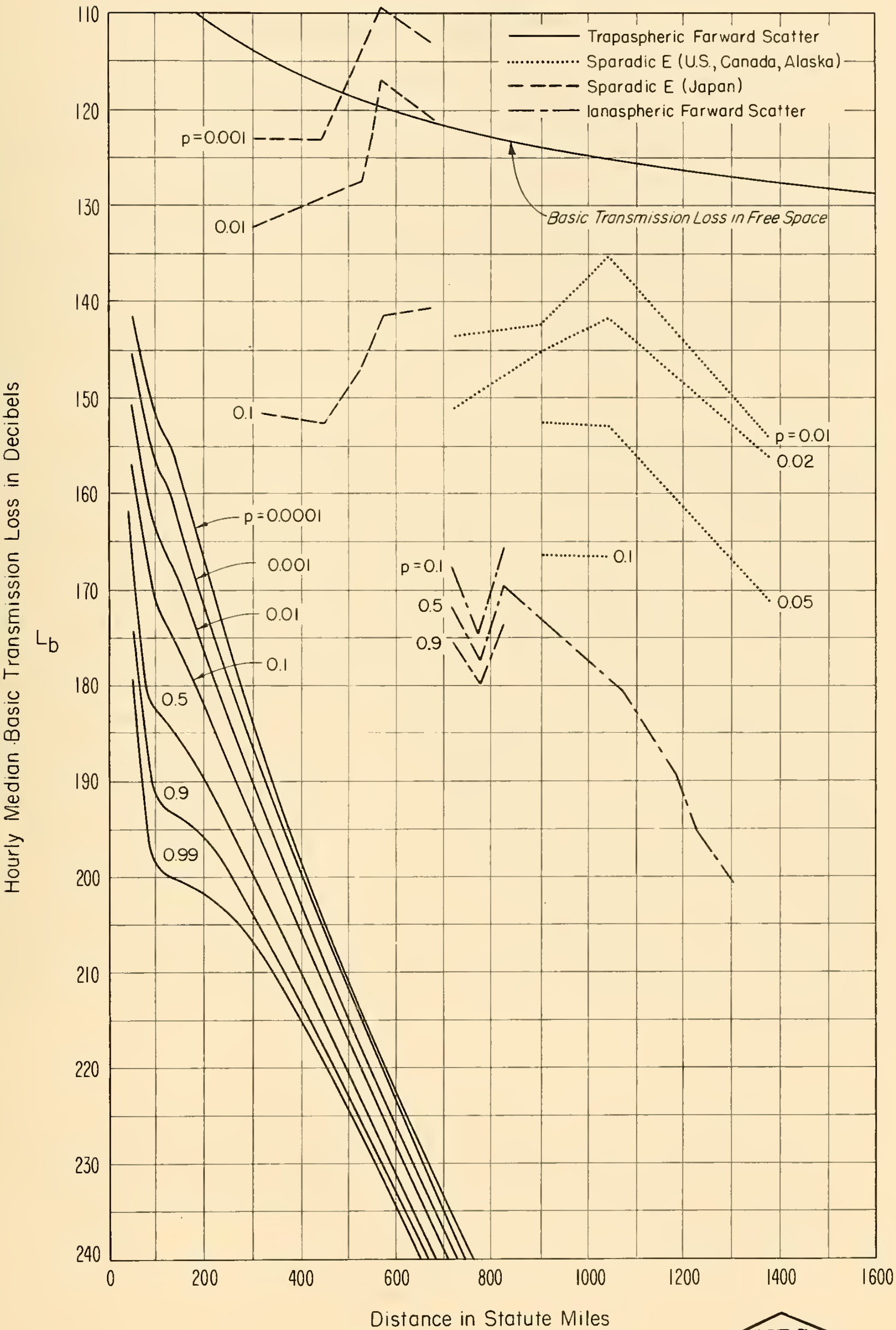


Figure 3

interference study of this kind showing the expected times of F2 interference from each of the transmitters presently assigned.

(b) Sporadic E Propagation

It has been known[17/] for many years that sporadic propagation by way of the E layer of the ionosphere occurs for small percentages of the time in the distance range 400 to 1500 miles throughout this band of frequencies. In fact, it was largely because of the relatively high incidence of this mode of propagation on frequencies below 50 Mc that the FCC decided to move the FM Broadcast Band from 42 to 50 Mc up to 88 to 108 Mc. Sporadic E propagation is well known as a source of interference to the lower television channels; a good review of this interference has been prepared by Smith. [21/]

Figs. 3, 4, 5, and 6 show the hourly median levels of sporadic E basic transmission loss versus distance extrapolated to the four frequencies: 25, 35, 45, and 55 Mc, respectively, from samples of data obtained (a) in the United States, (b) in Japan, and (c) in Alaska. The analysis of (a) and (b) leading to these estimates was made by E. K. Smith and is given in Appendix III. The observed values of sporadic E transmission loss are instantaneous values; a method of adjusting these to correspond to hourly median values is given in Appendix IV. This method was used in converting the instantaneous values given in Appendix III to the hourly median values shown on Figs. 3, 4, 5, and 6; these adjustments amount at most to a few decibels, and are equal to about 1 db on the average. Although the distance ranges do not quite overlap for the United States and Japanese samples, it is quite clear that sporadic E is much more prevalent in Japan than it is in the United States. This indicates the necessity for making much more extensive experimental studies of this mode of propagation before attempting to draw any precise estimates of its world-wide importance in radio frequency allocation.

21/ Ernest K. Smith, Jr., "The Effect of Sporadic E on TV Reception," Radio Electronics, Vol. XXIV, No. 6, pp. 54-56, June 1953. Also published in Trans. IRE, PGAP-2, pp. 54-61, March 1952.

BASIC TRANSMISSION LOSS VERSUS DISTANCE AT 35 MC

The Labels on the Curves Refer to the Probability, p, During a Period of One Year that the Observed Basic Transmission Loss will be Less than the Indicated Values

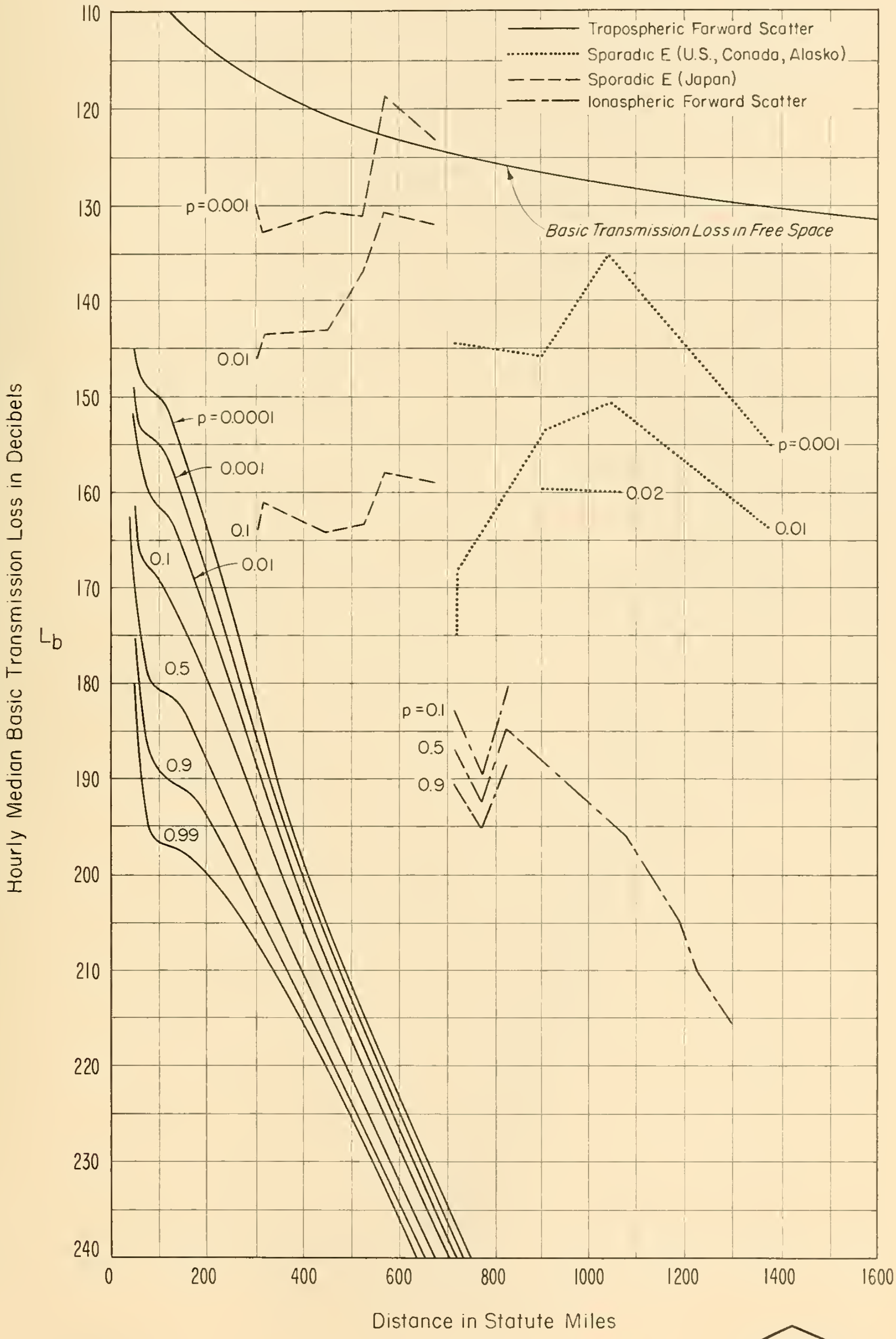


Figure 4

BASIC TRANSMISSION LOSS VERSUS DISTANCE AT 45 MC

The Labels on the Curves Refer to the Probability, p, During a Period of One Year that the Observed Basic Transmission Loss will be Less than the Indicated Values

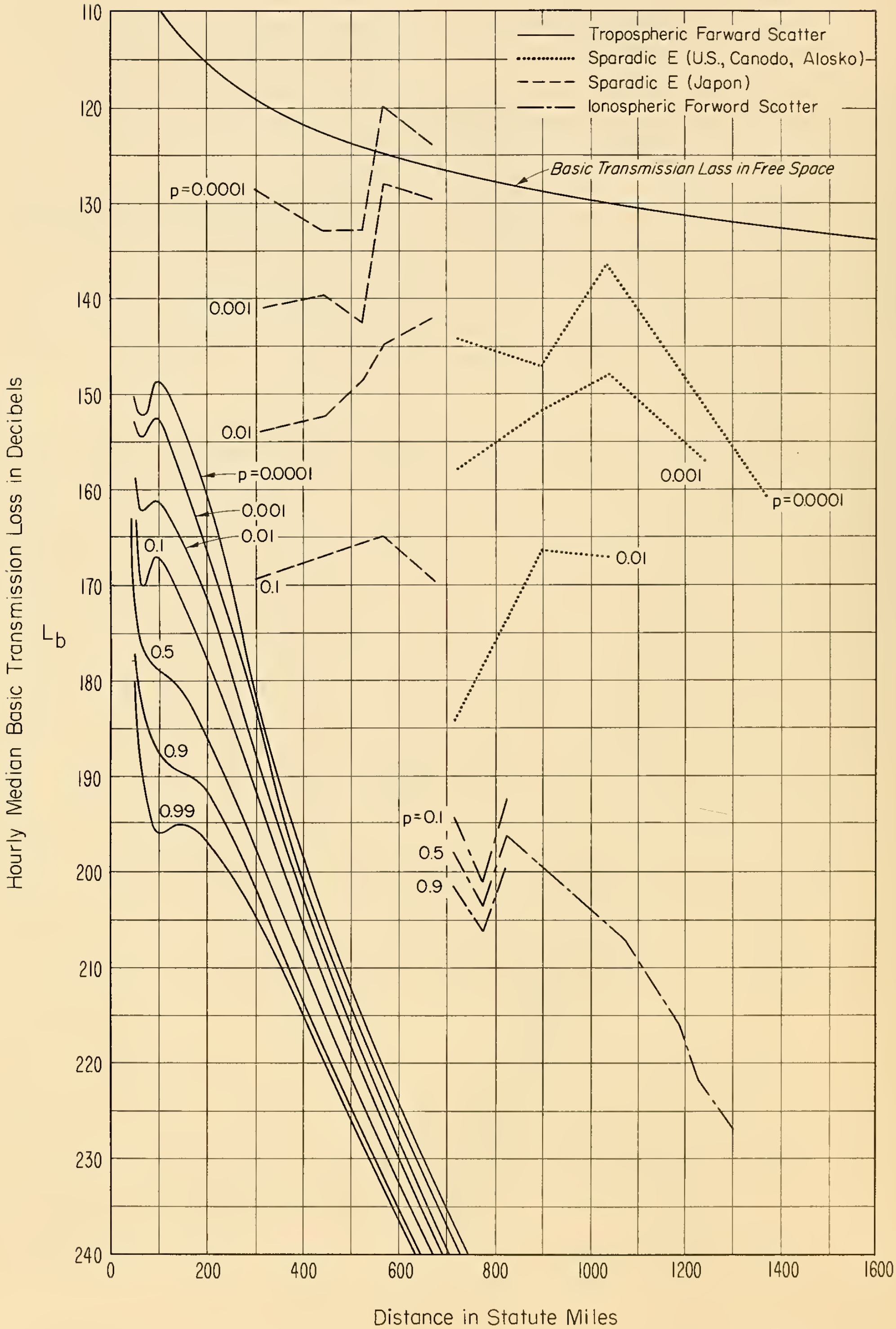
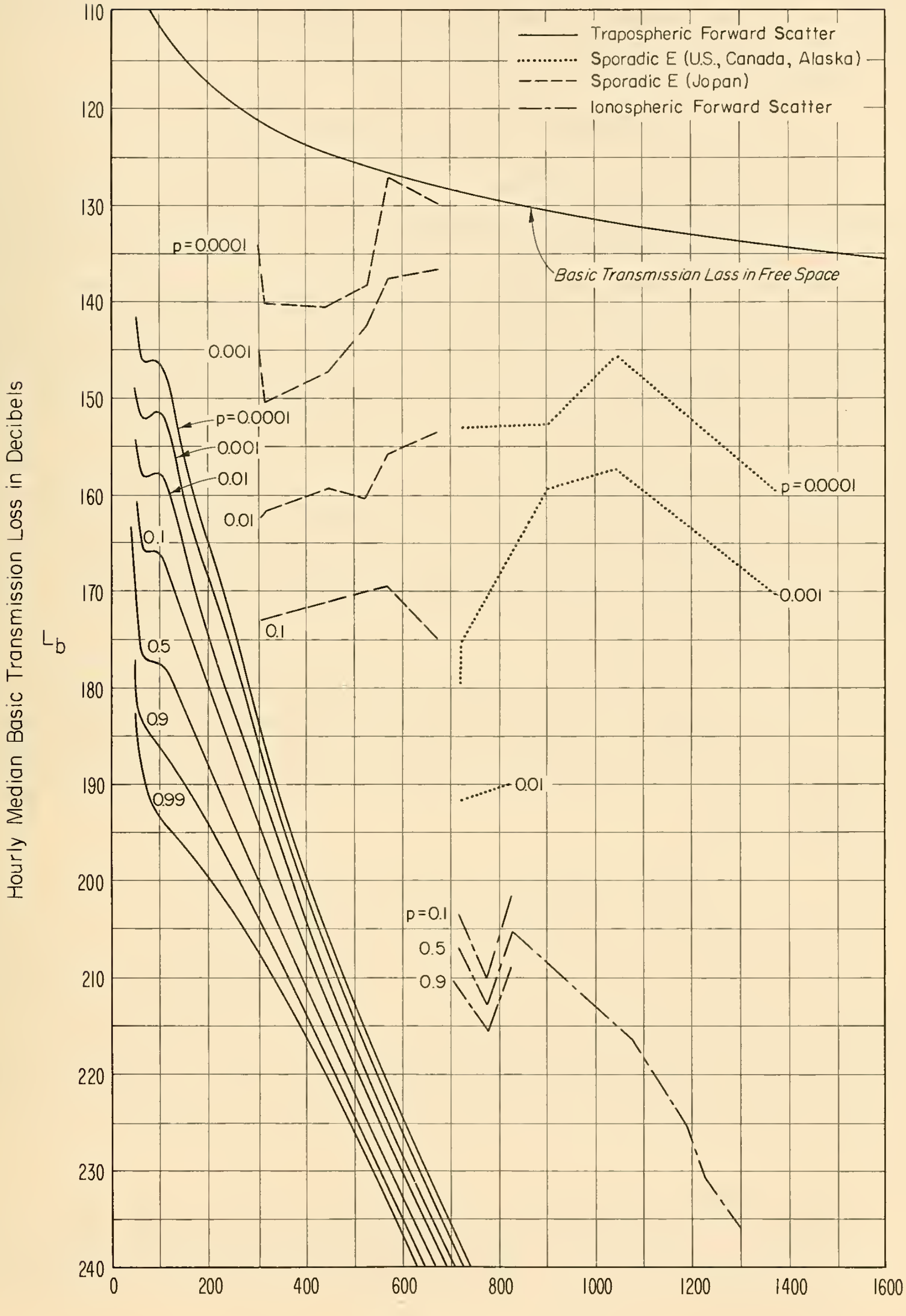


Figure 5

NBS

BASIC TRANSMISSION LOSS VERSUS DISTANCE AT 55 MC

The Labels on the Curves Refer to the Probability, p, During a period of One Year that the Observed Basic Transmission Loss will be Less than the Indicated Values



NBS

Figure 6

The Alaskan data and part of the United States data were reported by Bailey, Bateman, and Kirby. [8] These data are discussed in Appendix VII. The levels of sporadic E observed in Canada and Alaska are more nearly comparable to those observed in the U. S. than to those observed in Japan.

(c) Ionospheric Forward Scatter

This mode of propagation is, in some respects, difficult to distinguish from sporadic E propagation. Over short periods of time the instantaneous transmission loss is Rayleigh distributed, while the hourly median values are approximately log normally distributed, i. e., hourly median values of L are normally distributed. Thus sporadic E may be casually identified simply with those cases of ionospheric forward scatter for which the transmission loss and its probability of occurrence are both low. However, if we identify the ionospheric forward scatter mode of propagation with the larger transmission losses and correspondingly larger percentages of occurrence, then this mode of propagation does have this distinguishing characteristic - there is a considerable "loss in path antenna gain" with high gain antennas as regards these larger transmission loss levels.

The values of hourly median basic transmission loss shown on Figs. 3, 4, 5, and 6 for the ionospheric forward scatter mode of propagation were measured by Bailey, Bateman, and Kirby [8] and the methods used for determining L_b from their data are discussed in Appendix VII.

(d) Tropospheric Forward Scatter

Methods have recently become available [22, 23] for estimating the basic transmission loss expected with tropospheric forward scatter in this range of frequencies. These methods have been used for obtaining the estimates shown on Figs. 3, 4, 5, and 6, which are the values expected using transmitting and receiving antennas

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[22] J. W. Herbstreit, K. A. Norton, P. L. Rice and G. E. Schafer, "Radio Wave Scattering in Tropospheric Propagation," 1953 Convention Record of the IRE, Part 2, Antennas and Communications, pp. 85-93.

30 feet above an assumed smooth spherical earth with a standard atmosphere. A detailed description of the particular assumptions and approximations made in this method of calculation is given in an unpublished report by Daniel, Mansfield, Rice, and Short. 24/

Up until recently it had been assumed that the transmission losses associated with tropospheric forward scatter would be roughly the same throughout the world. This assumption was based on the fact that the levels observed in Colorado 25/ have a remarkably small seasonal dependence and the fact that the levels reported by many other observers, 26/ over both land and sea, were comparable to those observed in Colorado. Recently, however, some measurements made in Canada (so far unpublished) by the Defence Research Telecommunications Establishment have indicated that the levels there are lower by an order of magnitude than the levels reported elsewhere. For this reason the levels of

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23/ Kenneth A. Norton, "Dependence of the Transmission Loss in Tropospheric Radio Wave Propagation on the Angular Distance." This paper was originally presented with the title "The Role of Angular Distance in Tropospheric Radio Wave Propagation" at the West Coast Annual Meeting of the Institute of Radio Engineers at San Francisco in August 1953, and was later presented in a series of papers to the Eleventh General Assembly of the International Scientific Radio Union (URSI) at The Hague in August 1954. In preparation for publication.

24/ F. T. Daniel, W. V. Mansfield, P. L. Rice, and P. J. Short, "Radio Transmission Loss Versus Angular Distance and Antenna Height at 63, 100, 195 and 700 Megacycles," Report prepared January 7, 1954 for the use of the FCC Radio Propagation Advisory Committee.

25/ A. P. Barsis, J. W. Herbstreit and K.O. Hornberg, "Cheyenne Mountain Tropospheric Propagation Experiments," NBS Circular 554, January 3, 1955, which is available from the Superintendent of Documents, Government Printing Office, Washington, D.C.

26/ Kenneth Bullington, "Radio Transmission Beyond the Horizon in the 40- to 4,000-Mc Band," Proc. IRE, Vol. 41, No. 1, pp 132-135, January 1953.

transmission loss for tropospheric forward scatter shown on Figs. 3, 4, 5, and 6 cannot necessarily be considered applicable throughout the world. Furthermore, since these levels are extrapolations from data largely obtained on frequencies above 100 Mc, they should be verified experimentally in the lower frequency range with which we are here concerned.

This completes the detailed consideration of the various significant modes of propagation of the interference, and we are now in a position to consider the interference potentialities of these last three modes of propagation using the basic transmission loss levels shown on Figs. 3, 4, 5, and 6. We have already shown that interference will be present whenever $I_u > 0$ and, for $\Delta P_r = 0$, this is equivalent to the condition $L_{bu} - G_{pu} < L_{mu}$, where L_{bu} denotes the basic transmission loss on the path between an undesired transmitter and the desired receiver. Interference will exist for the percentages of time that L_{bu} is less than $(L_{mu} + G_{pu})$; Table IV gives the values of $(L_{mu} + G_{pu})$ for the various service-interference combinations considered in this report.

Reference to Figs. 3, 4, 5, and 6 indicates that the hourly median basic transmission loss will be less than the values $(L_{mu} + G_{pu})$ given in Table IV for appreciable percentages of the time throughout the range of distances up to 1500 miles. Thus we conclude that allocations, for either of these two types of service, of more than one transmitter on the same channel at these distance separations will result in potentially serious mutual interference.

6. TECHNICAL CONCLUSIONS

In the preceding three sections of this report an outline has been presented of the kinds of information desirable for the determination of the mutual interference likely between radio stations operating on the same or adjacent channels in the frequency range 25 to 60 Mc.

In particular it was shown that very intense and persistent interference may be expected whenever the F2 layer of the ionosphere will support propagation between an interfering transmitter and a desired receiver. The geographical, diurnal, seasonal and sunspot cycle variations in the occurrence of F2 propagation were discussed.

Table IV

Service	Source of Interference	G_{pu}	$(L_{mu} + G_{pu})$ in decibels			
			f=25Mc	f=35Mc	f=45Mc	f=55Mc
Fixed	Mobile	4.3 to 24*	171.6 to 191.3*	174.8 to 194.5*	177.2 to 196.9*	179.1 to 198.8*
Fixed	Fixed	4.3 to 45*	203.2 to 243.9*	206.4 to 247.1*	208.8 to 249.5*	210.7 to 251.4*
Mobile	Mobile	4.3	180.4	183.5	185.8	187.7
Mobile	Fixed	4.3 to 24*	196.4 to 216.1*	199.5 to 219.2*	201.8 to 221.5*	203.7 to 223.4*

* See the footnote to Table III for the qualifications to these maximum values. When the values in Table IV are applied to ionospheric forward scatter with high gain antennas, it must be remembered that G_{pu} is then a random variable, and thus the values of $(L_{mu} + G_{pu})$ will vary between the limits given above.

The other three modes of propagation: tropospheric forward scatter, sporadic E, and ionospheric forward scatter were shown to be less important from the standpoint of their intensity and probability of occurrence. However, one or more of these modes of propagation are capable of seriously disrupting communications in the range of distances out to 1500 miles for brief periods of time which may occur at any time of the day, season of the year, or phase of the sunspot cycle.

All modes of propagation of the interference except the tropospheric mode decrease in importance as the frequency is increased.

7. SOME PHILOSOPHY OF RADIO FREQUENCY ALLOCATION

Recently the Joint Technical Advisory Committee of IRE-RTMA prepared a report entitled "Radio Spectrum Conservation" and made it available in book form. Section 5.3 in this book deals with "Technical Measures to Implement Dynamic Conservation." Since this provides a good philosophical basis for my later recommendations, I will quote this section in full:

"5.3 <u>Technical Measures to Implement Dynamic Conservation</u>

"The limitations governing spectrum occupancy discussed in the previous section suggest a number of corrective measures, some rooted in the design and operation of technical equipment, others in the administration of allocations. The technical measures comprise the early adoption of methods contributing to spectrum conservation, with due regard for the benefits and costs involved. The administrative steps involve applying sound doctrine in comparing the economic and social values of competing services.

"In adopting these measures, great care must be exercised to avoid foreclosing future developments. The cornerstone of the conservative program should be the encouragement of and, as far as possible, advance provisions for new services having more extensive or comprehensive values than the old. Such unborn methods and services may have, in fact, at least as important claims on our natural resources as the services currently occupying the spectrum. The evaluation of the relative importarce of the old and the new is, in fact, the most delicate task in the administration of the spectrum.

"The following suggestions are offered, therefore, on the assumption that necessary steps have been taken and are in continuous effect to encourage experimentation with new services throughout the spectrum. The suggestions apply in particular to services which have passed the experimental stage and have entered or are about to enter regular operation.

"On this basis, the following measures are indicated:

"1. Experimental authorizations to develop new services should be granted in all regions of the spectrum, subject to reasonable safeguards to prevent interference with existing services. When a radio service performs a function which can be performed by nonradio equipment (e.g., wire lines), the permanent establishment of the radio service, beyond the developmental period, should not take place until the comparative costs and values of the radio and nonradio services have been assessed and compared and a determination made of other demands on that portion of the spectrum. Unless the costs of the radio service are appreciably less or their value appreciably greater than the corresponding costs and values of the nonradio service, conservation of the spectrum requires that nonradio services be used.

"2. The frequency tolerances applicable to carrier emissions should be a suitably small fraction of the channel width. In most cases "suitably small" implies as small as the state of the art permits, without incurring undue penalties in size, weight, or ease of operation and maintenance. Such penalties are not usually the controlling factor. The principal deterrent is cost. After a reasonable period to amortize the cost of substandard equipment has intervened, it should be replaced by equipment meeting a reasonable standard of carrier stability.

"3. Off-frequency operation and pirating of frequencies represent a gross derogation of the principles of spectrum conservation which must be brought under control by improved methods of international cooperation.

"4. The use of guard bands to accommodate apparatus deficiencies (such as excessive carrier-frequency tolerances, improper or inefficient transmitter modulation, or inadequate receiver selectivity) should be curtailed.

"5. The use of the most cfficient modulation methods, with respect to uniform frequency occupancy of the assigned channel, should be encouraged, particularly in the wide-band services such as FM and television broadcasting.

"6. Every practical method of restricting the extent to which the interference area of a station extends beyond its service area should be employed. Specific measures include restricting of transmitter power to the level required for adequate service, suppression of harmonic emissions, synchronization of carriers where practicable ('offset carrier' in television broadcasting), and the employment of directional antennas. Where the cost of such measures is substantial, a suitable amortization period should be allowed.

"7. Services occupying regions of the spectrum not particularly adapted to their needs and capabilities should be transferred to other regions, in accordance with the dictates of full spectrum occupancy, and outmoded services deleted. Economic resistance to such shifts can be overcome by announcement of the impending change with a statement of the technical and economic advantages to be obtained, sufficiently in advance to permit old equipment to be amortized and to allow new equipment to be procured and installed. As knowledge of propagation and equipment improves and becomes stabilized, it should be possible to establish in advance the basis for such transfers over periods as long as 25 years, although shorter periods should suffice in most cases.

"8. Frequency assignments should be shared to the fullest practicable extent. Time sharing of frequency assignments is looked upon with disfavor by nearly all users of the spectrum and by many of its administrators, largely as a result of unfortunate experience. Geographical sharing is common in many services, including all forms of broadcasting, but is uncommon in others, as, for example, between military and civilian services. The difficulties of shared operation are mainly administrative. While not belittling the problems, we must recognize that the increasing congestion of the spectrum will eventually force greater reliance on shared operation. The time is already past when a local assignment made under a military administration should preclude a similarly local assignment at a distance made under a civilian administration, when interference does not occur and is not anticipated."

8. RECOMMENDED ALLOCATION PROCEDURES

a. Since the new High Power Fixed Service (RPIS) provides a kind of communication facility which cannot readily be duplicated elsewhere in the entire radio spectrum, it should be favored relative to other services occupying this particular portion of the spectrum.

b. Because of the ease of jamming by means of F2 propagation, all services likely to be jammed should use frequencies sufficiently high so that F2 propagation will not occur during most, if not all, of the time.

c. High Power Fixed Services likely to be jammed should be allocated frequencies sufficiently high so that F2 propagation is not feasible even at sunspot maximum and geographically separated (by, say, 1500 miles or more) from other users of these same frequencies so that other modes of propagation do not cause interference.

d. High Power Fixed Services unlikely to be jammed may be allocated cleared channels anywhere within the 25 to 60 Mc range. Such cleared channels would necessarily have to be negotiated and cleared internationally.

e. Since the Land Mobile Services are evidently able to operate as at present under conditions of fairly severe sporadic interference such as that caused by tropospheric and sporadic E propagation, it seems likely that many more such stations can be allocated to individual channels in this band before the loss in service suffered by those stations already on the channels becomes greater than the additional service provided by the newly allocated stations. Only when such a balance is struck can it truly be said that efficient use is being made of this portion of the spectrum.

f. By the use of higher transmitter-carrier-frequency and receiver-oscillator-frequency stabilities, narrower range modulation schemes and improved receivers, more channels may be made available per megacycle of this valuable spectrum space.

g. Sufficiently high power should be used by all services so that noise does not limit the communications at any time in the case of point-to-point services or at any location within normal operational range in the case of mobile or broadcast services.

h. Many land mobile services can operate satisfactorily in higher frequency portions of the spectrum and, especially if reliable, continuous service is essential, should seek channels in these higher frequency bands.

9. RECOMMENDED FURTHER RADIO PROPAGATION RESEARCH

a. Methods should be developed for predicting F2 maximum usable frequencies for each two-hour period of the day rather than by the three geographical zones as at present.

b. Predictions should be made of the expected variance of the maximum usable frequencies as well as their median values.

c. Work should be expedited on methods for the prediction of sunspot activity.

d. Many further measurements should be made at as many locations as possible throughout the world of the tropospheric forward scatter, sporadic E and ionospheric forward scatter transmission losses expected throughout the frequency range 25 to 60 Mc.

* * * * *

Although some of the above work can be done within the present budgets of the Radio Propagation Engineering and Physics Divisions of NBS, the proposed additional measurement program would involve the expenditure of large additional appropriations. It seems likely that the expenditure of such sums for this purpose are justified in order to provide ultimately a sound technical basis for the efficient allocation of radio services to this band of frequencies.

10. RECOMMENDED FURTHER FREQUENCY ALLOCATION RESEARCH

As demands for various portions of the spectrum multiply, it becomes increasingly important for allocation engineers to have a detailed knowledge of the actual spectrum occupancy so that more services can be accommodated. In particular, it seems that it will actually be desirable at some time in the near future to have detailed interference studies made for every channel in the radio spectrum so as to see how other services may be allocated to it. These detailed studies should be made using technical data of the kind included in this report and with the accuracy made possible by the use of methods of the kind given in Appendix V.

Most government stations are allocated at present on a "non-interference" basis. In view of the sporadic nature of the interference, particularly in the 25 to 60 Mc band, this basis for allocation will often not lead to an efficient use of the spectrum since many services can tolerate a large amount of sporadic interference before the degree of degradation of the existing services outweighs in importance the new services provided by the proposed stations. Unless detailed and accurate technical information is available to the allocation engineers, these proposed additional uses of the spectrum are not likely to be realized.

The implication of the above discussion is that many additional personnel need to be assigned to allocation engineering if the important objective of efficient use of the spectrum is to be achieved.

Appendix I

The table in this appendix gives information as to the number of U.S. assignments (as of December 1954) by classes of service to the frequency band 25-60 Mc. In the case of the non-government services, information is also given as to the nature of the service, i.e., police, forestry conservation, broadcast, etc.

It is quite clear from Table I-1 that by far the majority (about 93 percent) of all of the assignments are for mobile services, either base stations or mobile stations.

Appendix I

Table I-I

FREQUENCY ASSIGNMENTS IN THE BAND 25-60 Mc

* Denotes government assignment

Item No.	Class and Nature of Service	Desig-nator	No. of Assign-ments	Percentage of the Assignments-By Frequency Bands						
				25-30 Mc	30-35 Mc	35-40 Mc	40-45 Mc	45-50 Mc	50-54 Mc	54-60 Mc
1	Mobile (Police)	PP MO	4032		0.25	79.46	13.94	6.35		
2	Base (Police)	PP FB	3521		0.11	64.55	28.34	6.99		
3	Base (Power; Industrial)	IW FB	3428		0.09	47.49	0.09	52.33		
4	Base (Petroleum; Industrial)	IL FB	3285	5.60	30.20	0.12	0.03	64.04		
5	Base (Forestry Conservation; Public Safety)	PO FB	2785		91.50			9.80		
6	Base (Special Industrial)	II FB	2781	4.78	11.11		46.24	37.86		
7	Land Station*	FL	2254	10.51	33.58	29.32	26.17	0.40		
8	Mobile Station*	MO	1900	14.74	34.10	29.47	20.89	0.63		0.16
9	Fixed Station*	FX	1764	12.64	30.16	28.23	21.94	6.97		0.06

Item No.	Class and Nature of Service	Designator	No. of Assignments	Percentage of the Assignments-By Frequency Bands						
				25-30 Mc	30-35 Mc	35-40 Mc	40-45 Mc	45-50 Mc	50-54 Mc	54-60 Mc
10	Mobile (Special Industrial)	II MO	1528	7.20	12.37		42.93	37.50		
11	Remote Pickup Mobile (Auxiliary Broadcast)	BA MLR	1310	99.85		0.08			0.08	
12	Mobile (Power; Industrial)	IW MO	1215	0.16	0.33	39.75	0.33	59.42		
13	Mobile (Domestic Public Land Mobile; Common Carrier)	CD MO	1073			3.45	96.56			
14	Base (Special Emergency; Public Safety)	PE FB	993		3.22	4.53		92.25		
15	Mobile (Special Emergency; Public Safety)	PE MO	957		3.45	5.12		91.44		
16	Base (Highway Maintenance; Public Safety)	PH FB	770		8.70	19.09		72.22		
17	Mobile (Fire; Public Safety)	PF MO	765		46.53	0.13		53.32		
18	Base (Fire; Public Safety)	PF FB	711		44.29	0.14		55.54		

Item No.	Class and Nature of Service	Desig- nator	No. of Assign- ments	Percentage of the Assignments - By Frequency Bands						
				25-30 Mc	30-35 Mc	35-40 Mc	40-45 Mc	45-50 Mc	50-54 Mc	54-60 Mc
19	Base (Highway Truck; Land Transportation)	LK FB	687			100.0				
20	Mobile (Petroleum; Industrial)	IL MO	667	28.18	33.73	0.15	0.15	37.77		
21	Base (Forest Products; Industrial)	ID FB	519	14.84				85.17		
22	Mobile (Highway Truck; Land Transportation)	LK MO	481			100.0				
23	Base (Automobile Emergency; Land Transportation)	LA FB	291			100.0				
24	Mobile (Automobile Emergency; Land Transportation)	LA MO	279			100.0				
25	Mobile (Forest Products; Industrial)	ID MO	258	9.30	0.39			90.31		
26	Remote Pickup Base (Auxiliary Broadcast)	BA FBR	239	100.00						
27	Mobile (Low Power; Industrial)	IZ MO	231	13.85	15.15	21.64	49.35			

Item No.	Class and Nature of Service	Designator	No. of Assignments	Percentage of the Assignments-by Frequency Bands						
				25-30 Mc	30-35 Mc	35-40 Mc	40-45 Mc	45-50 Mc	50-54 Mc	54-60 Mc
28	Base (Domestic Public Land Mobile; Common Carrier	CD FB	226			81.86	18.14			
29	Mobile (Forestry Conservation; Public Safety)	PO MO	186		91.39			8.60		
30	Aeronautical Station*	FA	173	90.75	2.89	4.05	2.31			
31	Mobile (Highway Maintenance; Public Safety)	PH MO	157		30.57	37.58		31.84		
32	Contract (Experimental)	E EXG	149	21.48	39.59	21.48	12.08	4.03	1.34	
33	Test (Domestic Public Land Mobile; Common Carrier)	CD FLT	114				100.00			
34	Ship Station*	MS	110	33.64	25.45	23.64	17.27			
35	Developmental (Experimental)	E EXD	99	15.15	10.10	38.38	36.36			
36	Base (Urban Transit; Land Transportation)	LT FB	84		38.08		61.88			
37	Base Station*	FB	83	46.99	30.12	4.82	18.08			

Item No.	Class and Nature of Service	Desig-nator	No. of Assign-ments	Percentage of the Assignments-by Frequency Bands						
				25-30 Mc	30-35 Mc	35-40 Mc	40-45 Mc	45-50 Mc	50-54 Mc	54-60 Mc
38	Base (Intercity Bus; Land Transportation)	LS FB	81				100.00			
39	Mobile (Urban Transit; Land Transportation)	LT MO	77		41.56		58.44			
40	Coast Station*	FC	75	84.00	.	6.67	9.33			
41	Aircraft Station*	MA	73	28.77	32.88	27.40	10.96			
42	Fixed (Special Emergency; Public Safety)	PE FX	61		3.28	1.64		95.08		
43	Land Mobile Station*	ML	61	26.23	19.67	45.90	8.20			
44	Experimental Station*	EX	58	20.69	20.69	29.31	15.52	6.90	1.72	5.17
45	*	FAX	45	93.33			2.22	4.44		
46	Research (Experimental)	E EXR	33	33.33	27.27	18.18	21.21			
47	Television Broadcasting (Broadcasting)	B BCT	31							100.00
48	Experimental Class I (Experimental)	E EX 1	30	6.67	33.33	30.00	20.00	10.00		

Item No.	Class and Nature of Service	Desig- nator	No. of Assign- ments	Percentage of the Assignments-by Frequency Bands						
				25-30 Mc	30-35 Mc	35-40 Mc	40-45 Mc	45-50 Mc	50-54 Mc	54-60 Mc
49	Mobile (Intercity Bus; Land Transportation)	LS MO	29				100.00			
50	Point-to-Point Telegraph (International Fixed Public; Common Carrier)	C FXG	26	50.00	3.85	26.92	7.69	11.54		
51	Point-to-Point Telephone (International Fixed Public; Common Carrier)	C FXP	16		6.25	43.75	25.00	25.00		
52	Mobile Relay (Power; Industrial)	IW FB2	15			93.33		6.67		
53	Ship Telephone or Public Ship Station (Maritime Mobile)	M MSP	12		25.00	75.00				
54	Mobile (Motion Picture; Industrial)	IM MO	8		12.50	12.50		75.00		
55	Amateur (Amateur Citizens Disaster and ISM)	Y AR	7	57.14					42.86	
56	Mobile Relay (Petroleum; Industrial)	IL FB2	6					100.00		

Item No.	Class and Nature of Service	Designator	No. of Assignments	Percentage of the Assignments-by Frequency Bands						
				25-30 Mc	30-35 Mc	35-40 Mc	40-45 Mc	45-50 Mc	50-54 Mc	54-60 Mc
57	Limited Coast Station, Public Class IB, IIB, IIIB Telephone (Maritime Mobile)	ML FCP	6			100.00				
58	Standard Frequency Station*	SS	5	60.00			40.00			
59	Control (Power; Industrial)	IW FX1	5					100.00		
60	Visual Broadcast (Auxiliary Broadcast)	BA EXV	5							100.00
61	Base (Taxi; Land Transportation)	LX FB	4			100.00				
62	Mobile (Taxi; Land Transportation)	LX MO	4			100.00				
63	Experimental Class II (Experimental)	E EX2	4	100.00						
64	Point-to-Point Telegraph (International Fixed; Public Press)	CP FXG	4	100.00						
65	Coastal Telephone or Coast Station Public Class IB, IIB, IIIB (Maritime)	M FCP	4		25.00	75.00				

Item No.	Class and Nature of Service	Designator	No. of Assignments	Percentage of the Assignments-by Frequency Bands						
				25-30 Mc	30-35 Mc	35-40 Mc	40-45 Mc	45-50 Mc	50-54 Mc	54-60 Mc
66	Land Radiopositioning Station*	PL	3		66.67	33.33				
67	*	FXH	3		100.00					
68	Television Pickup (Auxiliary Broadcast)	BA MLT	3	100.00						
69	Interzone (Police; Public Safety)	PP FXY	3						100.00	
70	(Fire)	PF FB2	3		100.00					
71	Industrial, Scientific and Medical Equipment (Amateur Citizens Disaster and ISM)	X ISM	2	50.00			50.00			
72	Base (Motion Picture; Industrial)	IM FB	2					100.00		
73	Telemetering Mobile (Experimental Services)	E MO	2		100.00					
74	(Experimental)	E EX-	2				50.00	50.00		
75	(Special Industrial)	II F2	2			50.00	50.00			

Item No.	Class and Nature of Service	Desig-nator	No. of Assign-ments	Percentage of the Assignments-by Frequency Bands						
				25-30 Mc	30-35 Mc	35-40 Mc	40-45 Mc	45-50 Mc	50-54 Mc	54-60 Mc
76	Flight Test Station*	FAT	1		100.00					
77	Geological, Geophysical, Petroleum Pipeline (Petroleum; Industrial)	IL	1			100.00				
78	(Power; Industrial)	IW	1			100.00				
79	Relay (Power;Industrial)	IW FX2	1			100.00				
80	Ship Telegraph or Public Ship Station Telegraphy Class I, II, III (Maritime Mobile)	M MSG	1			100.00				
81	Operational Fixed (Special Emergency; Public Safety)	PE FX0	1					100.00		
82	Control (Petroleum; Industrial)	IL FX1	1					100.00		
83	Control (Special Industrial)	II FX1	1					100.00		
84	Mobile (Relay Press; Industrial)	IY MO	1		100.00					

Item No.	Class and Nature of Service	Desig- nator	No. of Assign- ments	Percentage of the Assignments -by Frequency Bands						
				25-30 Mc	30-35 Mc	35-40 Mc	40-45 Mc	45-50 Mc	50-54 Mc	54-60 Mc
85	Mobile (State Guard; Public Safety)	PG MO	1		100.00					
86	Radio Positioning Mobile (Radio Location, Industrial)	IR PO	1		100.00					
87	(Experimental)	E EX	1			100.00				
88	Maritime Utility (Ship/Coast; Marine)	MU MO	1			100.00				
89	Ship (Marine Mobile)	M MS	1			100.00				
90	(Special Industrial)	II FB2	1				100.00			
91	Relay (Special Industrial)	II FX2	1				100.00			
		Total	40,931	3,516	7,559	11,882	6,545	11,376	10	43
		Percent	100.00	8.59	18.47	29.03	15.99	27.79	0.02	0.11

Appendix II

DESIRED-CARRIER TO NOISE, R, AND DESIRED-CARRIER TO UNDESIRED-CARRIER, R_u, RATIOS REQUIRED FOR SATISFACTORY RECEPTION OF F-S-K TELETYPE AND F-M VOICE COMMUNICATION SYSTEMS

By

A. D. Watt

The following system parameters are assumed for the purpose of calculating the required ratios:

Mobile F-M Voice Communication System

Voice modulated f-m with a maximum frequency deviation of ± 6 kc, an audio bandwidth of 3 kc and a receiver i-f noise bandwidth of 20 kc. The marginal performance of this system (used in calculating all the ratios where it is the desired service) is defined as "Obvious background noise and possible distortion; transmission understandable." This corresponds to Circuit Merit 3 of reference (11).

Fixed System

Frequency-shift-keyed teletype with a frequency deviation of ± 150 cycles, an equivalent square-wave keying rate of 60 cycles (i.e., multiplex operation), and a receiver i-f noise bandwidth of 500 cycles. The marginal performance of this system (used in calculating all the ratios where it is the desired service) is defined as a 1 percent binary error rate which corresponds to a synchronous teletype error rate of 50 characters per 1000.

The various conditions which can cause marginal performance are listed in table II-1 along with their corresponding unmodulated carrier ratios which are derived in the following paragraphs.

Table II-1

Case	Service	Source of Interference	Marginal R or R_u db
1	Fixed*	Noise	16.9
2	Fixed*	Mobile*	1.3**
3	Fixed*	Fixed*	16.9
4	Mobile	Noise	3.6
5	Mobile	Mobile*	6.6
6	Mobile	Fixed*	6.6

* The star indicates that the received power is fading in accordance with a Rayleigh distribution at the receiver site; the ratios, r and r_u, in these Rayleigh fading cases are in terms of the squares of the unmodulated carrier voltages averaged over a period of several minutes.

** This value applies during the time that the mobile transmitter is modulated; it provides a realistic measure of the interference on the assumption that the unmodulated carrier is offset so as to fall outside the Fixed service receiver pass-band.

Case 1. Fixed*/Noise.

From reference 9, equation (13) we find that the binary error rate for a narrow band f-s-k system with a Rayleigh fading carrier and random noise is:

$$P_\epsilon = \frac{1}{2(1+r)} \qquad \text{(II-1)}$$

where r is the ratio of the mean square carrier to mean square noise. When $P_\epsilon = 0.01$, we obtain $r = 49$, i.e., $R = 16.9$ db.

Case 2. Fixed*/Mobile*

There are three possible conditions for this case: (a) if the Mobile service carrier is offset relative to the Fixed service carrier and stabilized so as to remain outside the pass-band of the Fixed service receiver, then during periods when the Mobile service carrier is unmodulated there should be no interference, (b) whenever the unmodulated Mobile service carrier drifts into the Fixed service receiver pass-band, there will be substantial interference and $R_u = 16.9$ db, (c) when modulated, regardless of the precise location of the Mobile service carrier within its allocated band, $R_u = 1.3$ db. Since a combination of (a) and (c) results in the least interference and since it is technically possible to realize condition (a), it is assumed in this report that $R_u = 1.3$ db is a representative value for this case.

The basis for the above conclusions follows. Because of the nature of the Fixed service receiver, it is possible to assume a rather sharp transition (capture) point and, as a result, we can assume, for all practical purposes, that errors will result 50 percent of the time that the instantaneous-undesired-signal-power exceeds the instantaneous-desired-signal-power in the pass-band of the Fixed service receiver, and that no errors will occur in the converse situation.

The Mobile service signal power in the Fixed service receiver pass-band for condition (b) will be equal to the unmodulated carrier power, but for condition (c) will be 15.6 db ($10 \log_{10}(18000/500)$) less since the Mobile service transmitter carrier energy is spread out over an 18 kc band under conditions of full modulation.

Finally we must consider the probability (percentage of time/100) that the instantaneous-undesired-carrier-power exceeds the instantaneous-desired-carrier-power; for two Rayleigh fading carriers it has been shown[a/] that this probability may be expressed:

$$p = \frac{1}{(1 + r)} \qquad \text{(II-2)}$$

We find then for the probability of error in case 2(b):

$$P_\epsilon = \frac{1}{2(1 + r)} \qquad \text{(II-3)}$$

Since this is numerically the same as (II-1) we find that R_u = 16.9 db for the protection ratio against an unmodulated FM carrier in the pass-band of the Fixed Service receiver.

When the FM carrier is modulated this ratio becomes for case 2(c) $R_u = 16.9 - 15.6 = 1.3$ db.

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a/ Kenneth A. Norton, "The Effect of Fading on the Desired-to-Undesired Signal Ratio Required to Provide a Specified Grade of Service for a Given Percentage of a Specified Period of Time," Private Communication, Feb. 3, 1948.

Case 3. Fixed*/Fixed*

This case is similar to the preceding one except that the desired and undesired carriers are always equally effective in capturing the receiver limiter system. Because of this (II-3) is applicable.

Case 4. Mobile/Noise

The marginal performance specified for the mobile service requires operation of the FM receivers at input carrier-to-noise ratios where a gaussian input noise produces impulsive noise in the audio output. b/ Because the degree of impulsiveness is a function of the receiver characteristics as well as the input carrier-to-noise ratios for ratios less than 9 db, we shall not try to determine the rms signal-to-noise improvement over the input carrier-to-noise ratio as we would normally do at the higher input carrier-to-noise ratios where the audio noise is essentially gaussian. We shall instead consider a different method for determining the desired carrier-to-noise ratio. Since a typical good quality FM receiver provides an average instantaneous frequency equal to that of the strongest of two input voltages, we can consider that serious noise impulses occur only when the instantaneous-input-noise-envelope voltage is equal to or greater than the carrier envelope voltage. b/ The grade of service specified corresponds to the condition where noise pulses occur approximately 10 percent of the time, and the probability that the instantaneous-noise-envelope voltage exceeds its rms value by the ratio x is given by the cumulative Rayleigh distribution: +

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b/ A. D. Watt, "Statistical Characteristics of Sampled and Integrated AM and FM Noise," Naval Research Laboratory report No. 3856, October 22, 1951.

\+ It should be noted that x is the ratio of the noise envelope to the rms value of envelope, and not to the rms value of the input noise. This formula can, however, be used directly because the envelope of the carrier is equal to $\sqrt{2}$ times the rms carrier, and similarly the envelope noise rms value is equal to $\sqrt{2}$ times the input noise rms value.

$$P = e^{-x^2} \qquad \text{(II-4)}$$

For $P = 0.1$, $x^2 = 2.3$ and the rms carrier-to-noise ratio $R = 3.6$ db. It is interesting to note that although the 10 percent value chosen may seem arbitrary, the 3.6 db value is in good agreement with values obtained experimentally with a particular narrow-band FM system. [c/]

Case 5. Mobile/Mobile*

An exact solution in this case, as in the preceding one, would require the development of a new distribution by combining the capture characteristics of the receiver with the differential Rayleigh distribution; however, in this case, as before, we shall consider the capture transition as being very abrupt, which yields the conventional cumulative Rayleigh distribution (II-4).

Fading of the Mobile interfering carrier requires that the desired carrier exceed the instantaneous fading carrier about 99 percent of the time. This percentage value is considerably greater than the 90 percent used in case 4 above because of the greater effective loss, produced during a prolonged period where the desired carrier is exceeded, than is caused by short bursts of impulse noise. The distribution which results is the same in both cases; however, the signal fading rate in the VHF range is low enough to cause the loss of whole words rather than having very short portions of a syllable omitted as is the case with the much higher frequency noise. [+] Using $P = 0.01$, we obtain $x^2 = 4.6$ and $R_u = 6.6$ db for the required protection ratio.

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c/ E. Toth and J. D. Wallace, NRL Report No. 3230, June 1952.

+ This is demonstrated by the well known fact that a considerable portion of a speech wave can be chopped out without affecting its intelligibility if the chopping rate is high enough and the chopped interval small enough.

Case 6. Mobile/Fixed*

The same method and answer of Case 5 apply here.

Appendix III

SPORADIC E COMPUTATIONS

by

E. K. Smith

A. Introduction

This appendix describes the sources of sporadic E data used here and also the methods employed to reduce these data to a form suitable for obtaining the mean curves of sporadic E transmission loss which appear in the body of this report. The base data utilized are described in section B of this appendix. Section C considers the normalizing procedures employed to adjust data taken for a few hours of the day and over only part of the year to a twenty-four hour day over a full year. The method used here to extrapolate Es data taken at one frequency to a different one is discussed under section D. A justification of this relation is also shown in the same section. Section E describes the base data adjusted to their final form: instantaneous basic transmission loss on the desired frequencies of 25, 35, 45 and 55 Mc.

B. Description of Data

The only usable transmission loss data pertinent to sporadic E transmission at oblique incidence stemmed from two sources. The first of these consists of a series of reports[1/] released by the FCC in connection with the reallocation of the F.M. band after the last war. These describe transmission loss measurements of station WGTR Paxton, Mass (44.3 Mc, 340 kw) made at a series of FCC monitoring stations in the period 1943 through 1945. The second source is found in a recent paper in a Japanese journal.[2/] Following the recommendation of Study Program No. 22 of the Geneva Meeting of CCIR, a recording program was undertaken in Japan during the period of June through August 1952. Transmitters on 31.55 Mc, 43.85 Mc, and 65.82 Mc were located at Hiraiso on the northeastern coast of Honshu. Transmission loss measurements were then made at seven monitoring stations at distances of 302 to 674 miles from Hiraiso. The particulars of both of these sets of data are given in the table below.

1/ "Report on VHF Field Strength Measurements 1943-1944," FCC Docket No. 6651, Exhibit 4, Sept. 28, 1944; "Measurements of Sporadic E Field Intensities," FCC, 14100.

2/ "Study of Long Distance Propagation of VHF Waves by Sporadic E Ionization," by T. Kono, Y. Uesugi, M Hirai and G. Abe, Journal of the Radio Research Laboratories, Tokyo, Japan, vol. 1, pp. 1-10, March 1954.

Source of Es Transmission Loss Data Used in This Report

Transmitter				Receiver			Source of Data
Location	Power	Frequency	Assumed Operating Hours	Location	Miles Distance	Period	
Paxton, Mass. (WGTR)	340 kw	44.3 Mc	0600-2400	Allegan, Mich.	720	Sep.'43-Aug.'44	Ref. 1
				Atlanta, Ga.	900	"	"
				Grand Island, Neb.	1370	"	"
				Montgomery, Ala.	1040	Jun. - Aug.'45	"
Hiraiso, Japan	100 w	31.55 Mc	0000-2400	Osaka	302	Jun. - Aug.'52	Ref. 2
				Mt. Gyosei	316	"	"
				Kochi	447	"	"
				Mt. Ishigatake	524	"	"
				Yamagawa	674	"	"
Hiraiso, Japan	100 w	43.85 Mc	0000-2400	Osaka	302	"	"
				Kochi	447	"	"
				Nobeoka	570	"	"
				Yamagawa	674	"	"
Hiraiso, Japan	100 w	65.82 Mc	0000-2400	Osaka	302	"	"
				Kochi	447	"	"
				Nobeoka	570	"	"
				Yamagawa	674	"	"

C. Normalizing Procedure

It will be noticed in the table above that none of the measurements of sporadic E transmission loss were made for a full day over a period as long as a year. The FCC data which are mostly for a year's duration were taken only 18 hours per day. The Japanese data which are assumed to be 24 hours per day, on the other hand, are limited to three summer months. To make these data more readily usable and also to put them all on a comparable base, they have been normalized, in each case, to a full year. The U.S. data in normalized form refer to what would probably have been observed during the period September 1943 through August 1944 for a 24 hour day. The normalized Japanese data apply correspondingly to the calendar year 1952. No effort has been made to reduce the two sets of data to a common year, as this involves a possible error of a greater order of magnitude.

The normalizing procedure assumes that the seasonal or diurnal distribution of sporadic E observed over the oblique VHF path is proportional to that obtained for fEs > 7 Mc on the nearest vertical incidence ionosphere sounder for the period in question. The Washington, D.C. ionosphere sounder results as published in the CRPL -F series were used for the FCC paths. Data from the Yamagawa sounder was employed for the Japanese paths.

We may define:

p_1 = probability that the transmission loss is less than a given level for the year September 1943 - August 1944,

r_1 = measured fraction of the time that transmission loss is less than a given level for June, July and August, 06-24 hours in the United States,

r_2 = measured fraction of the time that transmission loss is less than a given level for September 1943 through August 1944 in the U.S.

Then for the FCC paths where Washington, D.C. data is used:

$$p_1 = 0.250 \; r_1 \qquad \text{(III-1)}$$

$$p_1 = 0.782 \; r_2 \qquad \text{(III-2)}$$

Correspondingly for the Japanese paths let

p_2 = probability that the transmission loss is less than a given level for the calendar year 1952,

r_3 = measured fraction of the time that transmission loss is less than a given level during June, July and August, 1952, in Japan.

Then, when the Yamagawa sounder data is used:

$$p_2 = 0.391 \; r_3 \qquad \text{(III-3)}$$

These normalized data are presented in form of a series of broken-line curves of instantaneous basic transmission loss versus distance with probability of occurrence as parameter in Figs. III-1, III-2 and III-3. These data refer approximately to the frequencies of

SPORADIC E BASIC TRANSMISSION LOSS VERSUS DISTANCE AT 32 MC

The Labels on the Curves Refer to the Probability, p, During a Period of One Year that the Observed Basic Transmission Loss will be Less than the Ordinate Values

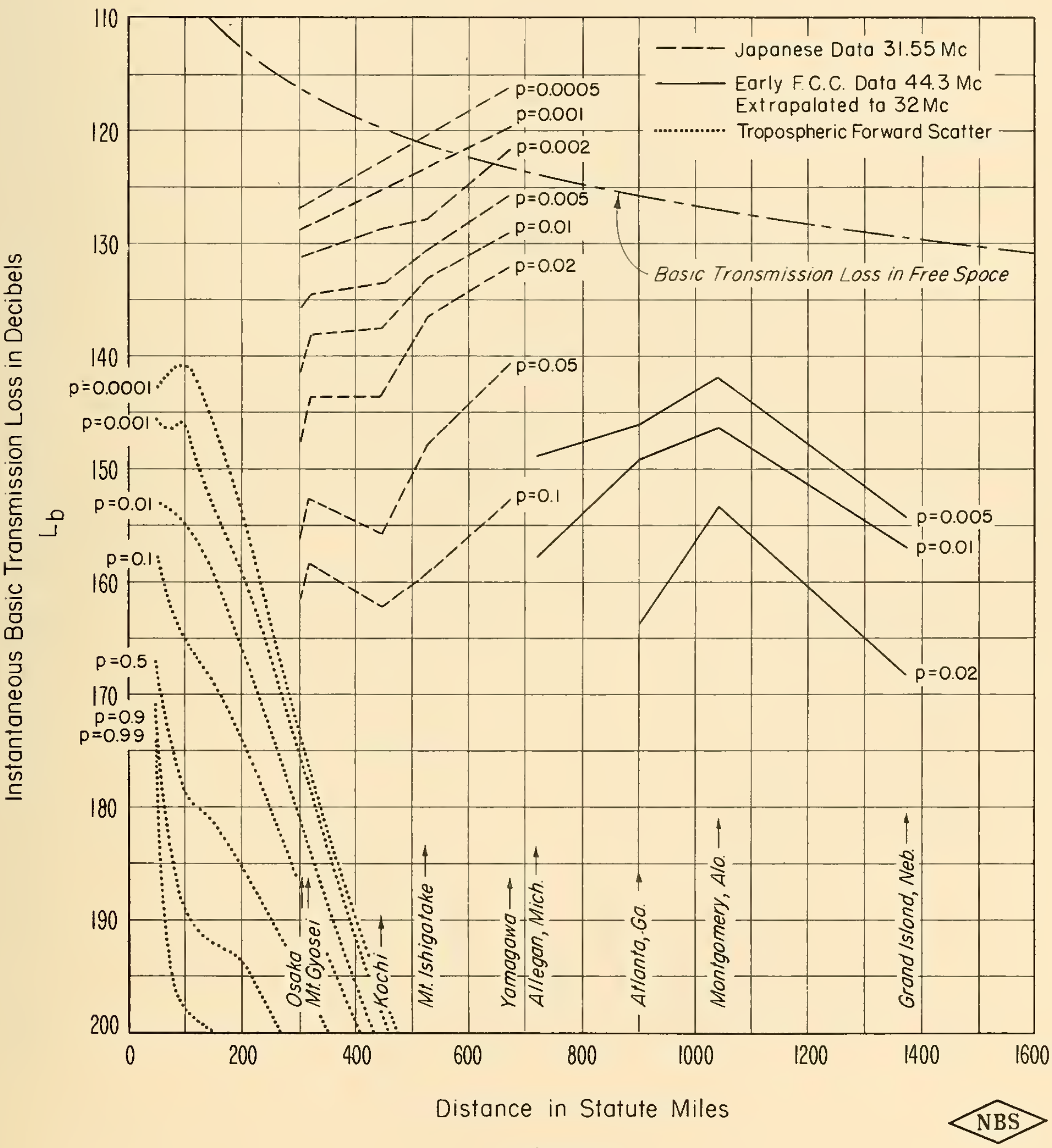


Figure III-1

SPORADIC E BASIC TRANSMISSION LOSS VERSUS DISTANCE AT 44 MC

The Labels on the Curves Refer to the Probability, p,
During a Period of One Year that the Observed
Basic Transmission Loss will be Less than the Ordinate Values

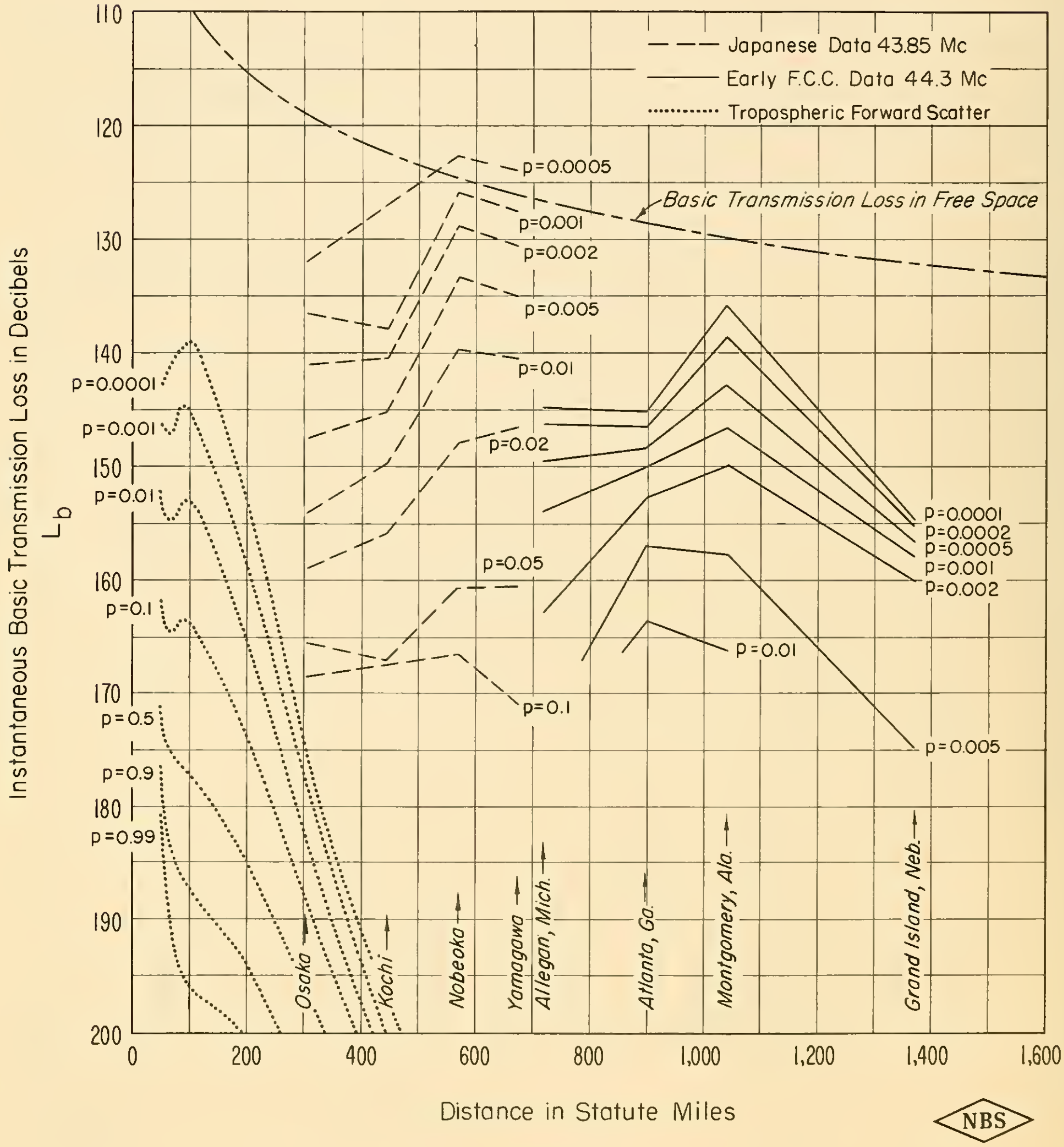
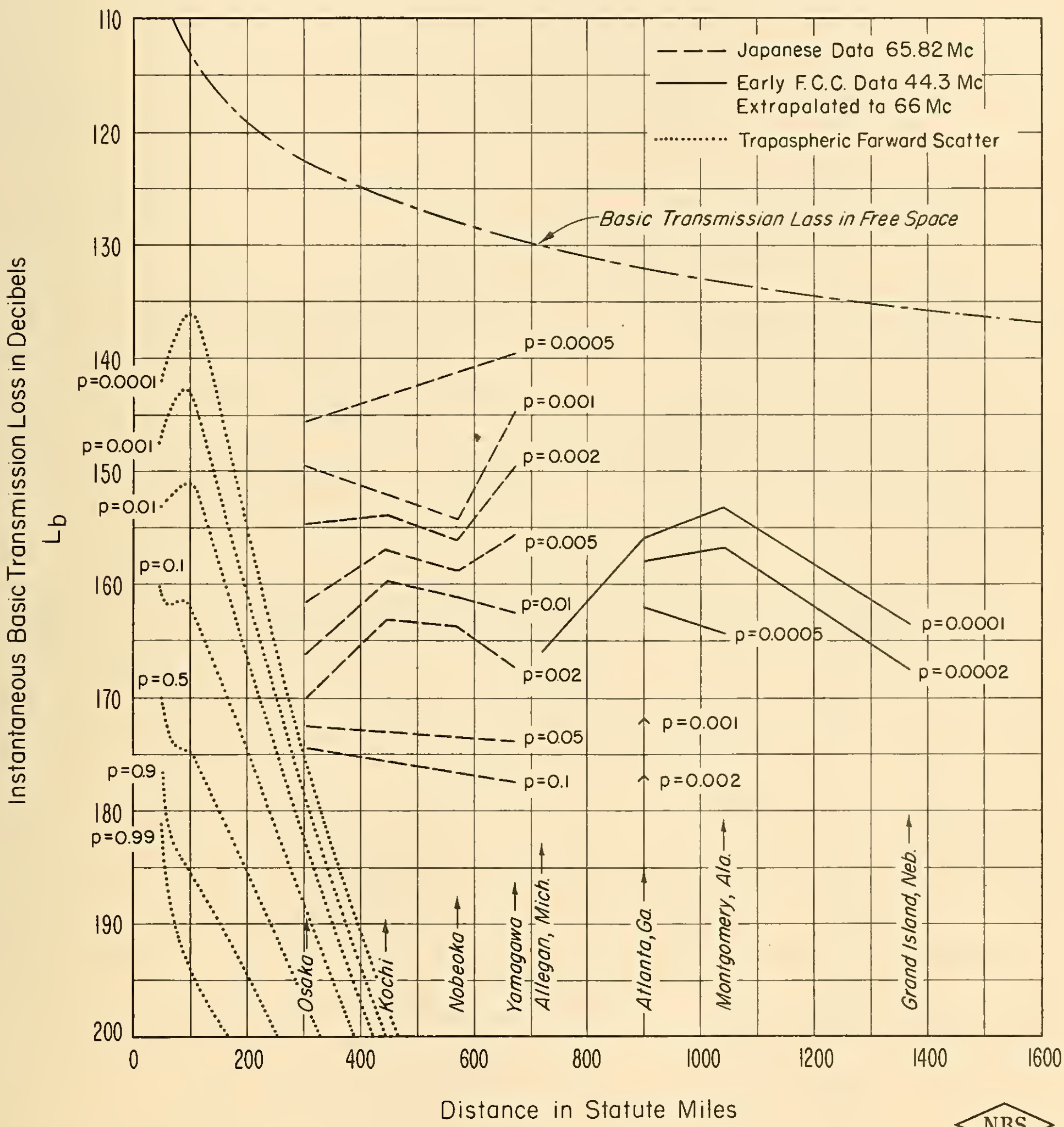


Figure III-2

SPORADIC E BASIC TRANSMISSION LOSS VERSUS DISTANCE AT 66 MC

The Labels on the Curves Refer to the Probability, p,
During a Period of One Year that the Observed
Basic Transmission Loss will be Less than the Ordinate Values



NBS

Figure III-3

32 Mc, 44 Mc and 66 Mc. The dotted curves of tropospheric forward scatter are theoretical values added for reference.

D. Variation of Es Incidence with Frequency

The relation derived by Mrs. Phillips[3/] from the distribution of fEs at vertical incidence stations had the form

$$\log p = a + bf \qquad \text{(III-4)}$$

where p = probability that fEs > f

a, b are adjustable constants.

If we make the assumption $a = 0$ in (III-4), the relation becomes a simple proportionality. The constant b can be eliminated by dividing (III-4) by the same relation referred to a different frequency and value of p. Thus

$$\frac{\log p_1}{\log p_2} = \frac{f_1}{f_2} \qquad \text{where } p_1, p_2 = \text{probabilities}; \quad f_1, f_2 = \text{frequencies} \qquad \text{(III-5)}$$

This relation has no arbitrary constants but does, of course, contain the implicit assumption that $a = 0$ in (III-4). Its use in this section will be demonstrated through a numerical problem. For example, for any given level of transmission loss relative to the expected free space transmission loss, if a level of 30 db below free space were observed on a frequency $f_1 = 60$ Mc at a probability of $p_1 = 0.01$ or 1% of the time, then at $f_2 = 30$ Mc we may solve for p_2 from (III-5):

3/ "Variations in Sporadic E Ionization," by M. L. Phillips, Trans. AGU, Vol. 28, p. 77 (Feb. 1947); IRPL "Radio Propagation Conditions," Oct. 14, 1943, pp. 3-4, and Feb. 14, 1944, pp. 3-4.

OBSERVED DISTRIBUTIONS OF SPORADIC-E BASIC TRANSMISSION LOSS

Data Normalized to Represent a Full Year

a) Transmitters for Japanese Paths Located at Hiraiso, 31.55, 43.85, 65.82 Mc, 100 Watts

b) Transmitter for U. S. Paths Located at WGTR, Paxton, Mass., 44.3 Mc, 340 kw

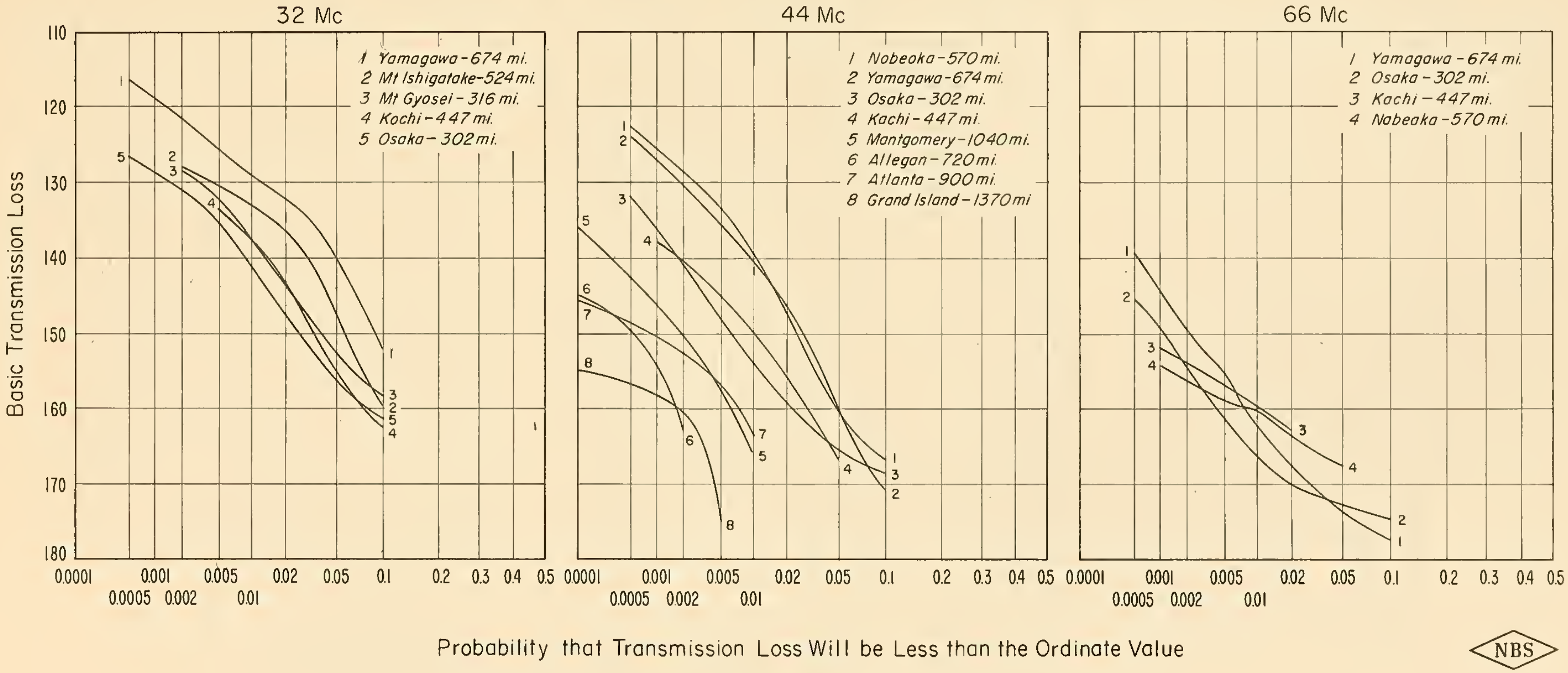


Figure III - 4

COMPARISON OF PREDICTED FIELD INTENSITY WITH THAT OBSERVED AT YAMAGAWA

Prediction Relation: $f_1 \log P_2 = f_2 \log P_1$

Observed Level Probabilities at 43.85 Mc Were Used as Reference

Yamagawa Data Normalized to Represent Full Year 1952

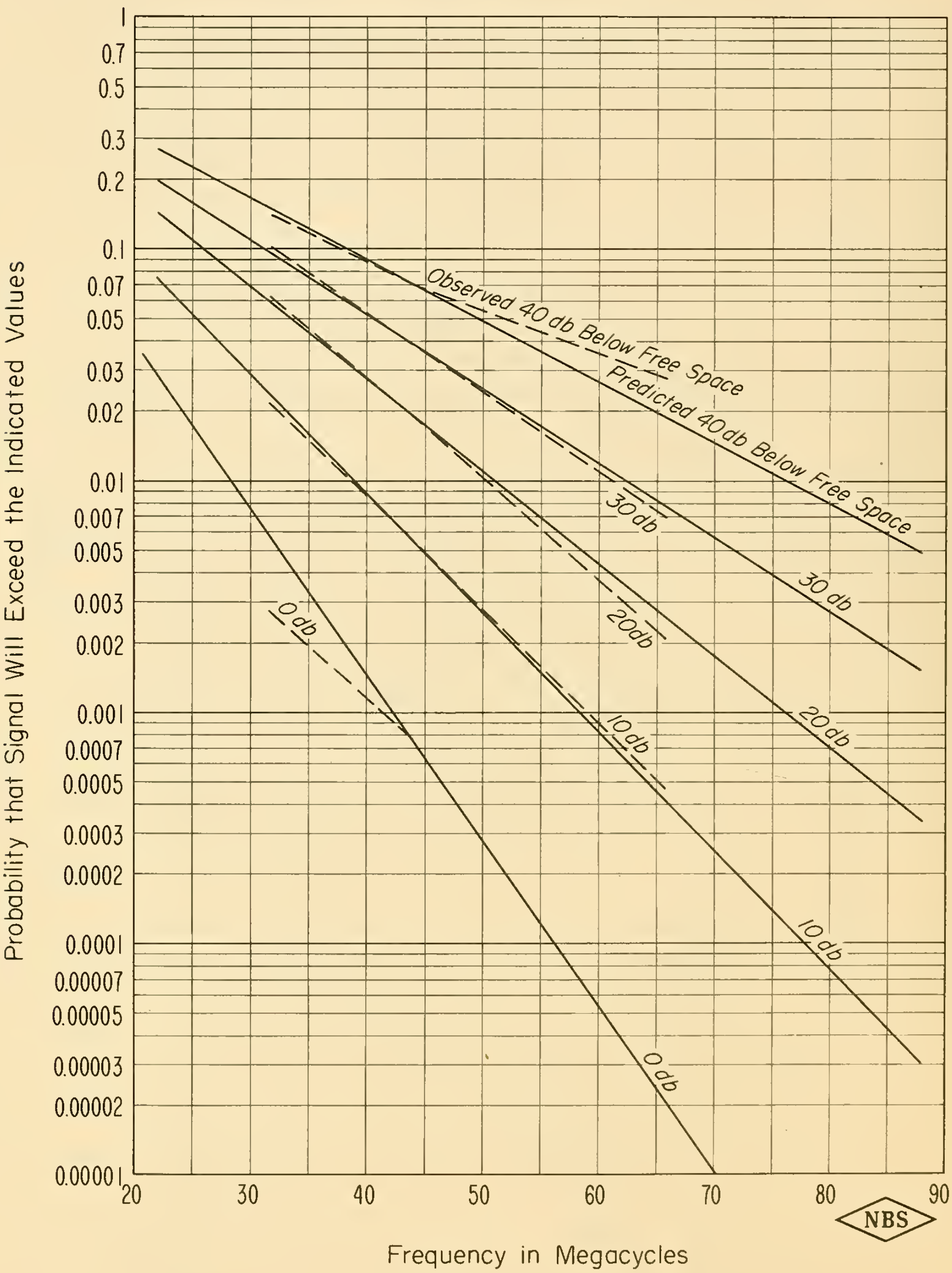


Figure III-5

$$\log p_2 = \frac{f_2}{f_1} \log p_1 = \frac{30}{60} (-2) = -1 \qquad \text{(III-6)}$$

Thus for $p_2 = 0.1$ or 10% of the time, we would expect by this method of extrapolation a transmission loss relative to free space less than 30 db on 30 Mc if, during the period in question, these levels relative to free space were observed for 1% of the time on 60 Mc.

To the best of our knowledge the Japanese data[2/] present the first opportunity to test this relation for oblique incidence transmission loss data at VHF frequencies. The basic data are given on Fig. III-4 which presents the measured distributions of basic transmission loss for three frequencies near 32 Mc, 44 Mc and 66 Mc. The Japanese data represent a coherent set of measurements all taken during the same period. Three stations, Yamagawa (674 mi.), Kochi (447 mi.) and Osaka (302 mi.), have distributions available for all three frequencies. Osaka and Kochi are at distances such that one might suspect tropospheric contamination to the 66 Mc data, but Yamagawa should be pure sporadic E on all three frequencies. Therefore it was selected for a test of relation (III-5). The results of this comparison of prediction and measurement are given in Fig. III-5. It should be stressed that the transmission loss levels held constant here were in terms of "db below free space" and not "basic transmission loss." In terms of the relation for basic transmission loss L_b in db we have:

$$L_b = 20 \log_{10} d + 20 \log_{10} f + A + 36.58 \qquad \text{(III-7)}$$

where d = distance in miles,

f = frequency in Mc,

A = propagation path attenuation in db relative to the free space value.

The term which is set constant in (III-7) when the relation (III-5) for probability at a different frequency is to be used is A, the attenuation relative to free space. Relation (III-5) was also applied to basic transmission loss, but there was a systematic deviation by the amount of the variation of the frequency term in (III-7) with frequency.

As relation (III-5) appeared to meet the test through comparison with the Yamagawa data, it was then used to extrapolate the FCC data from 44.3 Mc to both 32 Mc and 66 Mc in terms of db below free space, which was then reconverted to basic transmission loss and entered on Figs. III-1 and III-3.

E. Estimates of the Distributions of Instantaneous Basic Transmission Loss at 25, 35, 45 and 55 Mc

If it is assumed that distribution of instantaneous sporadic E transmission loss relative to free space obeys, at least to some extent, the law of (III-5), we may use this law to derive probability distributions at the desired frequencies of 25, 35, 45 and 55 Mc. Thus we can extrapolate each measured distribution to four frequencies, in exactly the same way that the FCC data were extrapolated to 32 and 66 Mc in Figs. III-1 and III-3 respectively. These extrapolations for the ten paths (six Japanese and four U.S.) are shown in Figs. III-6 through III-10, arranged in order of increasing distance. There is some indication in the Japanese data that the applicability of (III-5) increases with decreasing f cosi where f is the frequency at which the data were taken and i the incident angle on the sporadic E region of the ionosphere (f cosi is, of course, the equivalent vertical incidence frequency if the cosine law is assumed to apply). This appears particularly true from the derived distributions for Osaka (poor agreement for all three data frequencies), Kochi (some agreement between the curves for the two lower data frequencies), and Yamagawa (good agreement for all three data frequencies). Fig. III-11 illustrates the variation of f cosi for the four frequencies on which data were recorded. If we limit f cosi to values, say less than 16, we see from Fig. III-11 that our cases of poor agreement are eliminated. The success of this limit is possibly fortuitous and thus should not necessarily be taken literally for application elsewhere.

EXTRAPOLATED DISTRIBUTIONS OF TRANSMISSION LOSS

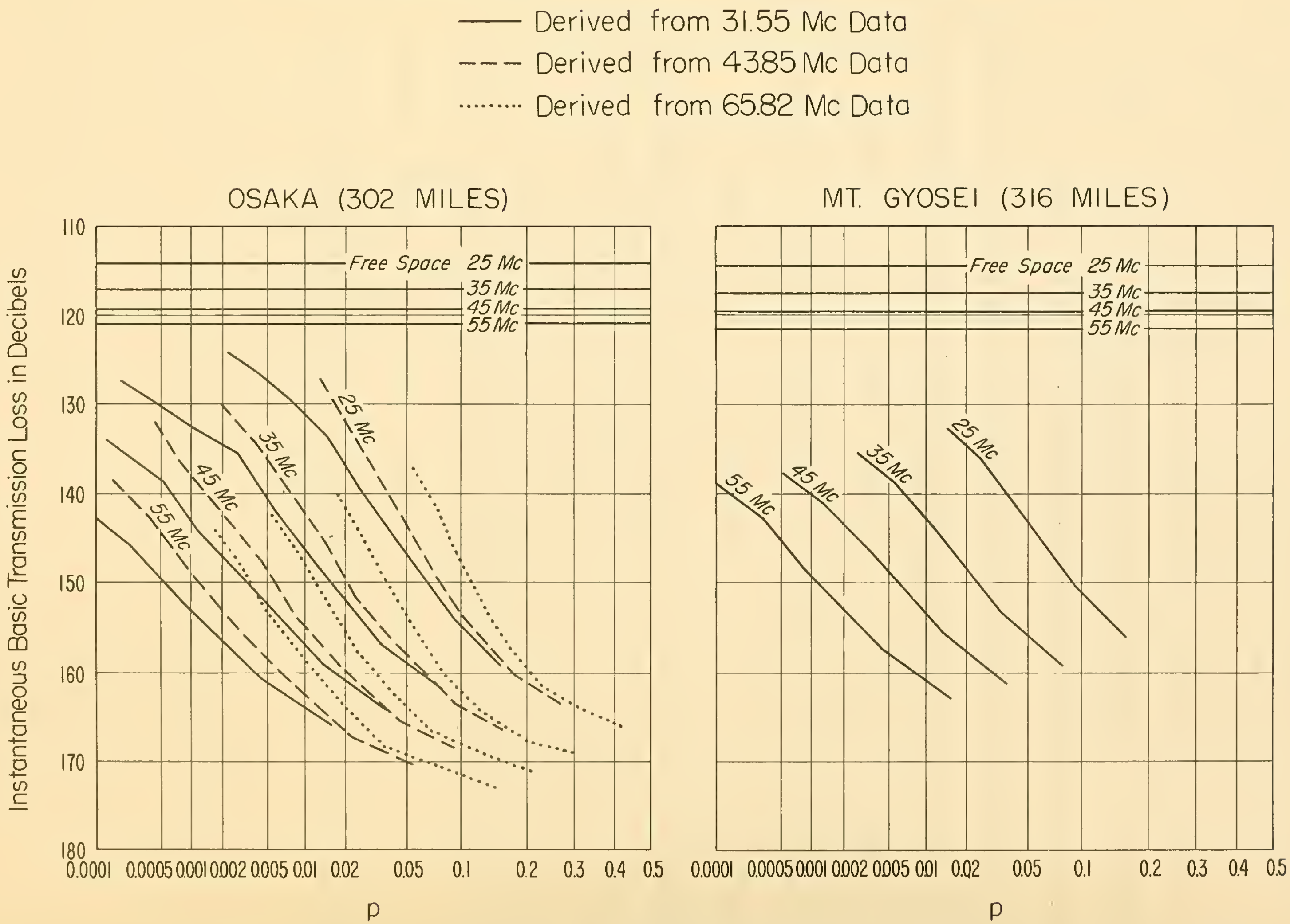


Figure III - 6

EXTRAPOLATED DISTRIBUTIONS OF TRANSMISSION LOSS

——— Derived from 31.55 Mc Data
---- Derived from 43.85 Mc Data
········· Derived from 65.82 Mc Data

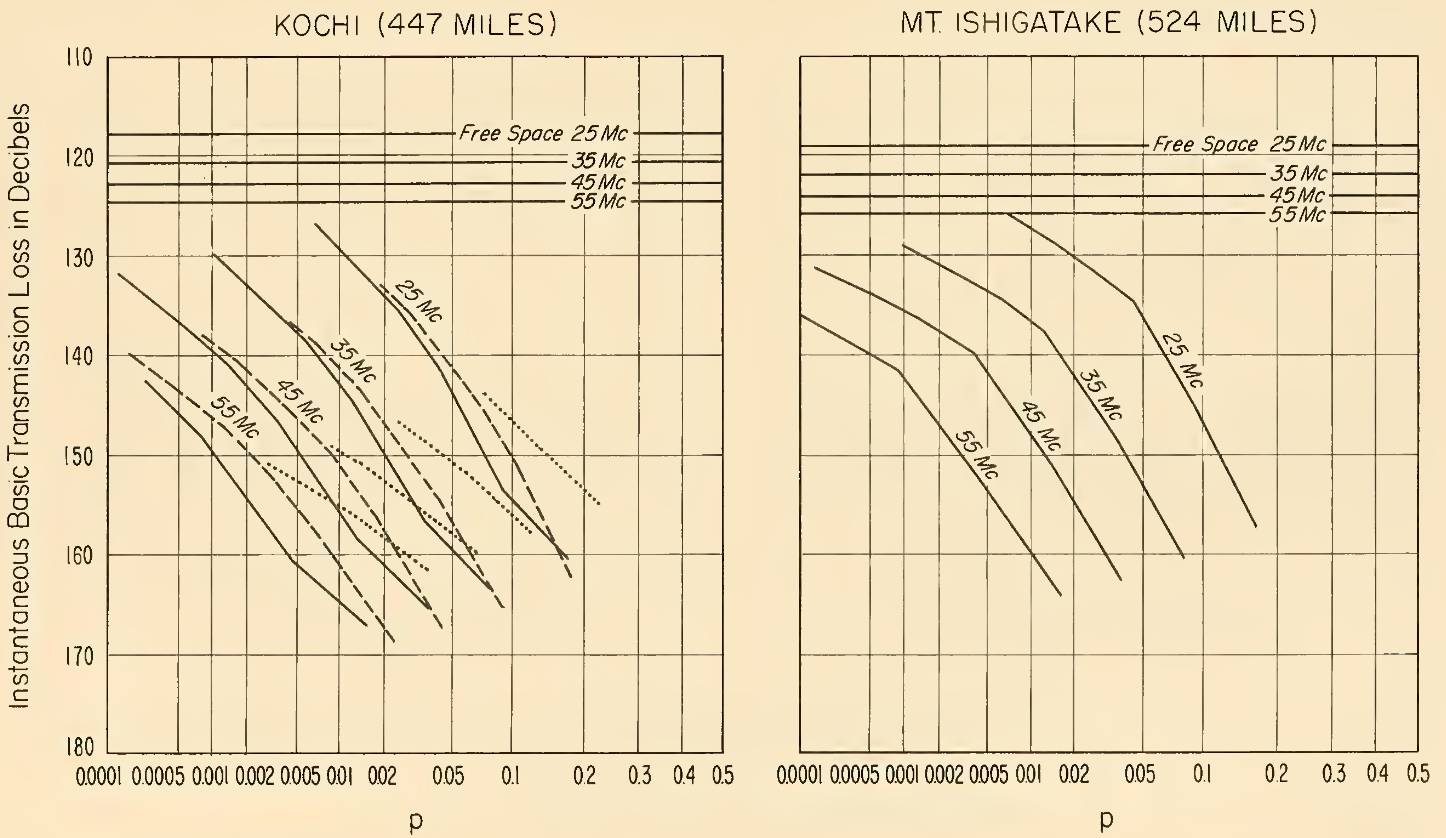


Figure III-7

NBS

EXTRAPOLATED DISTRIBUTIONS OF TRANSMISSION LOSS

——— Derived from 31.55 Mc Data
– – – – Derived from 43.85 Mc Data
·········· Derived from 65.82 Mc Data

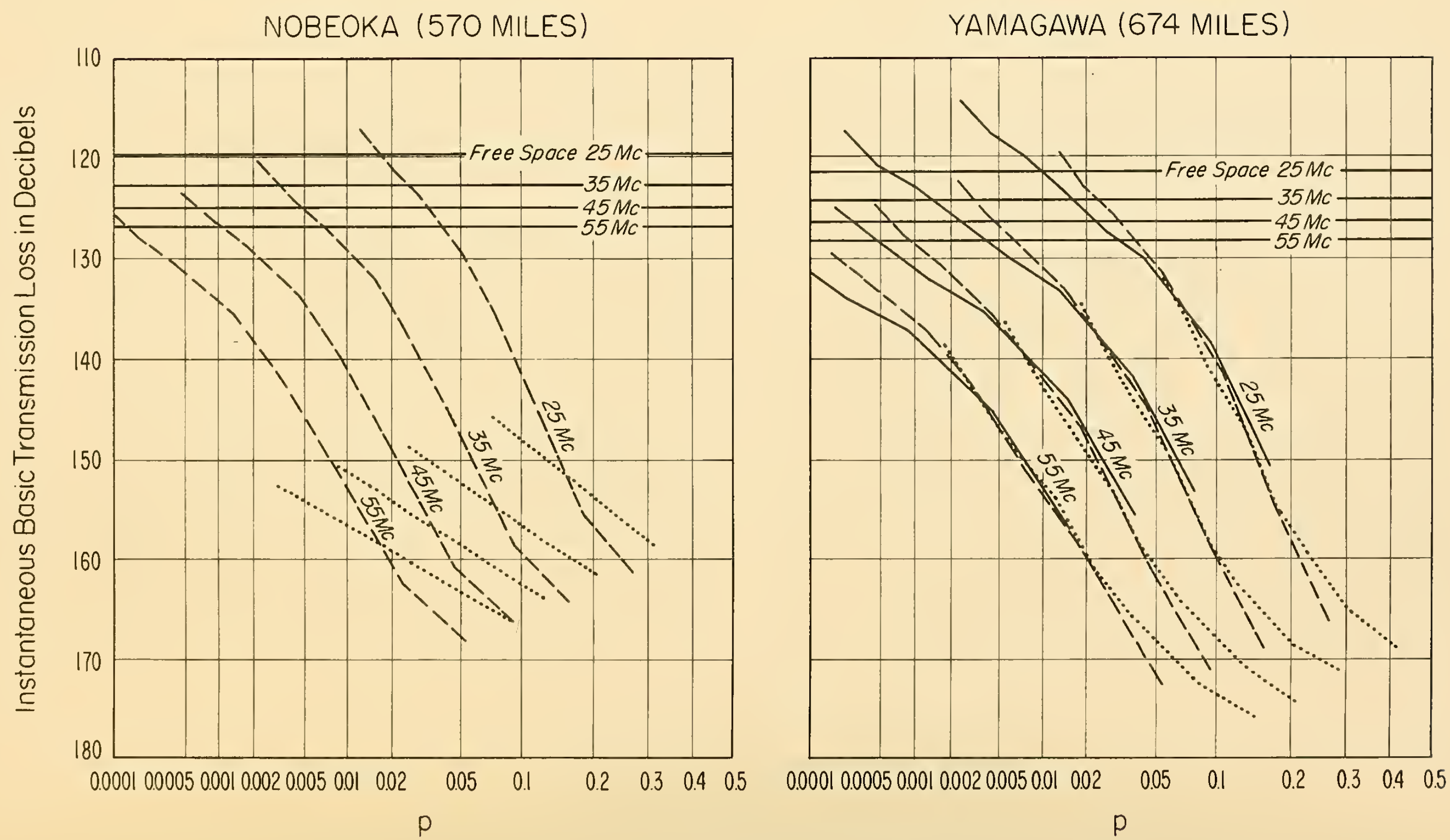


Figure III – 8

NBS

EXTRAPOLATED DISTRIBUTIONS OF TRANSMISSION LOSS

Derived from 44.3 Mc Data

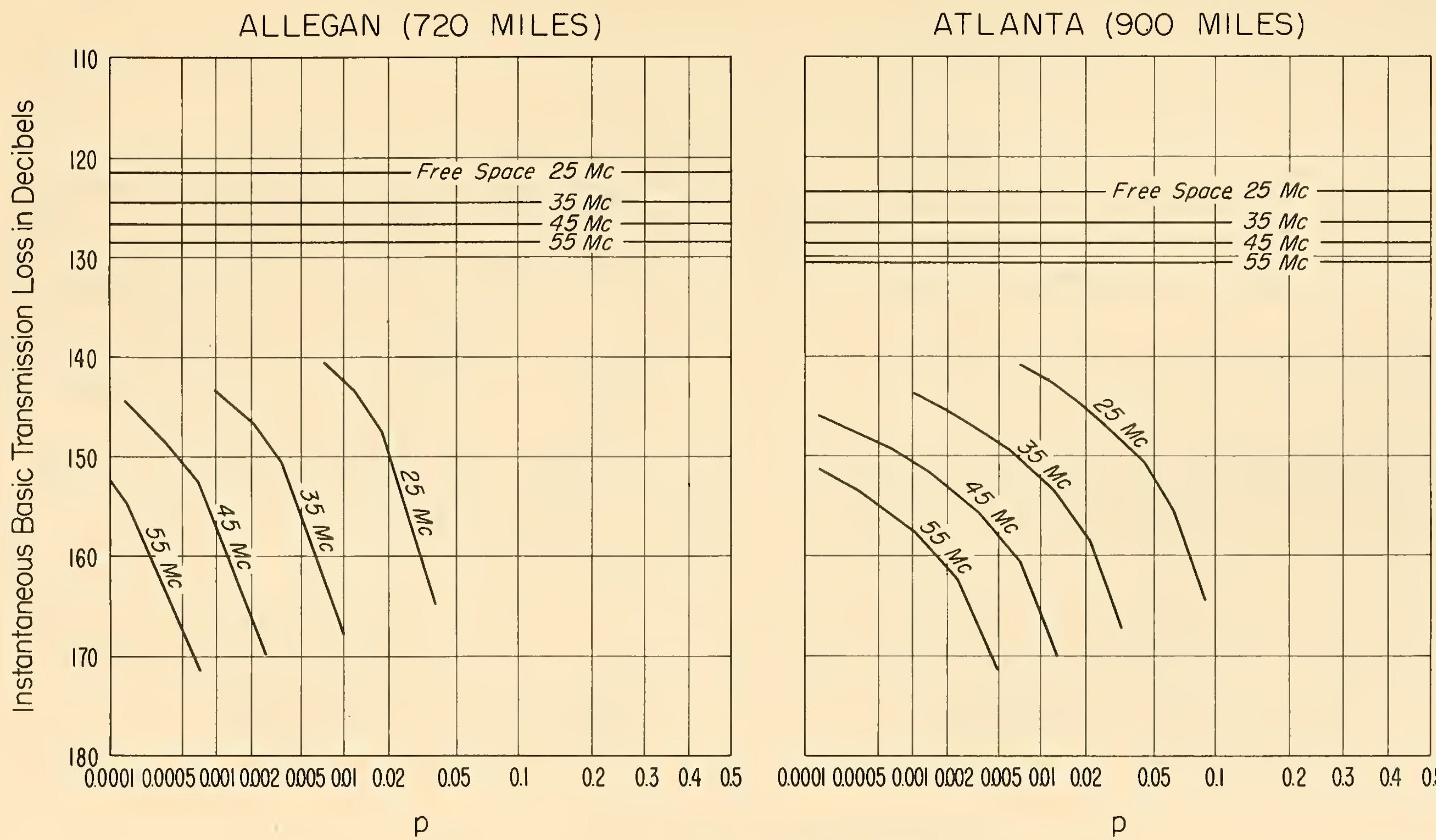


Figure III-9

EXTRAPOLATED DISTRIBUTIONS OF TRANSMISSION LOSS

Derived from 44.3 Mc Data

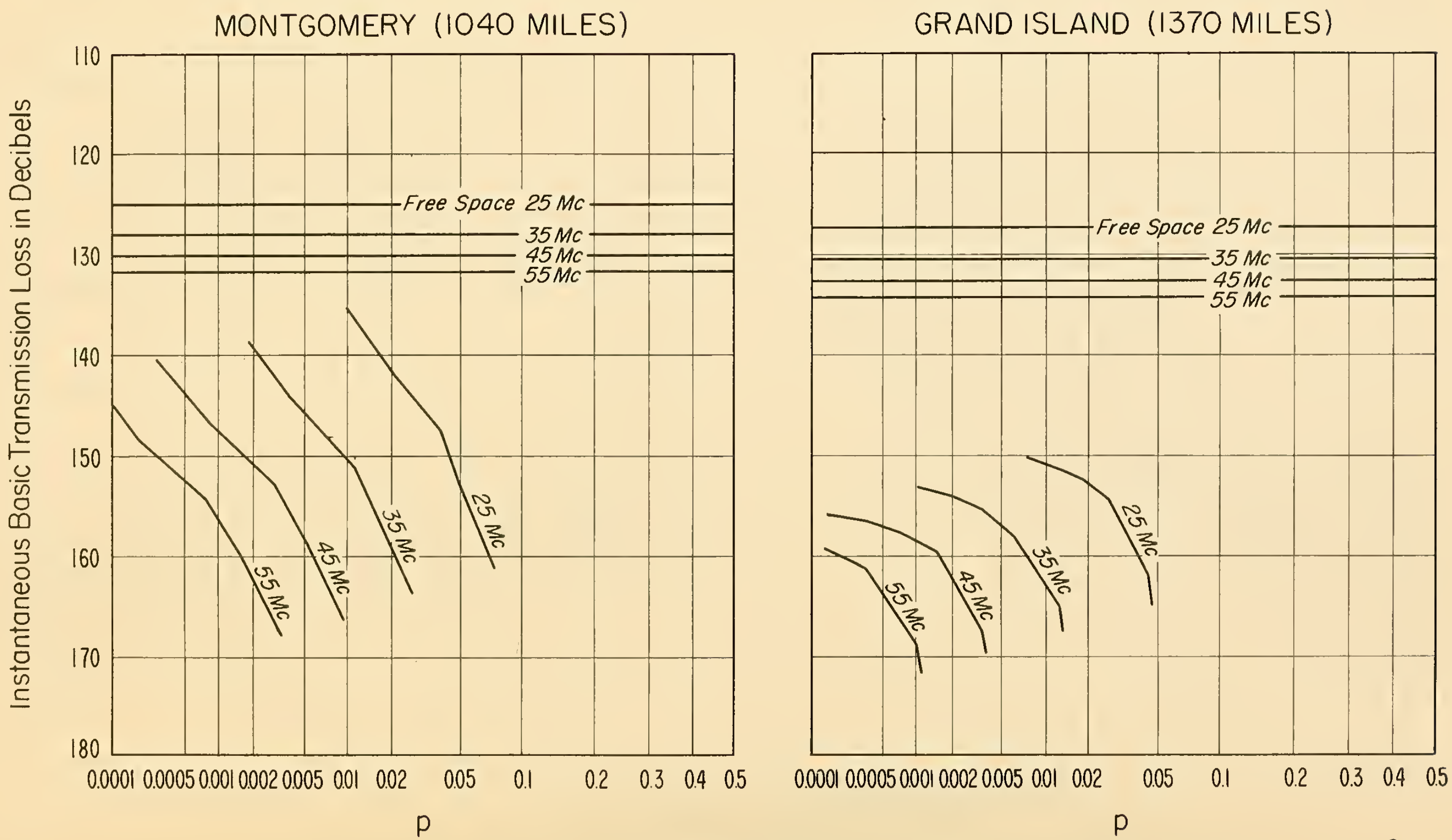
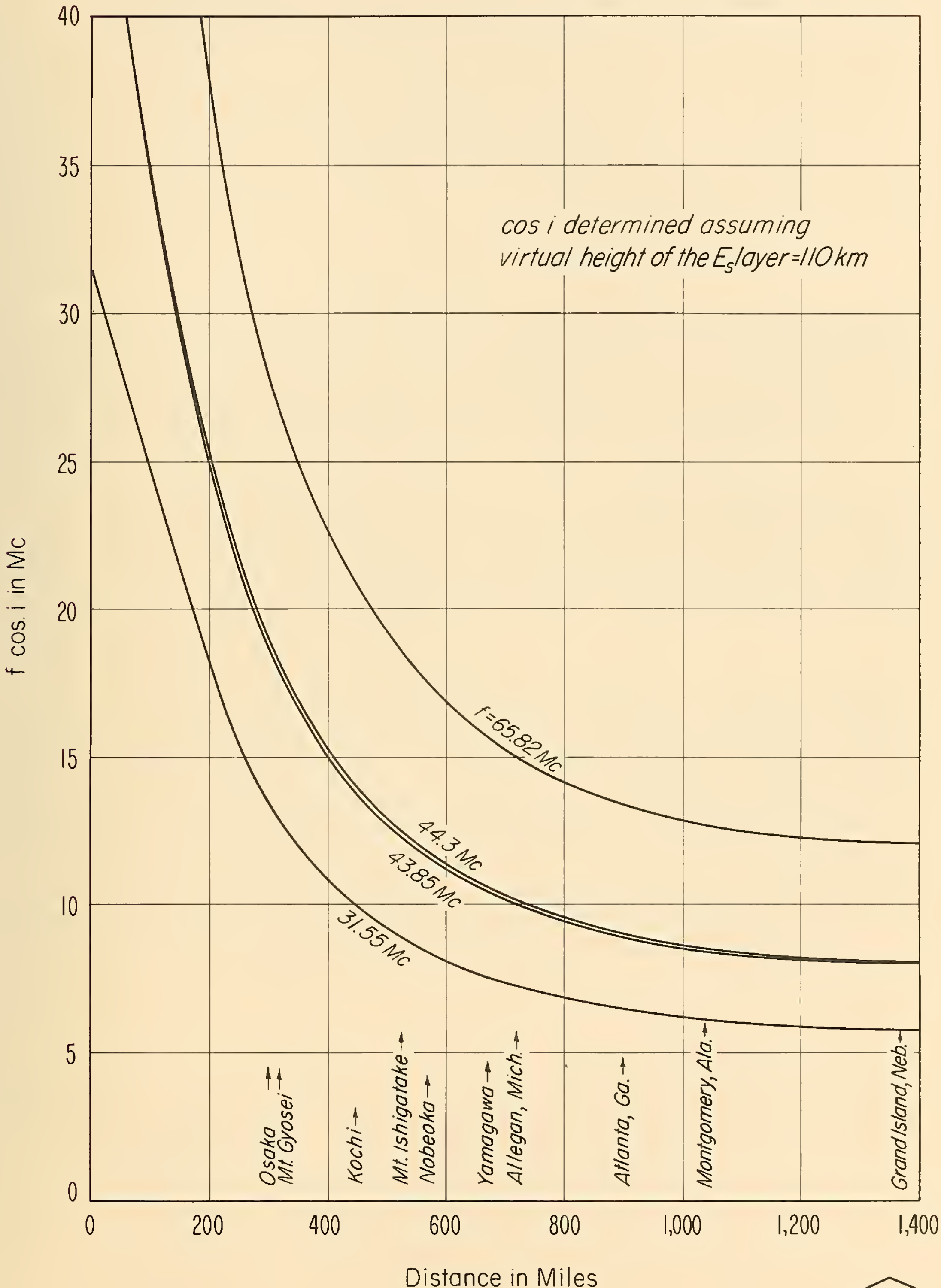


Figure III-10

EQUIVALENT VERTICAL INCIDENCE FREQUENCY
IN TERMS OF GREAT CIRCLE DISTANCE



NBS

Figure III -11

Appendix IV

LONG-TERM CUMULATIVE DISTRIBUTION OF INSTANTANEOUS RECEIVED POWER

By

Garner McCrossen

1. INTRODUCTION

For certain analyses, the Central Radio Propagation Laboratory of the National Bureau of Standards has found it convenient to tabulate data in the form of hourly median values of transmission loss. It is observed that the hourly medians of received power are approximately log-normally distributed in time.[1/]

Other types of analyses, however, require statistical characteristics of transmission loss within each hour. These analyses indicate that, where scattering is predominant, the instantaneous received power is approximately Rayleigh-power distributed for certain periods of time. [1/]

It is the major intent of this note to derive, under certain restrictive conditions, a cumulative distribution function for the instantaneous received power, expressed in decibels above unit power, over an indefinitely long period of time for regions where scattering is the only important propagation mechanism. Such a cumulative distribution function will have a form which involves an improper integral. Another intent of this note is to indicate a numerical method for obtaining the cumulative distribution of instantaneous received power in decibels above unit power.

1/ NBS Circular 554, "Cheyenne Mountain Tropospheric Propagation Experiments," by A. P. Barsis, J. W. Herbstreit, and K. O. Hornberg, issued January 3, 1955.

2. THE CUMULATIVE DISTRIBUTION FUNCTION

The assumption is made that the fields dealt with are ones where scattering is the only important propagation mechanism. It is further assumed that at a given instant and at a given receiving point, a large number, m, of independent vector voltages $v_1, \ldots, v_m$ of approximately equal amplitudes $x_1, \ldots, x_m$ arrive in random relative phase. The theoretical instantaneous received power is v^2/ζ, where

$$v = \left| \sum_{i=1}^{m} v_i \right| \tag{1}$$

and ζ is the impedance at the point of measurement. The phase of v is random. The quantity x^2/ζ is defined as follows:

$$\frac{x^2}{\zeta} = \frac{1}{\zeta} \sum_{i=1}^{m} x_i^2 \tag{2}$$

We now define the Rayleigh-voltage distribution of v as that distribution whose frequency function is

$$f(v|x) = \frac{2v}{x^2} \exp\left\{-v^2/x^2\right\}, \tag{3}$$

where x is considered constant.

As mentioned previously, analyses of transmission loss data indicate that instantaneous received power has a Rayleigh-power distribution for certain periods of time which are of the order of 10 minutes to one hour. If $r \equiv v^2/\zeta$ represents instantaneous received power, then (3) leads to a definition of the Rayleigh-power distribution of r as that distribution whose frequency function is

$$f(r\,|\,q) = \frac{1}{q} \exp\{-r/q\}\,, \tag{4}$$

where $q \equiv x^2/\zeta$ is considered constant. In this note the period of time during which r is Rayleigh-power distributed with a distribution function (4) will be assumed to last as long as q is constant. If in (4) q varies, then $f(r\,|\,q)$ must be interpreted as a conditional frequency function.

If z is the median value of r when q is constant, then

$$\int_z^{\infty} \frac{1}{q} \exp\{-r/q\}\, dr = \frac{1}{2}\ . \tag{5}$$

Integrating the left member of (5), it is seen that z satisfies the relation

$$z = q \log_e 2\ . \tag{6}$$

But the relation in (6) is one between q and the median z. As mentioned previously, it has been observed that hourly medians of received power have approximately a log-normal distribution. It will now be assumed in this note that $Z \equiv 10 \log_{10} z$ has a normal distribution with mean $\overline{Z}$ in decibels above unit power and standard deviation σ_Z in decibels. The frequency function of Z is

$$f(Z) = \frac{1}{\sigma_Z \sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left(\frac{Z - \bar{Z}}{\sigma_Z}\right)^2\right\} \qquad (7)$$

Using (7) and the relation $z = 10^{Z/10}$ we obtain

$$f(r|Z) = (\log_e 2)\, 10^{-Z/10} \exp\left\{-(\log_e 2) 10^{-Z/10} r\right\} \qquad (8)$$

as the conditional frequency function of r in terms of Z.

Letting $f(r, Z)$ denote the joint frequency function of r and Z and using the relation $f(r, Z) = f(Z) f(r|Z)$, we write, by (7) and (8),

$$f(r, Z) = \left[\frac{1}{\sigma_Z \sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left(\frac{Z - \bar{Z}}{\sigma_Z}\right)^2\right\}\right] \left[\frac{\log_e 2}{10^{Z/10}} \exp\left\{\frac{-r \log_e 2}{10^{Z/10}}\right\}\right]. \qquad (9)$$

We desire the probability that r exceeds r_o. This probability is obtained by integrating $f(r, Z)$ over the region defined by $r \geq r_o$, $Z \geq \pm \infty$. Thus, using (9),

$$p(r > r_o) = \frac{1}{\sigma_Z \sqrt{2\pi}} \int_{-\infty}^{\infty} \exp\left\{-\frac{1}{2}\left(\frac{Z - \bar{Z}}{\sigma_Z}\right)^2\right\} dZ \int_{-r_o}^{\infty} \frac{\log_e 2}{10^{Z/10}} \exp\left\{-\frac{r \log_e 2}{10^{Z/10}}\right\} dr\,, \qquad (10)$$

or

$$p(r > r_o) = \frac{1}{\sigma_Z \sqrt{2\pi}} \int_{-\infty}^{\infty} \exp\left\{-\left[\frac{r_o \log_e 2}{10^{Z/10}} + \frac{1}{2}\left(\frac{Z - \bar{Z}}{\sigma_Z}\right)^2\right]\right\} dZ. \qquad (11)$$

If $R \equiv 10 \log_{10} r$ is the instantaneous received power expressed in decibels above unit power, then it follows immediately from (11) that

$$p(R > R_o) = \frac{1}{\sigma_Z \sqrt{2\pi}} \int_{-\infty}^{\infty} \exp\left\{-\left[(\log_e 2) 10^{(R_o - Z)/10} + \frac{1}{2}\left(\frac{Z - \bar{Z}}{\sigma_Z}\right)^2\right]\right\} dZ, \quad (12)$$

which yields the desired cumulative distribution function.

In practice, $\bar{Z}$ may be regarded as the theoretical mean of hourly medians Z of transmission loss in decibels above unit power and σ_Z as the theoretical standard deviation of these hourly medians.

The integral in (12) was evaluated by numerical methods of integration for $\sigma_Z = 1, 2, 4, 8$ and $\bar{Z} = 0$, and curves were obtained of the theoretical cumulative distributions of instantaneous received power in decibels above unit power, $R \equiv 10 \log_{10} r$, and of hourly medians of transmission loss above unit power, $Z = 10 \log_{10} z$ (Fig.IV-1).

3. METHOD FOR APPROXIMATING THE CUMULATIVE DISTRIBUTION FUNCTION FOR LARGE VALUES OF σ_Z

The numerical method, mentioned in the introduction, for obtaining curves of the theoretical cumulative distribution of instantaneous received power in decibels above unit power will now be described assuming, without loss in generality, that $\bar{Z} = 0$. The method is due to P. L. Rice of the Central Radio Propagation Laboratory. Its graphical analogue has proved to be highly accurate and efficient for large values of σ_Z. The interval (0, 1) is divided into n equal sub-intervals with midpoints $p_1(Z > Z_{oi}) = (2i - 1)/(2n)$, $i = 1, \ldots, n$. As discussed later, n must be sufficiently large to yield adequate accuracy in the final calculations. In practice, $p_1 (Z > Z_{oi})$ is interpreted as the probability that an hourly median Z will exceed Z_{oi}. If

LONG-TERM CUMULATIVE DISTRIBUTION OF INSTANTANEOUS RECEIVED POWER

$R = 10 \log_{10} r$

Hourly Medians z are Log-Normally Distributed ($Z = 10 \log_{10} z$)

Within-Hour Instantaneous Rayleigh-Power Distribution is Assumed:

$p(r > r_0) = \exp(-r_0/q)$

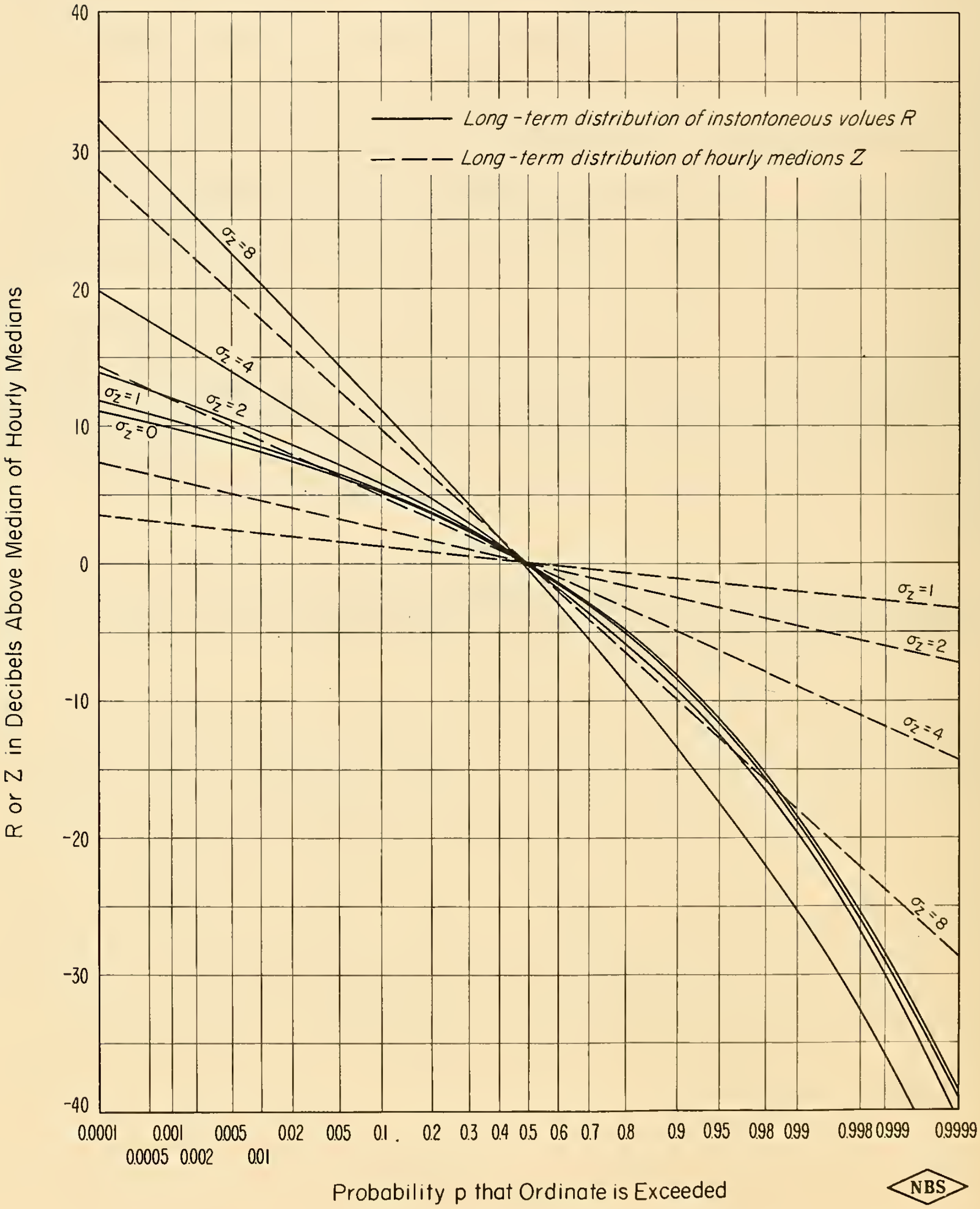


Figure IV - 1

$$p_2(W) = \frac{2}{\sqrt{2\pi}} \int_0^W \exp\{-\alpha^2/2\}\, d\alpha, \qquad (13)$$

then the following relations exist between p_1 and p_2:
If $1 - 2p_1(Z > Z_{oi}) \geq 0$, then $Z_{oi} \geq 0$ and

$$p_2(W_{oi}) = 1 - 2p_1(Z > Z_{oi}),\ Z_{oi} = \sigma_Z W_{oi}\ ; \qquad (14)$$

If $1 - 2p_1(Z > Z_{oi}) < 0$, then $Z_{oi} < 0$ and

$$p_2(W_{oi}) = 2p_1(Z > Z_{oi}) - 1,\ Z_{oi} = -\sigma_Z W_{oi}\ . \qquad (15)$$

Tables can be used to calculate each W_{oi}. Then the relations $Z_{oi} = \sigma_Z W_{oi}$ or $Z_{oi} = -\sigma_Z W_{oi}$ are used to calculate each Z_{oi}.

The Z_{oi} are levels which the hourly medians exceed with a probability $(2i - 1)/(2n)$. We now use the Z_{oi} as median values of received power in decibels, and assume that over a long period of time these values of Z are actually taken on for an hour at a time with a probability $1/n$, i.e., we assume $p(Z = Z_{oi}) = 1/n$.

The next step is to pick a level of instantaneous received power in decibels, $R_o = 10 \log_{10} r_o$. For a fixed Z_{oi} we seek the probability, $p(R > R_o | Z_{oi})$, that R exceeds R_o on the hypothesis that $Z = Z_{oi}$. Now $r_o = 10^{R_o/10}$ and, by (6) and the definition of Z_{oi}, $q_i = \{10^{Z_{oi}/10}\}/\log_e 2$. By the preceding relations and (8) we may write, since $p(r > r_o | Z_{oi}) = p(R > R_o | Z_{oi})$,

$$p(R > R_o | Z_{oi}) = \exp\left\{ -r_o(\log_e 2)/10^{Z_{oi}/10} \right\}$$

$$= \left(\frac{1}{2}\right)^{10^{(R_o - Z_{oi})/10}} \tag{16}$$

Thus if $Z = Z_{oi}$, then R exceeds R_o with the conditional probability given in (16). Now the total probability that R exceeds R_o is approximated as follows:

$$p(R > R_o) \cong \sum_{i=1}^{n} p(R > R_o, \; Z = Z_{oi}) \tag{17}$$

Using the relation $p(R > R_o, \; Z = Z_{oi}) = p(R > R_o \mid Z_{oi}) \, p(Z = Z_{oi})$ we get, from (16), (17), and the assumption that $p(Z = Z_{oi}) = 1/n$,

$$p(R > R_o) \cong \frac{1}{n} \sum_{i=1}^{n} \left(\frac{1}{2}\right)^{10^{(R_o - Z_{oi})/10}} \tag{18}$$

where $p(R > R_o)$ is the probability that the instantaneous received power in decibels above unit power exceeds R_o. It may be shown that (18) approaches (12) in the limit as n approaches infinity.

Using (18), curves of the theoretical cumulative distribution of instantaneous received power in decibels above unit power, for probabilities less than 0.5, were obtained for values of $\sigma_Z = 15$, 20, 30, and $\bar{Z} = 0$ (Fig.IV-2).These curves were obtained by letting

LONG-TERM CUMULATIVE DISTRIBUTION
OF INSTANTANEOUS RECEIVED POWER

$R = 10 \log_{10} r$

Hourly Medians z are Log-Normally Distributed ($Z = 10 \log_{10} z$)
Within-Hour Instantaneous Rayleigh-Power Distribution is Assumed:

$p(r > r_0) = \exp(-r_0/q)$

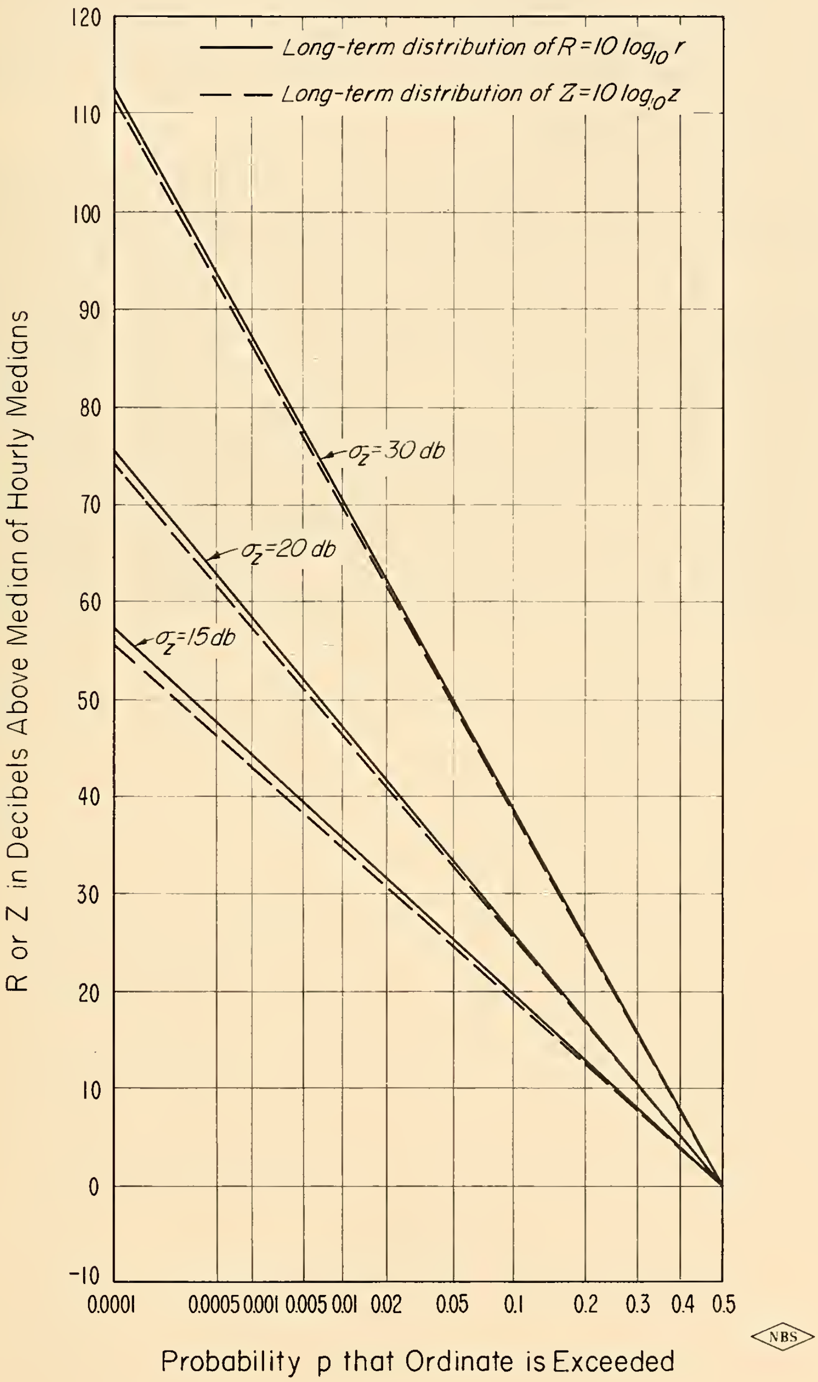


Figure IV − 2

n = 10,000 for those calculated points lying to the left of the p = 0.002 vertical line, n = 1,000 for those calculated points lying between the p = 0.002 and p = 0.05 vertical lines, and n = 100 for those calculated points lying between the p = 0.05 and p = 0.05 vertical lines. It was found that the usually required accuracy of about 0.1 decibel was obtained by retaining only a relatively small number of terms in (18), e.g., with m = 1,000, σ = 30 db, R_0 = 80 db, the use of 11 terms yielded an accuracy of better than 0.01 decibel.

From the curves representing the cumulative distribution of instantaneous received power in decibels aboveunit power (for σ_Z = 0, 1, 2, 4, 8, 15, 20, 30, and $\bar{Z}$ = 0) other curves were obtained as follows: The difference between levels of instantaneous received power R and hourly medians Z, each exceeded with the same probability p (p = 0.0001, 0.001, 0.01, 0.1), was plotted versus the standard deviation σ_Z of hourly medians Z (Fig. IV-3). The difference between two levels of instantaneous received power R, corresponding to two given probabilities, was plotted versus the standard deviation σ_Z of hourly medians Z; also, the difference between two levels of hourly medians Z, corresponding to two given probabilities, was plotted versus the standard deviation σ_Z of hourly medians Z (Fig. IV-4).

DIFFERENCE BETWEEN LEVELS OF INSTANTANEOUS RECEIVED POWER R AND HOURLY MEDIANS Z, EACH EXCEEDED WITH THE SAME PROBABILITY p, VERSUS THE STANDARD DEVIATION σ_Z OF Z

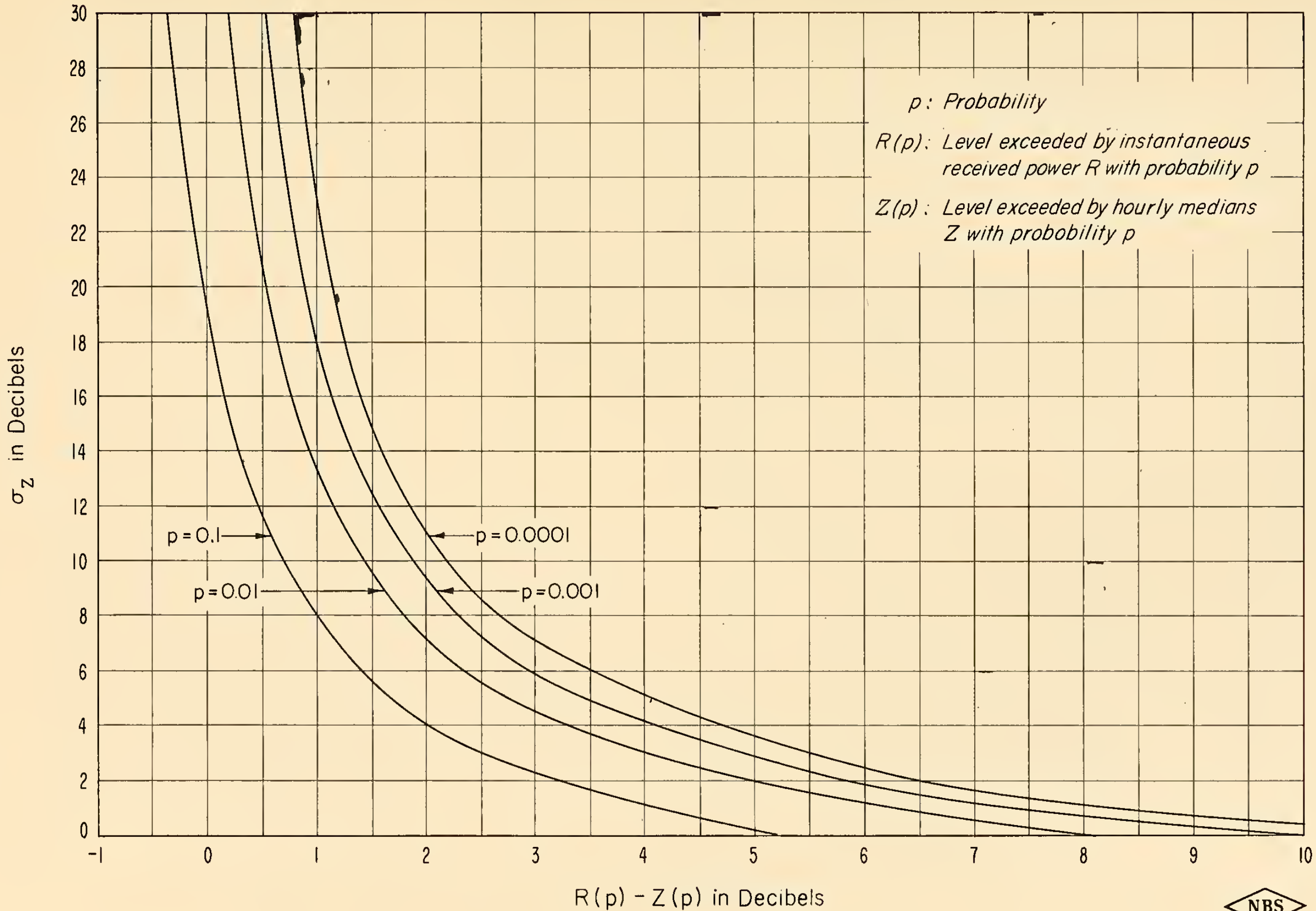


Figure IV - 3

DIFFERENCE BETWEEN TWO LEVELS OF RECEIVED POWER R, OR OF HOURLY MEDIANS Z, CORRESPONDING TO TWO GIVEN PROBABILITIES, VERSUS THE STANDARD DEVIATION σ_Z OF Z

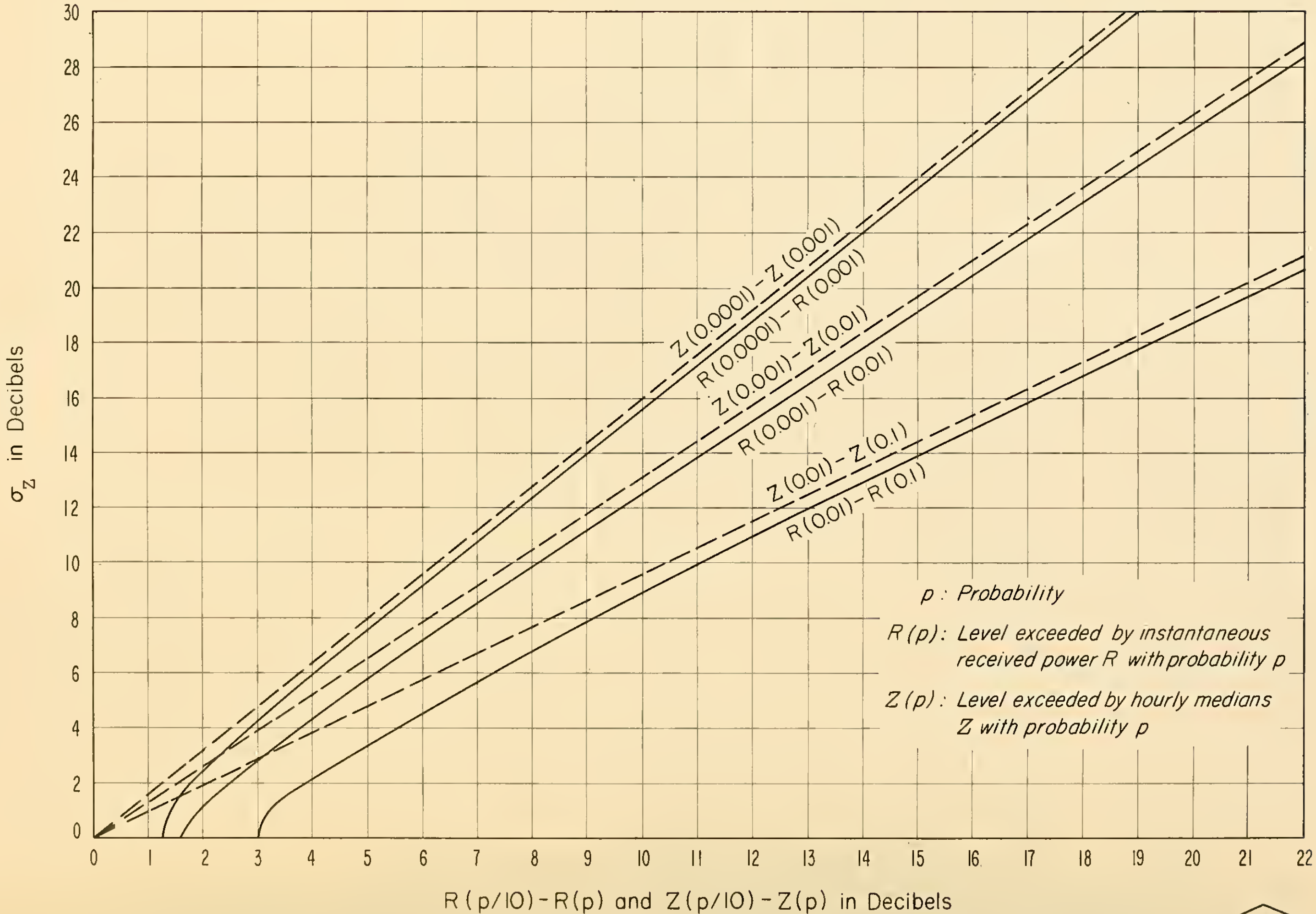


Figure IV - 4

Appendix V

ACCURATE EQUATIONS FOR DETERMINING THE INTERFERENCE TO BE EXPECTED BETWEEN RADIO SERVICES OPERATING ON THE SAME OR ADJACENT CHANNELS

Let $P_a \equiv 10 \log_{10} p_a$ denote for the desired station the average available power from the receiving antenna, expressed in decibels above one watt, and assume initially that the reception of this desired station is limited by noise alone, i. e., that signals other than the desired signal are not perceptible in the noise. If the desired station transmitter power is now varied up and down, it is possible to determine the minimum value, R, of the signal-to-noise ratio which will provide reception of a given grade, e. g., reception over short periods of time with less than 1 percent binary error rate.

Thus, if we use a prime to denote instantaneous values, and let R' denote the instantaneous ratio of the desired signal power to undesired noise power, we may write:

$$R' = P_a' - 10 \log_{10} (f' k t b) = P_a' - F' - B + 204 \qquad \text{(V-1)}$$

Note that both P_a' and F' will vary with time. Over short periods of time of the order of from 10 minutes to an hour, p_a' and f' may be considered to be indepenaently distributed in accordance with the Rayleigh distribution, and on this assumption a formula (II-1) was derived in Appendix II giving the value of R for various grades of service. Note that these values of R correspond to the values p_a and f averaged over these short intervals of time. Thus it is convenient to write:

$$\overline{R}' = P_a - F - B + 204 \qquad \text{(V-2)}$$

Over long periods of time of the order of days, months, or years, it has been observed that P_a and F may be considered to be normally distributed variates, and thus $\overline{R}'$ will be a normally distributed variate. If we let $\sigma_{\overline{R}'}$, σ_a, and σ_F denote the standard deviations of these normal distributions, then we see that:

$$\sigma^2_{\overline{R}'} = \sigma^2_a + \sigma^2_F - 2\rho_{aF}\sigma_a\sigma_F \qquad \text{(V-3)}$$

In the above ρ_{aF} denotes the correlation coefficient between the variations of P_a and F. We now have a means for determining the average available power of the desired station, $\overline{P}_n$, required to provide service (in the presence of noise alone) of a given grade, R or better, with a given probability, (1 - p), or for a given percentage, 100(1 - p), of a long period of time:

$$\overline{P}_n = \overline{F} + B - 204 + R + \lambda(p)\sigma_{\overline{R}'} \qquad \text{(V-4)}$$

The function $\lambda(p)$ may be determined inversely from the cumulative normal distribution:

$$p = \frac{1}{\sqrt{2\pi}} \int_{\lambda(p)}^{\infty} \exp(-t^2/2)\, dt \qquad \text{(V-5)}$$

For example $\lambda(p) = 2.326$ for $p = 0.01$, i.e., service of grade R, or better, for 99 percent of the time.

Consider next the case in which the signal power, p_{au}, from the single undesired station, u, is so strong as to completely override the noise and any other undesired signals. If the desired station transmitter power is now varied up and down, it is possible to determine the minimum value, R_u, of the desired signal to undesired signal ratio which will provide reception of a given grade. In a manner similar to the above we may determine the average available power, $\overline{P}_u$, of the desired station required to provide service of a given grade, R_u, or better, over short periods of time with a probability, $(1-p)$, or for a percentage of time, $100(1-p)$:

$$\overline{P}_u = \overline{P}_{au} + R_u + \lambda(p)\sigma_{\overline{R}''} \qquad \text{(V-6)}$$

where $$\sigma^2_{\overline{R}''} = \sigma^2_a + \sigma^2_u - 2\rho_{au}\sigma_a\sigma_u \qquad \text{(V-7)}$$

In the above σ_a denotes the standard deviation of the normally distributed variate, P_a, σ_u denotes the standard deviation of the normally distributed variate P_{au} and ρ_{au} denotes the correlation coefficient (usually positive) between P_a and P_{au}.

In order to generalize the above special cases to the actual situation in which noise and several undesired signals may be present simultaneously in the pass band of the desired station receiver, we may let R''' denote the instantaneous ratio of the desired signal power to the sum of the undesired noise and undesired signal powers:

$$R''' = P'_a - 10\log_{10}\left(f'ktb + \sum_{u=1}^{m} p'_{au}\right) \qquad \text{(V-8)}$$

When we note that P'_a, f', and p'_{au} all vary with time, it is evident that the solution of (V-8) will, in general, be much more complex than the corresponding solution of (V-1). The above may be solved, however, in the following important special case. Assume that f', p'_a, and p'_{au} are all Rayleigh distributed over short periods of time. It is shown in Appendix II that R and R_u are the same, (II-1) and (II-3), respectively, in that case. Thus we may write (V-8):

$$P_m = R + 10 \log_{10}(fktb + \sum_{u=1}^{m} p_{au}) \qquad \text{(V-9)}$$

In (V-9), as before, P_a, F, and P_{au} may be considered to be normally distributed variates. Norton, Staras and Blum[1/] have developed a method for determining the average value P_m required to provide service of a given grade R, or better, in the presence of noise and m undesired signals for a given percentage of a long period of time; this method allows for the correlations between P_a, F, and P_{au}.

Equation (4) in the body of this report was obtained by arbitrarily introducing r and r_u as multipliers to f and p_{au} in (V-9) when r and r_u are not the same and even when f' and p'_{au} are not both Rayleigh distributed. The above mentioned method[1/] of solving (V-9) may then also be used for solving (4).

In view of the great complexity of (4) or (V-9), it is often sufficient to solve (V-4) and (V-6) separately for all values of u and then simply use the largest of the resulting values of $\bar{P}_n$ and $\bar{P}_u$.

In the body of this report the further approximation was made of neglecting the correlation between the long term variations of the desired and undesired signals. A correction for this particular approximation can, in principle, be made by adding:

1/ K. A. Norton, H. Staras, and M. Blum, "A Statistical Approach to the Problem of Multiple Radio Interference to FM and Television Service," Trans. IRE, PGAP-1, February 1952.

$$C = \lambda(p)\,(\sigma_a + \sigma_u - \sigma_{\overline{R}''}) \qquad \text{(V-10)}$$

to the hourly median values of L_b given on Figs. 3, 4, 5, and 6. This will have the effect of reducing the interference expected by C decibels. Unfortunately, the value of ρ_{au} to use in various cases is not well known so that this correction factor will be difficult to apply in practise. In order to obtain some idea of the possible magnitude of C in a particular case, assume (a) that the desired signal is received by ionospheric forward scatter and has a standard deviation $\sigma_a = 7$ db, (b) that the undesired signal is received by sporadic E and has a standard deviation $\sigma_u = 15$ db, and (c) that $\rho_{au} = +0.2$. For a 99 percent service, i.e., $p = 0.01$, we obtain $C = 2.326\ (7 + 15 - 15.23) = 15.7$ db; for $\rho_{au} = +0.5$ this would increase to 20.9 db, and for $\rho_{au} = 0$, $C = 12.7$ db.

It should be clear from the above discussion that the use of approximate statistical methods of the kind used in the body of this report may lead to substantially incorrect conclusions. This fact lends force to the recommendation made in Section 10 of this report that much further frequency allocation research be carried out.

Appendix VI

THE CARRIER FREQUENCY DEPENDENCE OF THE TRANSMITTER POWER REQUIRED TO PROVIDE VARIOUS TYPES OF SERVICE IN THE PRESENCE OF NOISE

A general equation was developed in Section 4 for the radiated power, P_{rr}, required to just over-ride the noise in the absence of other forms of interference. If we add a term L_ℓ to (5), this general equation may be written:

$$P_{tr} = R + B - 204 + L_\ell + F + L \qquad \text{(VI-1)}$$

In the above the required transmitter power, P_{tr}, is expressed in decibels above one watt; the minimum signal-to-noise ratio, R, required for satisfactory reception is expressed in decibels, $B \equiv 10 \log_{10} b$ where b is the effective receiver noise bandwidth in cycles per second; L_ℓ is the transmission line and circuit loss at the transmitting end of the circuit which is expressed in decibels and allows for the usually small difference between the total power actually radiated from the antenna and that available from the transmitter; F is the effective receiver noise figure expressed in decibels and allows in an appropriate way not only for the actual receiver noise figure but also for the noise picked up externally by the receiving antenna as well as for any transmission line and receiver input circuit losses at the receiving end of the circuit. A brief discussion of the effective receiver noise figure, F, is given by the author in reference 2 and in more detail by Crichlow, Smith, Morton, and Corliss in reference 7.

In the above equation R and B will not vary appreciably with the carrier frequency and may be considered constant for any given type of service. The terms $(L_\ell + F)$ may be expected to be of the order of 25 db at 25 Mc, will decrease with increasing frequency reaching a minimum value of the order of 7 db in the neighborhood of 100 Mc, and will then increase again at higher frequencies approximately in accordance with the relation:

$$(L_\ell + F) = 6 \log_{10} f_{Mc} - 5 \quad (f_{Mc} > 100) \tag{VI-2}$$

The value of $(L_\ell + F)$ will vary significantly with the engineering design and the components used in the equipment, and the above estimates are based on the assumption that the best available equipment is used. Below 100 Mc, cosmic noise largely controls the value of $(L_\ell + F)$, while above 100 Mc this value is largely determined by the equipment and is essentially independent of external noise. The above estimates of $(L_\ell + F)$ were based on the assumption that a quiet receiving location, free from man-made noise, is available. Man-made noise levels are likely to limit reception at least part of the time for some types of service and, when these man-made noise levels are high, we may expect $(L_\ell + F)$ to be roughly of the form:

$$(L_\ell + F) = N - 27 \log_{10} f_{Mc} \quad (N > 65) \tag{VI-3}$$

for frequencies up to that frequency at which (VI-3) gives the same value as (VI-2); at still higher frequencies (VI-2) will again be applicable.

Consider next the remaining variable, L, in (VI-1). In free space the transmission loss, L, is given by:

$$L_f = 36.58 + 20 \log_{10} f_{Mc} + 20 \log_{10} D - G_t - G_r \tag{VI-4}$$

In the above D is the path distance expressed in statute miles. It is convénient to consider three different cases corresponding to three types of service in which (a) non-directional half-wave dipole antennas are used at both ends of the path, (b) a non-directional half-wave dipole antenna is used at one end of the path while a directional antenna is used at the other end, and (c) point-to-point services in which directional antennas may be used at both ends of the path. For the half-wave dipole G = 2.15 db, while a directional antenna with an effective absorbing area of A_e square meters has a gain:

$$G = 10 \log_{10} A_e + 20 \log_{10} f_{Mc} - 38.54 \qquad \text{(VI-5)}$$

where $f_{Mc} > 100 \sqrt{A_e}$

Using the above gains in (VI-4) we obtain the following relations for the transmission loss expected in free space for the three cases described above:

Case (a) Half-Wave Dipoles at Both Terminals

$$L_f = 32.28 + 20 \log_{10} D + 20 \log_{10} f_{Mc} \qquad \text{(VI-6)}$$

Case (b) Directional Antenna at One Terminal and a Half-Wave Dipole at the Other Terminal

$$L_f = 72.98 + 20 \log_{10} D - 10 \log_{10} A_e \quad \text{(VI-7)}$$

Case (c) Directional Antennas at Both Terminals

$$L_f = 113.67 + 20 \log_{10} D - 20 \log_{10} A_e - 20 \log_{10} f_{Mc} \quad \text{(VI-8)}$$

Note that the free space transmission loss increases with frequency in case (a), is independent of frequency in case (b), and decreases with frequency in case (c).

Finally, to determine the actual transmission loss, L, it is necessary to add to the above free-space transmission losses, L_f, the attenuation A, relative to these free-space values. This will be different for the different modes of propagation. The following discussion will be confined to the range of frequencies above 25 Mc. For propagation via the F2 layer of the ionosphere A is essentially zero for frequencies up to the MUF (maximum usable frequency) of the F2 layer, and then increases rapidly with increasing frequency until a final practical cut-off is reached at frequencies of the order of 10 to 15 percent above the MUF. 2/ For the ionospheric forward scatter mode of propagation A depends on frequency in the following way:

2/ This phenomenon of F2 propagation just above the MUF has recently been explained by D. K. Bailey, first in a paper on forward scattering in the ionosphere presented at the XIth General Assembly of the URSI at The Hague in August 1954, and more recently and in much more detail in a colloquium talk entitled "The Role of Ionospheric Forward Scatter in Oblique Incidence MUF" which was presented on February 24, 1955 at the Central Radio Propagation Laboratory in Boulder, Colorado.

$$A = A(f_o) + 84 \log_{10}(f/f_o) \qquad \text{(VI-9)}$$

For ground-wave propagation over a smooth flat earth:

$$A = A(f_o) - 20 \log_{10}(f/f_o) \qquad \text{(VI-10)}$$

The curvature of the earth[1/] and terrain roughness[3/] introduce additional frequency effects so that the attenuation, A, for the ground wave usually decreases only slightly with increasing frequency at points within the line of sight and increases slightly with increasing frequency at points just beyond the line of sight. At points far beyond the line of sight in the tropospheric forward scatter region the attenuation, A, is independent of the frequency.[1/] However, when high-gain antennas are used, with a fixed size, the "loss in antenna gain" will increase with increasing frequency for either ionospheric or tropospheric forward scatter, and additional transmitter power must be allowed for this effect.

At sufficiently high frequencies atmospheric absorption[4/] may become an important factor and, in the range above, say, 2000 Mc, A increases rapidly with increasing frequency.

3/ K. A. Norton, M. Schulkin, and R. S. Kirby, "Ground-Wave Propagation Over Irregular Terrain at Frequencies above 50 Mc," Reference C to the Report of the FCC Ad Hoc Committee for the Evaluation of FM and TV Propagation Factors Between 50 and 250 Mc, June 6, 1949; also, K. A. Norton, "A Formula for the Transmission Loss of Space Waves Propaged Over Irregular Terrain," Trans. IRE, PGAP-3, August 1952.

4/ Howard E. Bussey, "Microwave Attenuation Statistics Estimated from Rainfall and Water Vapor Statistics," Proc. IRE, Vol. 38, No. 7, p. 781, July 1950; see also NBS Tech. News Bulletin, Vol. 33, No. 12, p. 144, December 1949.

It should be clear from the above discussion that the required transmitter power, P_{tr}, may either increase or decrease with increasing frequency, depending on the type of service or mode of propagation.

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