EPORT CRPL-4-2

ISSUED JANUARY 13, 194

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
CENTRAL RADIO PROPAGATION LABORATORY
WASHINGTON, D. C.

THE TECHNICAL FACTORS INVOLVED IN THE CHOICE OF A CARRIER FREQUENCY FOR A WORLD-WIDE LOW FREQUENCY LORAN SYSTEM

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SUMMARY AND CONCLUSIONS

This paper deals with the propagational and other technical problems involved in L. F. Loran operation on carrier frequencies between 100 kc and 450 kc. The optimum frequency is determined when the distance between transmitting stations is a maximum, consistent with reliable synchronization, since this maximum separation provides the highest accuracy and results in a minimum number of stations for world-wide coverage. For over-land synchronization paths, the lower frequencies in this band provide the greater separations between transmitting stations, but for over-sea synchronization paths, the higher frequencies are better, provided surface-wave synchronization is employed. Assuming that most of the synchronization paths will be over the sea, it is concluded that the higher frequencies in this band are more favorable with surface-wave synchronization than the lower frequencies for L. F. Loran operation.

It is shown in the report that the use of sky-wave synchronization should provide a navigational system with the same effective accuracy as surface-wave synchronization with the use of considerably fewer transmitting stations, especially in arctic regions. The optimum frequency for this more efficient sky-wave synchronization system is probably also in the higher part of the band under consideration. It should be pointed out that a sky-wave synchronization system operating at high latitudes will be subject to interruptions due to ionospheric storms; such effects have not been evaluated in this report because of a lack of adequate data and, as a consequence, the 99% reliability shown for a sky-wave synchronization system in arctic regions may be optimistic; since ionospheric storms

cause a greater degradation in service on the higher frequencies, this factor should also be kept in mind when evaluating the conclusions reached in this report.

A discussion of the problem of sky-wave synchronization with J. A. Pierce of Harvard University brought out the fact that surface-wave synchronization using cycle matching techniques will probably be more accurate than sky-wave synchronization with envelope matching only when the surface waves are comparable in intensity to the sky-waves. Thus, the maximum range of a surface-wave synchronization system is effectively that at which fading becomes objectionable and cannot be increased beyond that point by the use of higher powered transmitters. This lends further weight to the suggestion that the longer range sky-wave synchronization system be used; the range of such systems can be increased considerably with the use of higher powered transmitters.

Mention is made of the very large improvements in accuracy which are expected with the use of a wider channel than that used in the present experimental system. It is hoped that the use of this wider channel will permit a sufficiently rapid time of rise on the pulse so that the slightly longer delayed ionospheric waves will not contaminate the surface-wave with a surface-wave synchronization system, or, alternatively, so that ionospheric-wave pulses arriving at the synchronization point after one, two, etc. reflections at the ionosphere will not overlap and thus greatly increase the synchronization errors in a sky-wave synchronization system. In selecting a frequency for a world-wide Low Frequency Loran System, it is considered to be very important that this possible requirement for a very wide channel be kept in mind.

It is important to emphasize that, although the conclusions reached in this report are based upon the best data and theories of propagation available to the author, nevertheless, this available information is not considered adequate to form a proper basis for deciding such an important question as the choice of an optimum frequency for L. F. Loran. This is due to the fact shown in the report that either night or day propagation may limit the range of a sky-wave synchronization system under particular circumstances and this leads to the requirement of a more precise knowledge of the various propagation factors in order to determine the optimum frequencies; thus, we must know with accuracy (1) the absolute values of the day and night sky-wave field intensities, as well as their variations with frequency, (2) the magnitude of the ratio (determined by measurements to be approximately equal to 10) between day and night required signal-to-average-atmospheric-noise ratios, and (3) the influence of latitude on the intensities of sky-waves (an influence well established in the standard broadcast band). This requirement of an accurate knowledge of these three factors arises since a small change in the magnitude of any one of them can shift the limitation from night to day sky-wave propagation. In view of these limitations, the conclusions reached should be considered to be tentative and, if the report serves to guide the efforts of research workers in this field, it will have served its purpose.

(The present report is a slightly revised edition of a preliminary report originally distributed in January 1947; most of the revisions are in the summary and conclusions and were made on May 29, 1947)

ACKNOWLEDGMENTS

The author wishes to acknowledge the advice and assistance of his colleagues, William Q. Crichlow and Jack W. Herbstreit, who made many valuable suggestions during the course of this investigation. The typing and drafting were done by Mrs. Marian D. Adams and Mr. John C. Harman.

THE TECHNICAL FACTORS INVOLVED IN THE CHOICE OF A CARRIER FREQUENCY FOR A WORLD-WIDE LOW FREQUENCY LORAN SYSTEM

I RANGE WITH SURFACE-WAVE SYNCHRONIZATION

The factors involved in determining the expected performance of an L. F. Loran system were discussed in great detail in the report. "The Range Reliability and Accuracy of a Low Frequency Loran System."1/ It is the purpose of this report to extrapolate the results of that study to other frequencies within the range 100 kc to 450 kc with the object of choosing an optimum frequency for a world-wide L. F. Loran system.

It was shown in the report "Proposed Antenna Design for L. F. Loran"2/ that a steel tower with a height in excess of 500 feet and with umbrella loading would provide a satisfactory radiator for an L. F. Loran system operating on 180 kc. Using the data presented in Figure 1(a) of that report and assuming that the radiated fields for a given input power will be the same for a given electrical length of antenna throughout the frequency range under consideration, we may readily obtain the expected unabsorbed field intensities at one mile for an input power of 100 kw at frequencies throughout this range. These values are given in Table I;

1/ William Q. Crichlow, Jack W. Herbstreit, Earl M. Johnson, Kenneth A. Norton and Carl E. Smith, Report No. ORS-P-23, "Range Reliability and Accuracy of a Low Frequency Loran System," January 1946, prepared in the Operational Research Staff, Office of the Chief Signal Officer, The Pentagon, Washington 25, D. C.

2/ Earl M. Johnson and Carl E. Smith, Report No. ORS-P-22-2, "Proposed Antenna Design for L. F. Loran," prepared in the Operational Research Staff, Office of the Chief Signal Officer, The Pentagon, Washington 25, D. C.

the values above 250 kc were estimated by using an unpublished antenna efficiency study made for the Federal Communications Commission by Kenneth A. Norton and Ross Bateman.

TABLE I

UNABSORBED FIELD INTENSITY AT ONE MILE TO BE EXPECTED FOR A TRANSMITTER PEAK PULSE POWER OF 100 KW DELIVERED TO A 625 FOOT STEEL TOWER WITH OPTIMUM UMBRELLA LOADING

kc	mv/m
100	1230
150	1600
200	1750
250	1850
300	1900
350	1950
400	2000
450	2050

Using the above estimates of radiated power and the methods of calculation given in a recent paper[3/] by the author, the curves of surface-wave-field-intensity versus distance shown on Figures 1 and 2 are obtained.

It was shown in the report ORS-P-23[1/] that the maximum accuracy over the largest coverage area can be obtained when the L. F. Loran transmitters are located on the four corners of a square with the distance separation

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3/ Kenneth A. Norton, "The Calculation of Ground Wave Field Intensity Over a Finitely Conducting Spherical Earth," Proc. I.R.E., Vol 29, pp 623-639, December 1941.

between transmitters at the maximum value consistent with reliable synchronization. This maximum distance is determined when the pulse signal intensities become so weak that they are no longer discernible in the atmospheric noise for a sufficiently large percentage of the time. With surface-wave synchronization, this maximum distance is determined by the summer night noise at low latitudes and the winter night noise in the arctic since the surface-wave-pulse-signal to atmospheric noise ratio is a minimum at these times. In the arctic the atmospheric noise level is higher in the winter than it is in the summer because the ionospheric propagation of the noise from its point of origin at lower latitudes involves less absorption in the winter-time, i.e., the change from summer to winter in the arctic has somewhat the same effect as a change from day to night conditions at lower latitudes. Figures 2 and 4 of the ORS Report[1/] give the required median-peak-pulse-field-intensity in microvolts per meter to permit pulse matching at night for the percentages of time shown in areas of various noise grades while Figures 5 and 6[1/] show the corresponding distributions of noise grades throughout the world. The curves of Figures 2 and 4 were derived from the experimental data of the L. F. Loran survey and thus correspond to a situation where pulses of varying intensity are observed in noise of varying intensity; they will thus be applicable to the surface-wave synchronization problem only at the 50% point since the surface-wave pulses will not vary appreciably with time. However, Figure 50 in ORS-P-23-S[4/] gives the time distributions

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4/ William Q. Crichlow, Jack W. Herbstreit, Earl M. Johnson and Carl E. Smith, Report No. ORS-P-23-S, "Measurement Technique and Analysis of a Low Frequency Loran System," prepared in the Operational Research Staff, Office of the Chief Signal Officer, The Pentagon, Washington 25, D. C.

of the noise alone as measured at Dayton, Ohio, and at Galveston, Texas, and we may use the slopes of these curves rather than those of Figures 2 and 4 to extrapolate from the 50% point on Figures 2 and 4 to any higher or lower percentages of the time. If we assume that synchronization for 99% of the total time is satisfactory, then, since synchronization will be possible for nearly 100% of the time during the low latitude winter day at the same distance where synchronization is possible for 98% of the time during the low latitude summer night, we may achieve the 99% goal by requiring that the pulse field intensities be sufficiently strong to permit synchronization for only 98% of the summer night hours. The above argument contains a factor of safety since surface-wave synchronization will be possible practically 100% of the daytime hours in both winter and summer. Using the data of Figures 2 and 4 of ORS-P-23 and of Figure 50 of ORS-P-23-S, we find that a pulse field intensity of 157 microvolts per meter is required on 180 kc in areas of noise grade 1 while a pulse field intensity of 1290 microvolts per meter is required on 180 kc in areas of noise grade 3.5 Noise grade 1 is the lowest to be encountered anywhere in the world; while noise grade 3.5 is not the highest in the world, it is believed that synchronizing locations can be so chosen that areas of higher noise grades than 3.5 can be avoided. Thus, all synchronization paths throughout the world may be expected to exhibit characteristics intermediate between those shown for noise grades 1 and 3.5

The next problem is the extrapolation of these required field intensities to other frequencies in the band 100 kc to 450 kc. This question was discussed by the author in a report[5] in which it was shown that the variation of radio atmospheric intensities with frequency depends upon two factors: (a) the variation at the source and (b) the superimposed variation due to propagation effects. At the source, atmospheric noise intensities are known to vary inversely with the frequency.[6] At night the propagation of the atmospheric noise is principally by ionospheric waves, the intensities of which are known to be approximately independent of the frequency throughout this band.[7] Thus, the expected atmospheric noise at night may be expected to vary inversely with the frequency. The solid curves on Figure 3 are based on the above discussion and show as a function of frequency the pulse field intensities required on arctic winter nights or low latitude summer nights, for surface-wave synchronization 98% of the time. It should be noted that the required fields shown on Figure 3 are based on the assumption that the character of the atmospheric noise is the same at all frequencies throughout the band under consideration, i.e., that the same signal-to-noise ratio is required for a given reliability at all frequencies. This may not be the case. For example, it is known[1] that the required peak-pulse-field-intensity-to-average-atmospheric-noise ratio for a given degree of reliability on 180 kc is 10 times as high

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5/ Kenneth A. Norton, "Frequency Distribution of the Intensities of Radio Atmospherics," paper presented at the U.R.S.I. meeting held in Washington, D. C. on April 27, 1934 and later that same year at the U.R.S.I. meeting held in London.

6/ R. K. Potter, "An Estimate of the Frequency Distribution of Atmospheric Noise," Proc. I.R.E., Vol 20, pp 1512-1518, September 1932.

7/ Kenneth A. Norton, "Supplementary Report on Wave Propagation for the CCIR," Part III, A Theoretical Determination of the Intensity of Sky Waves at Intermediate Frequencies," 1937, Federal Communications Commission, Mimeo No. 84810.

at night as during the day. This factor of 10 is not very well understood at the present time but is probably due to the difference in character of the day and night atmospheric noise, and there is thus some reason to expect that this factor may vary with frequency throughout the band under consideration. Using the required field intensities on Figure 3 in conjunction with the expected surface-wave field intensities shown as a function of distance on Figures 1 and 2, we obtain the surface-wave synchronization ranges shown as solid curves on Figure 4 for transmission paths over land of average conductivity and on Figure 5 for sea-water paths. It is evident from these curves that the higher frequencies are slightly better for over-sea-water propagation while the lower frequencies are better for over-land propagation.

II RANGE WITH SKY-WAVE SYNCHRONIZATION

During the course of this frequency study, it was discovered that greatly extended base lines could be used by synchronizing on the sky waves which are quite strong in these frequency bands at large distances both day and night. The use of this method of synchronization makes possible much larger service areas within which the distance errors will be less than 10 miles for 99% of the fixes made.

Figures 1 and 2 show the expected median values of the daytime sky waves. The values shown for 200 kc were estimated from the measurements made on 180 kc and reported in detail in ORS-P-23-S.[4/] The values shown on Figure 1 for over-land propagation on the other frequencies were interpolated and extrapolated from this 180 kc data and a series of measurements made on Broadcast Station WLW operating on 700 kc; these latter measurements were reported in a memorandum to the Chief Engineer of the Federal Communications Commission prepared by the author. The daytime sky-wave field intensities shown on Figure 2 for over-sea propagation on the other frequencies were interpolated and extrapolated from the 180 kc data and the data obtained from a continuous field intensity record of Broadcast Station KFI operating on 640 kc made on a voyage of the M. S. Jeff Davis from San Pedro, California, to Honolulu.[8/]

At night the sky-wave field intensities may be estimated by means of the theory in the Federal Communications Commission report[7/] already mentioned. This theory was checked experimentally at 180 kc by means of the data obtained in the L. F. Loran study[1,4/] and was originally derived to explain standard broadcast band sky-wave field intensities; it would thus be expected to give reliable results in the band 100-450 kc. This theory does not include an allowance for a latitude effect in night sky-wave propagation which has recently been established as being of considerable importance in the standard broadcast band being, in fact, included in the recently proposed Federal Communications Commission Standards of Good Engineering Practice for Standard Broadcast Stations; consequently, our expected sky-wave synchronization ranges in the arctic may be somewhat optimistic and may not increase with frequency at a sufficiently rapid rate.

The required median sky-wave fields at night may be determined by increasing by a factor of 2.55 the surface-wave fields required at night as given by the solid curves on Figure 3. This factor of 2.55 allows for the

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8/ Testimony of Kenneth A. Norton, Ross Bateman, and Charles A. Ellert at the Ship Power Hearing, November 14, 1938, before the Federal Communications Commission, FCC Mimeo No. 30539.

fading of the sky waves and ensures that the received pulses will be sufficiently strong to permit synchronization for 98% of the time for arctic winters or low latitude summers. Alternatively, the required sky-wave fields may be determined on 180 kc directly from Figures 2 and 4 of the ORS report.1/

The sky-wave field required in the low latitude summer daytime on 180 kc may be determined by reference to the 98% point on the 3.5 noise grade curve of Figure 1 of ORS-P-23 1/ which shows that a median field intensity of 165 microvolts per meter is required; the corresponding value for arctic winter days is 2.6 microvolts per meter as given by Figure 3 of ORS-P-23.1/ During the daytime, since most of the atmospheric noise arrives at the receiver by surface waves, the intensities of which decrease rapidly with increasing frequency, the received atmospheric noise intensitie also decrease rapidly with increasing frequency. This is shown by the dashed curves of Figure 3. These atmospheric noise intensity variations with frequency were obtained from the report "Minimum Required Field Intensities For Intelligible Reception of Radiotelephony in the Presence of Atmospheric or Receiving Set Noise." 9/ It should be noted that the frequency distribution in the low noise grade area is steeper than that in the higher noise grade area; this is due to the fact that the atmospheric noise is propagated over longer paths in the former case and thus is subject to more surface-wave attenuation.5/

Using the above data on the expected and required sky-wave pulse field

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9/ Radio Propagation Unit Technical Report No. 5, December 1945, prepared under the direction of the Chief Signal Officer by the Radio Propagation Unit, 9463rd TSU, Holabird Signal Depot, Baltimore 19, Maryland.

intensities, we obtain the day and night sky-wave synchronization ranges shown as dashed curves on Figure 4 for transmission paths over land of average conductivity and on Figure 5 for sea-water paths. We see by Figure 4 that the night sky-wave propagation controls the range over land at the lower frequencies while the daytime sky-wave propagation controls the range over land at the higher end of the band. Thus, the lower of the two dashed curves for a given noise grade on Figure 4 controls the effective sky-wave synchronization range if we assume that service must be maintained both day and night. We see by Figure 5 that the effective sky-wave synchronization range over the sea is determined by the expected range at night for all frequencies in this band. Thus, the higher frequencies are superior both for over-sea-water paths and for over-land paths when sky-wave synchronization is employed.

Transmitters with the capability of handling a pulse peak power of 1000 kw are now being designed and it is thus desirable to show the expected ranges for such transmitters. The expected field intensities in this case will be simply $\sqrt{10}$ times those shown on Figures 1 and 2 and the corresponding expected distance ranges are given on Figures 6 and 7. It is interesting to note that the use of one megawatt transmitters shifts the optimum sky-wave synchronization frequency for over-land paths from about 400 kc (using 100 kw) down to about 250 kc.

III ACCURACY OF NAVIGATIONAL FIXES WITH SURFACE-WAVE AND SKY-WAVE SYNCHRONIZATION

We see by Figures 4 and 5 that the use of sky-wave synchronization increases the expected range substantially in many cases. It thus becomes of considerable importance to investigate the accuracy to be expected with a sky-wave synchronization system. It has been shown[10/] that the variance, σ_g^2, for a surface-wave synchronized system may be expressed:

$$\sigma_g^2 = \sigma_1^2 + \sigma_2^2 + \sigma_0^2 \tag{1}$$

where σ_1 and σ_2 are the standard deviations of the times of propagation from the two Loran transmitters to the receiving point and σ_0 is the standard deviation of the operator errors. In the above, we have omitted the (usually small) term due to correlation between the times of propagation from the two transmitters. For sky-wave synchronization, we need only add to (1) a term σ_3^2 corresponding to the variance of the synchronization path propagation time, in order to obtain an estimate of the expected variance, σ_s^2, for delay measurements made on a system employing sky-wave synchronization. Thus,

$$\sigma_s^2 = \sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \sigma_0^2 \tag{2}$$

If we assume that the variances for all three propagation paths are nearly equal, then $\sigma_1 = \sigma_2 = \sigma_3$ and we may estimate the value of σ_s from the known values of σ_g and σ_0 by means of the following:

$$\sigma_s^2 = \sigma_g^2 + \frac{1}{2}\left(\sigma_g^2 - \sigma_0^2\right) = 1.5\ \sigma_g^2 - 0.5\ \sigma_0^2 \tag{3}$$

10/ Reference 1, Equations (14), (15) and (16).

Table II gives the values of σ_g and σ_0 as given in Table V of ORS-P-23[1/] together with the estimated value of σ_s as obtained from (3):

TABLE II

EXPECTED STANDARD DEVIATIONS OF THE DELAY READINGS EXPRESSED IN MICROSECONDS

	Surface-Wave Synchronization		Sky-Wave Synchronization	
	σ_g	σ_0	σ_s	σ_0
Day	15.4	9.4	17.7	9.4
Night	22.3	10.9	26.2	10.9

It is evident from the above table that the expected additional random errors in the delay readings due to the use of sky-wave synchronization are probably not large and are far outweighed in importance by the much larger base lines which are made possible thereby.

In addition to these random errors there will be certain systematic sky-wave delays along the synchronization path but these can, of course, largely be eliminated by calibration.

Figure 8 shows the expected coverage areas based on the data in Table II for a surface-wave synchronization system on 200 kc compared with that to be expected using a sky-wave synchronized system on 400 kc; results are given over land and over sea and for the two noise grade areas. The fix accuracy contours shown correspond to regions within which the distance error of a fix will be less than the value for which the contours are labelled for approximately 99% of the time. The methods of calculating such contours are discussed in ORS-P-23[1/] and those shown on Figure 6 were obtained by using a distance error 2.2 times the value of d_{rms} expected at night; this yields a distance error which will be exceeded less than about 1% of the total time. It is evident from Figure 8 that only about one-fourth as many transmitters will be required using sky-wave synchronization on 400 kc instead of surface-wave synchronization on 200 kc in order to provide a world-wide L. F. Loran navigation system with a distance error of less than 10 miles for 99% of the time.

In a recent C.R.P.L. report[11/] general methods are given for calculating the expected service areas of all types of radio navigational systems in terms of the standard deviations of the parameters determining a navigational fix. Figure 19 of that report gives the effective service area, A, of a hyperbolic navigation system consisting of four stations on the four corners of a square. This effective service area is defined to be the area inside of a contour on which the root mean square distance error, d_{rms}, has a specified value. If we assume that an error of fix less than 10 miles must be attained for 99% of the time, we find by referring to the results shown on Figure 26 of ORS-P-23[1/] that the root mean square distance error, d_{rms}, must be less than (10/2.2) = 4.5 miles in those cases where the ratio of major to minor axes of the error ellipse is near unity. Inside the square, as may be seen by reference to Figure 28 of ORS-P-23,[1/] the angle of cut is always good and this results in an error-ellipse-axis-ratio near unity. Using the value of d_{rms} = 4.5 miles and using the values of σ_g and σ_s given in Table II above, we can determine the expected effective service areas expressed in terms of square base line units from the relation

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11/ William Q. Crichlow, "The Comparative Accuracy of Various Existing and Proposed Radio Navigation Systems," prepared in the Central Radio Propagation Laboratory, National Bureau of Standards, Washington 25, D. C. (Report No. CRPL-4-1) shown on Figure 19 of Report CRPL-4-1.[11/] These are given in Table III.

TABLE III

THE EXPECTED EFFECTIVE SERVICE AREAS OF AN L. F. LORAN SYSTEM

(Optimum arrangement of four transmitting stations on the four corners of a square; required accuracy throughout the service area corresponds to a distance error less than 10 miles for 99% of the navigational fixes; pulse widths and receiver band widths assumed to be the same as those used in the experimental L. F. Loran system.)

	Effective Service Area Expressed in Square Base Line Units			
	Surface-Wave Synchronization		Sky-Wave Synchronization	
	σ/d_{rms}	A/B^2	σ/d_{rms}	A/B^2
Day	3.39	1.70	3.89	1.55
Night	4.91	1.27	5.76	1.025

The following example will illustrate the use of the data given in Table III. Figure 6 indicates that an over-land base line length $B = 815$ miles is feasible in the arctic with 1000 kw power using surface-wave synchronization on 200 kc; thus, a service area $A = 1.7 \times \overline{815}^2 =$ 1,130,000 square miles can be expected in the daytime and a service area $A = 1.27 \times \overline{815}^2 = 844{,}000$ square miles can be expected at night. On the other hand, if sky-wave synchronization with 1000 kw power on 400 kc is employed, we see by Figure 6 that an over-land base line length $B = 1975$ miles is feasible; thus a service area $A = 1.55 \times \overline{1975}^2 = 6{,}050{,}000$ square miles can be expected in the daytime and a service area $A = 1.025 \times \overline{1975}^2 =$ 4,000,000 square miles can be expected at night.

IV THE FREQUENCY BAND REQUIRED BY L. F. LORAN

The above discussions of the expected ranges and accuracies of an L. F. Loran system were based on the experimental system in use during 1945 in the Caribbean and Eastern United States. The time of rise of the pulses at the receiver output for this system was so large that delayed pulses propagated via the ionosphere arrived at the output of the receiver before the surface-wave pulse had risen to its full amplitude and this contamination resulted in a very large decrease in the accuracy with which the total propagation delays could be determined. With the standard Loran system, operating on medium frequencies, the time of rise at the receiver output is sufficiently short and the ionospheric propagation delays enough longer (due to a slightly higher ionosphere virtual height at this frequency) so that the pulses arriving via the surface wave and the waves arriving after one, two, etc. reflections at the ionosphere do not appreciably over-lap in the receiver output. This made possible a much higher degree of accuracy in the determination of propagation delays via either the surface wave or a single ionospheric wave since a match can be made on either one or the other without the deleterious effects of mutual contamination. However, with the M. F. Loran system, the components of the transmitted pulse occupied a larger part of the spectrum than used by the experimental L. F. system, and thus caused interference throughout a wider band and the receiver with its wider band accepted noise over a greater range of frequencies.

This comparative situation for the present M. F. Loran system and the experimental L. F. Loran system is outlined in Table IV. The data for this table were obtained from an IRPL report.[12/] The first line of this table gives an estimate of the minimum propagation delay to be expected between the first sky-wave pulse and the surface-wave pulse or between successive sky-wave pulses. The two values of 35 μs and 55 μs given for L. F. Loran are lower and upper bounds to the values that might be encountered on frequencies below 500 kc, the higher value corresponding, in general, to higher frequencies. The 62 μs value has been determined with accuracy at 1950 kc.

If pulse rise times and band widths were obtainable with L. F. Loran as shown in the last column of Table IV, then it seems quite likely that the higher accuracy corresponding to the uncontaminated pulses could be obtained. In fact, it seems likely that pulse rise times twice as wide as shown in this last column might still resolve L. F. Loran pulses since the time of rise in the receiver output would be only 46 μs and this is less than the required 55 μs delay; however, this maximum usable time of rise should be determined experimentally. The required band width is approximately inversely proportional to the time of rise of the pulse, and thus it may be found that band widths half as wide as those shown in this last column could be used.

To the extent that an uncontaminated pulse L. F. Loran system is feasible at all, it will certainly be much easier to achieve in the higher part of the frequency band under consideration, having regard to the fact

12/ "Relations Between Band Width, Pulse Shape and Usefulness of Pulses in the Loran System," Report No. IRPL-R24, prepared by Interservice Radio Propagation Laboratory, National Bureau of Standards, Washington, D. C.

TABLE IV

CHARACTERISTICS OF TRANSMITTED AND RECEIVED LORAN PULSES

		STANDARD M.F.LORAN	EXPERIMENTAL L.F.LORAN	CALCULATED L. F. LORAN WITH DISCRIMINATION AGAINST DELAYED PULSES EQUIVALENT TO M. F. LORAN	
				Lower Estimate	Upper Estimat
Minimum Expected Propagation Delay		62 µs		35 µs	55 µs
Time of Rise(Transmitted Pulse)		12.5 µs	72 µs	7.1 µs	11.1 µs
Base Width(Transmitted Pulse)		64 µs	330 µs	36 µs	56.8 µs
Transmitted Pulse Spectrum Width	6 db	33 kc	5.7 kc*	58.5 kc	37.2 kc
	20 db	112 kc	19 kc*	198 kc	126 kc
	50 db	322 kc	56 kc*	570 kc	363 kc
Receiver Band Width	6 db	80 kc	10 kc	150 kc	90.2 kc
Time of Rise(Receiver Output Pulse)		26 µs	176 µs**	14.7 µs	23.1 µs
Base Width(Receiver Output Pulse)		75 µs	400 µs***	42.4 µs	66.5 µs

*Estimated by assuming that the L. F. pulse occupies a portion of the spectrum less than M. F. Loran in proportion to the respective times of rise of the two transmitted pulses.

**Estimated by using a band width B = 10 kc x 72/12.5 = 57.6 kc on Figure 25 of Report No. IRPL-R24, and increasing the given rise time of 30.5 µs in the ratio 72/12.5.

***Estimated by using a band width B = 10 kc x 72/12.5 = 57.6 on Figure 27 of Report No. IRPL-R24, and increasing the given base width of 77 in the ratio 330/64.

that the required band will be a smaller percentage of the carrier frequency in this case.

Assuming that uncontaminated pulses can be obtained with L. F. Loran, then the expected accuracy of determination of the propagation delays would be expected to be the same as that obtainable with M. F. Loran within its surface-wave range and slightly better than that obtainable with S. S. Loran employing sky-wave synchronization, due in the latter case to the expected greater stability of the ionosphere heights at the lower frequencies. With uncontaminated pulses on L. F. Loran, it is feasible to expect that a navigational fix distance error of 0.385 miles would be exceeded less than 1% of the time for fixes made anywhere on a contour consisting of a square with the four Loran transmitters on its corners when these are synchronized with surface waves. The corresponding uncontaminated pulse accuracy on this contour employing sky-wave synchronization is only 3.74 miles. These figures serve to illustrate the large increases in accuracy which might be expected with the uncontaminated pulses.

More transmitter power for the same distance range would be necessary with the uncontaminated pulse system because of the greater receiver band width required, and the consequent increase in interfering noise.

EXPECTED LF LORAN FIELD INTENSITIES OVER LAND FOR 100KW IN A 625 FOOT STEEL TOWER WITH UMBRELLA LOADING

$\sigma = 5 \times 10^{-14}$ E.M.U. $\varepsilon = 15$

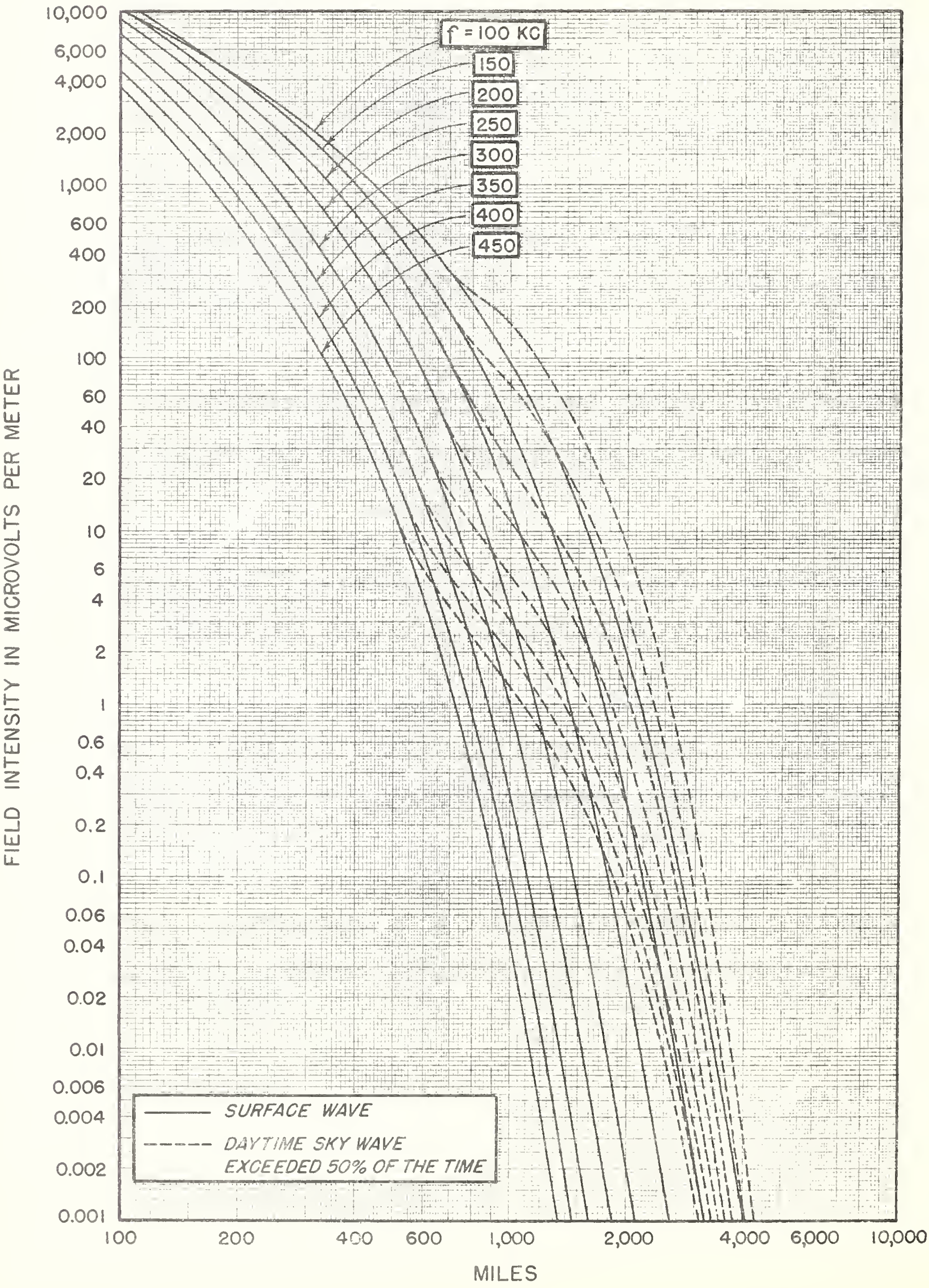


FIG. 1

EXPECTED L F LORAN FIELD INTENSITIES OVER THE SEA FOR 100 KW IN A 625 FOOT STEEL TOWER WITH UMBRELLA LOADING

$\sigma = 5 \times 10^{-11}$ E.M.U. $\varepsilon = 80$

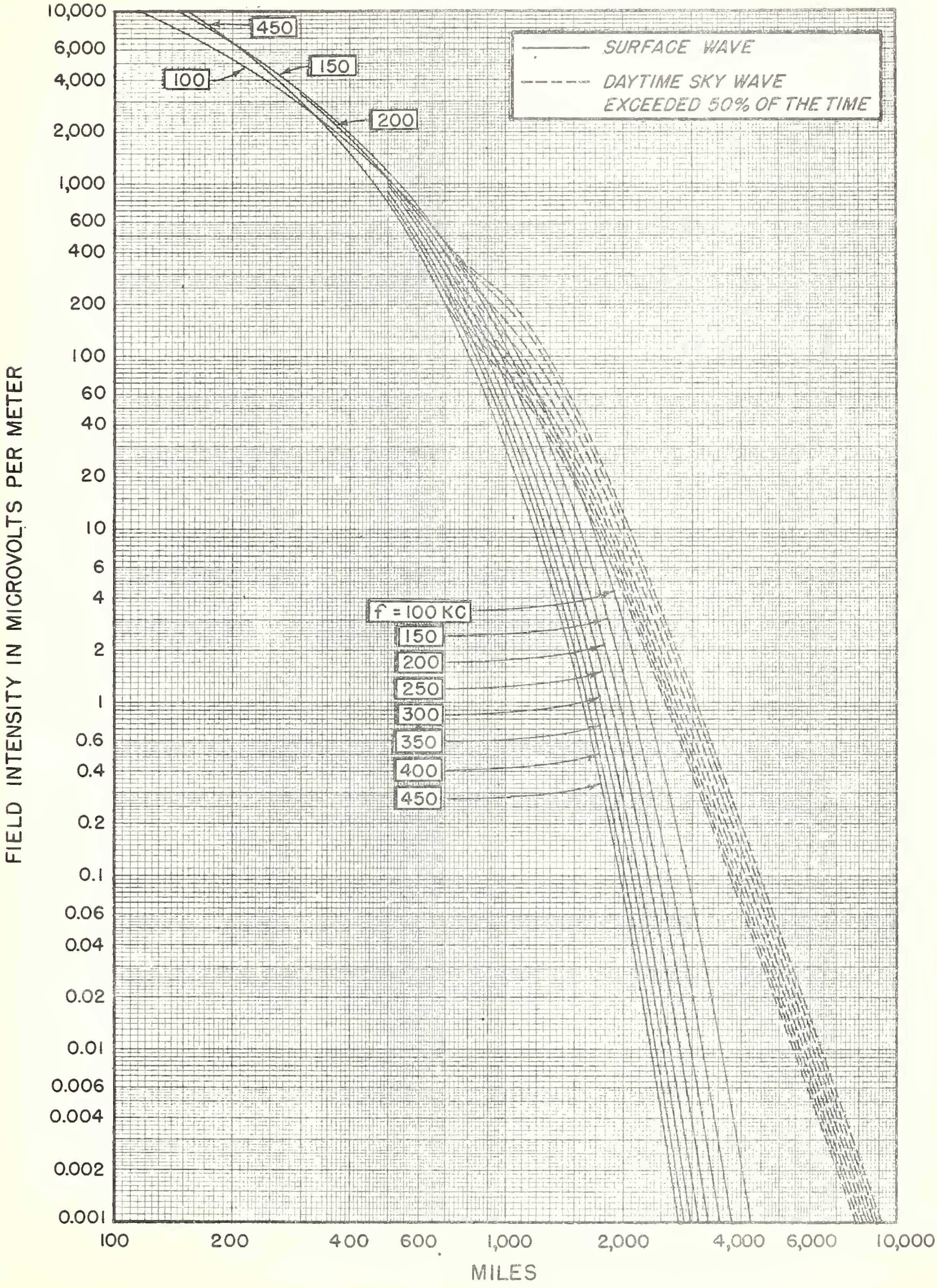


FIG. 2

PULSE FIELD INTENSITIES REQUIRED FOR SYNCHRONIZATION
98% OF THE TIME FOR ARCTIC WINTERS OR LOW LATITUDE SUMMERS

(BASED ON THE PULSE WIDTH AND RECEIVER BAND WIDTH
USED IN THE EXPERIMENTAL L. F. LORAN SYSTEM)

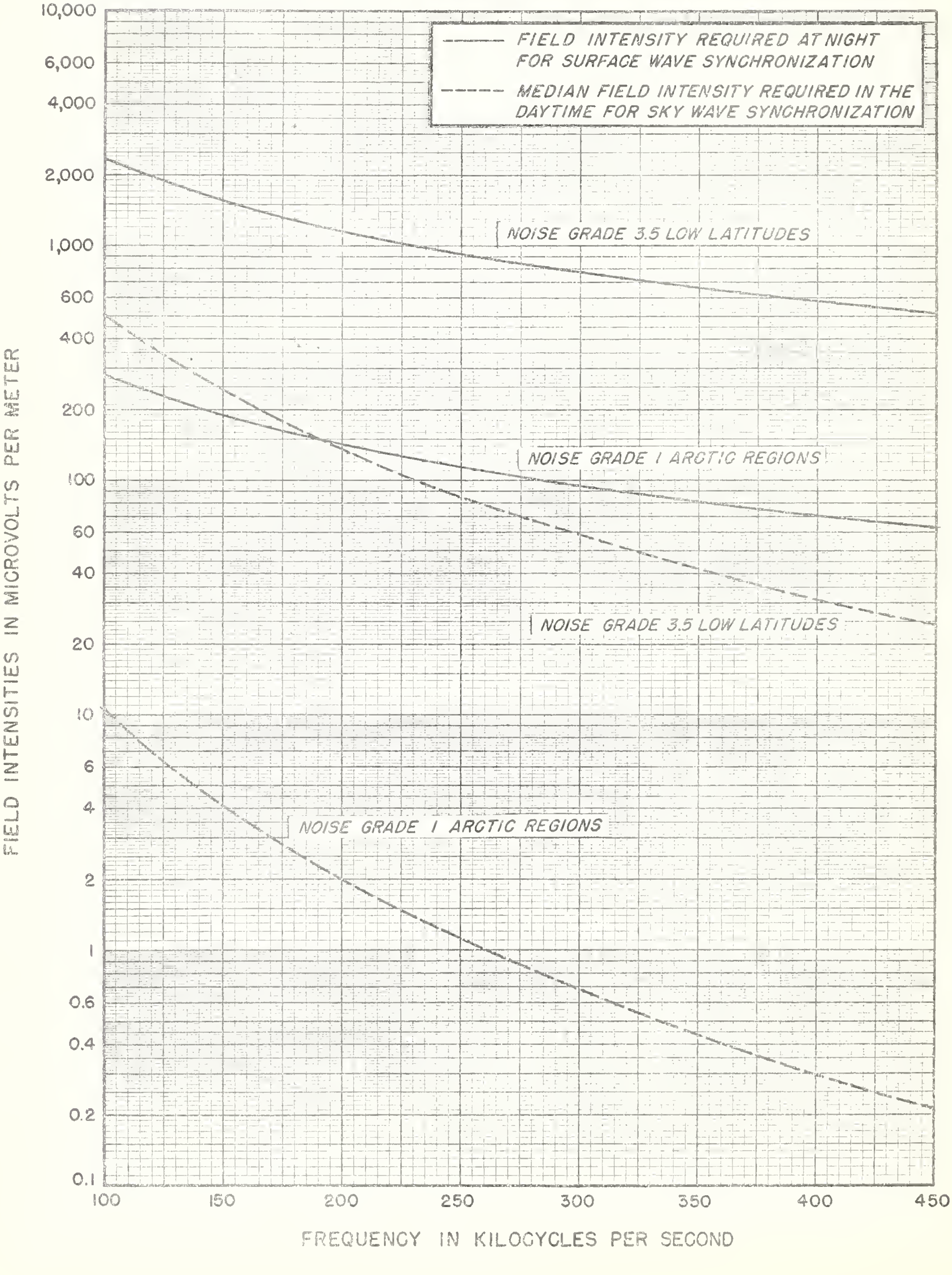
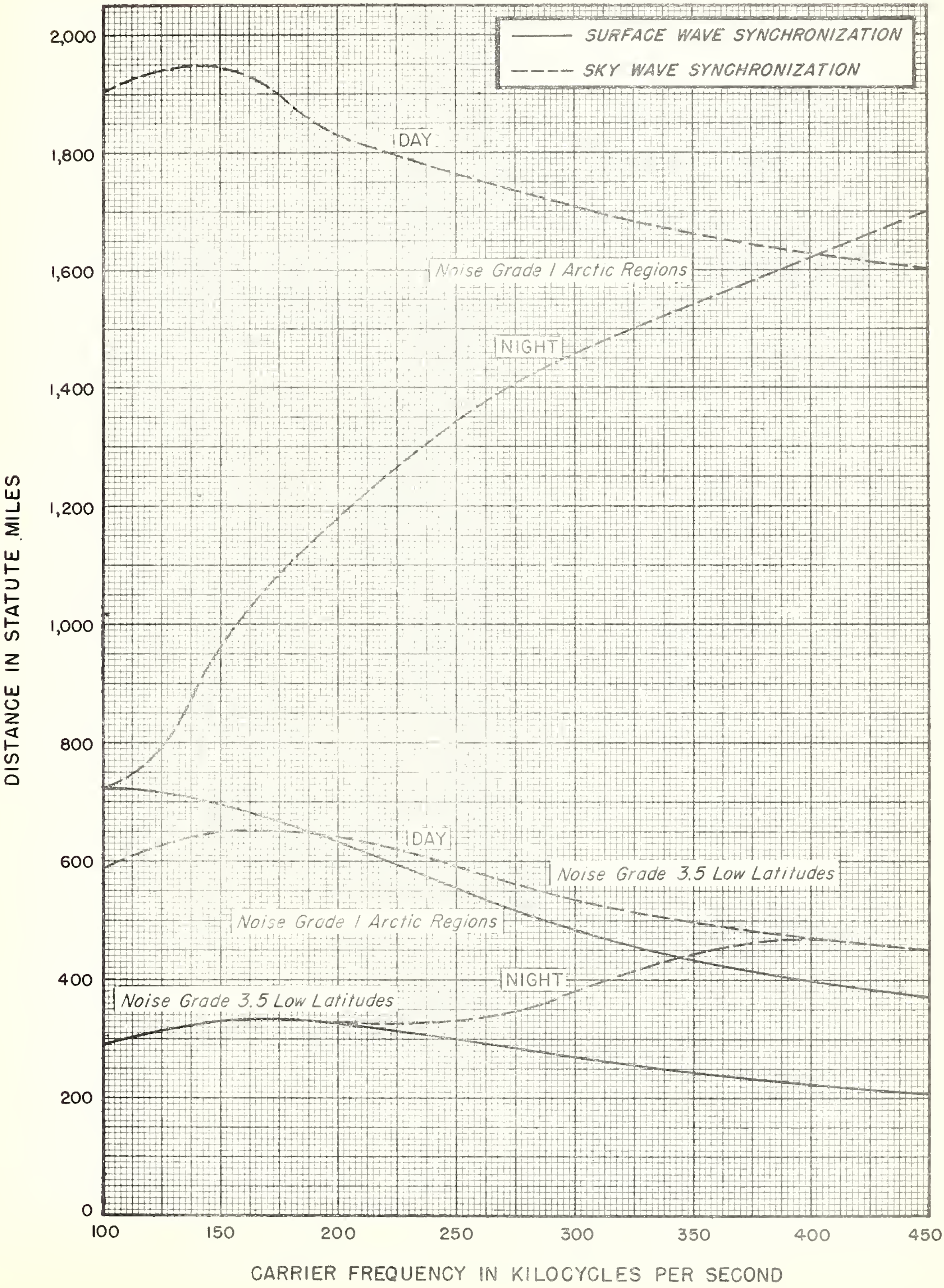


FIG. 3

THE MAXIMUM DISTANCE AT WHICH L.F. LORAN TRANSMITTERS MAY BE SYNCHRONIZED FOR 99% OF THE TIME WITH THE TRANSMISSION PATH OVER LAND

100 KW POWER IN A 625 FOOT STEEL TOWER WITH UMBRELLA LOADING

$\sigma = 5 \times 10^{-14}$ E.M.U. $\varepsilon = 15$



THE MAXIMUM DISTANCE AT WHICH L.F. LORAN TRANSMITTERS MAY BE SYNCHRONIZED FOR 99% OF THE TIME WITH THE TRANSMISSION PATH OVER THE SEA

100 KW POWER IN A 625 FOOT STEEL TOWER WITH UMBRELLA LOADING

$\sigma = 5 \times 10^{-11}$ EMU $\varepsilon = 80$

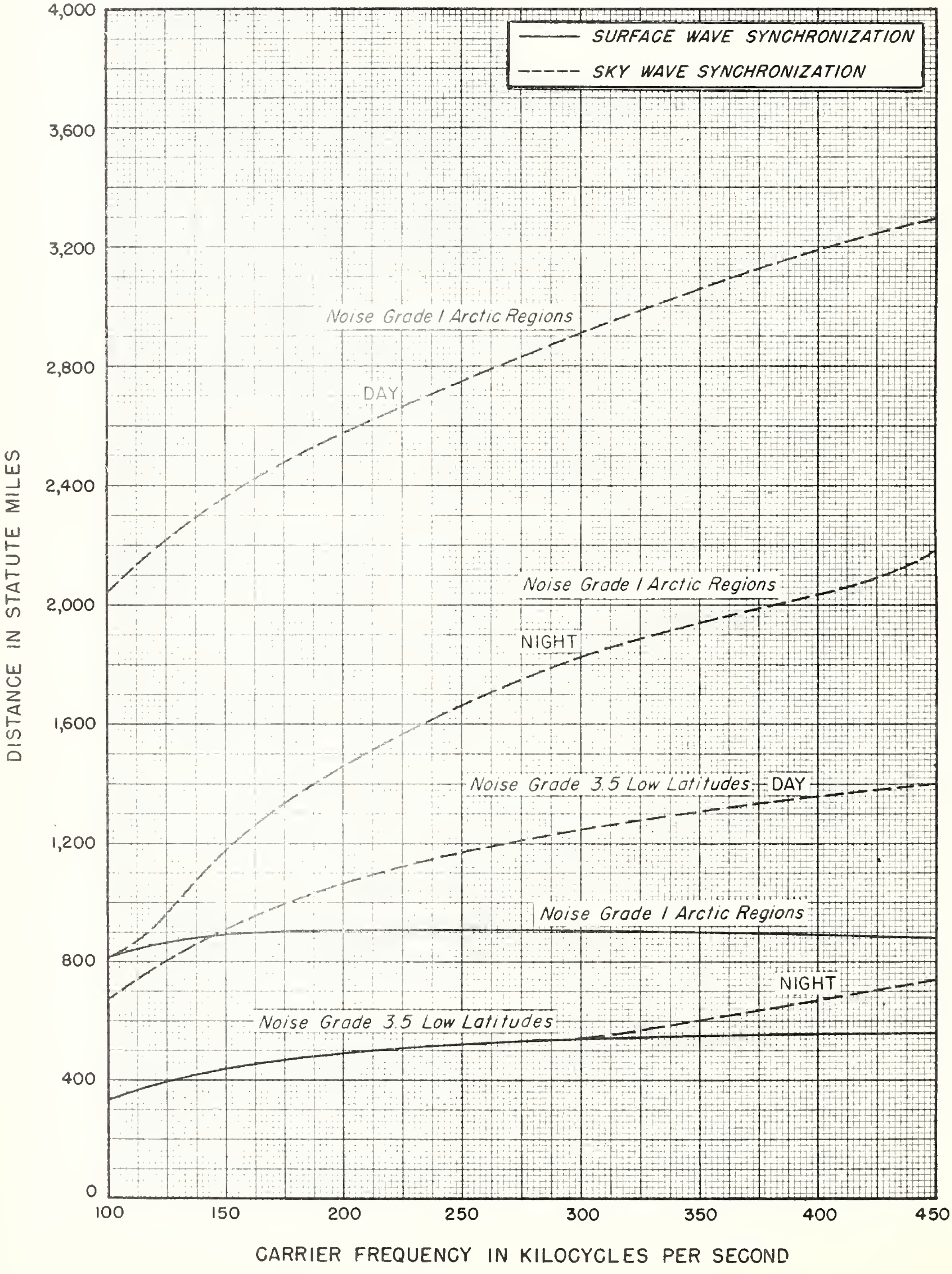
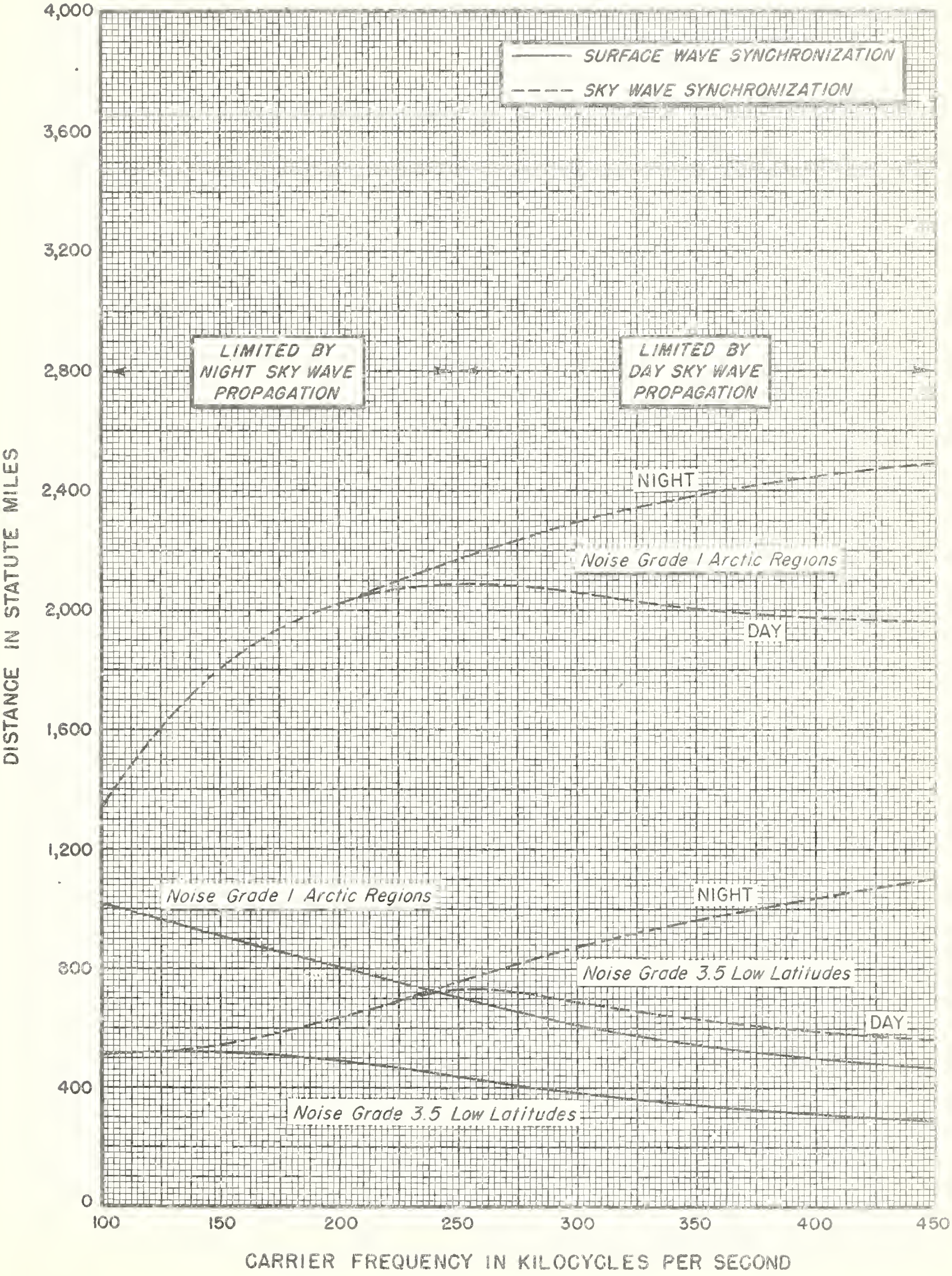


FIG. 5

THE MAXIMUM DISTANCE AT WHICH L.F. LORAN TRANSMITTERS MAY BE SYNCHRONIZED FOR 99% OF THE TIME WITH THE TRANSMISSION PATH OVER LAND

TRANSMITTER POWER 1,000 KW DELIVERED TO A 625 FOOT STEEL TOWER WITH UMBRELLA LOADING

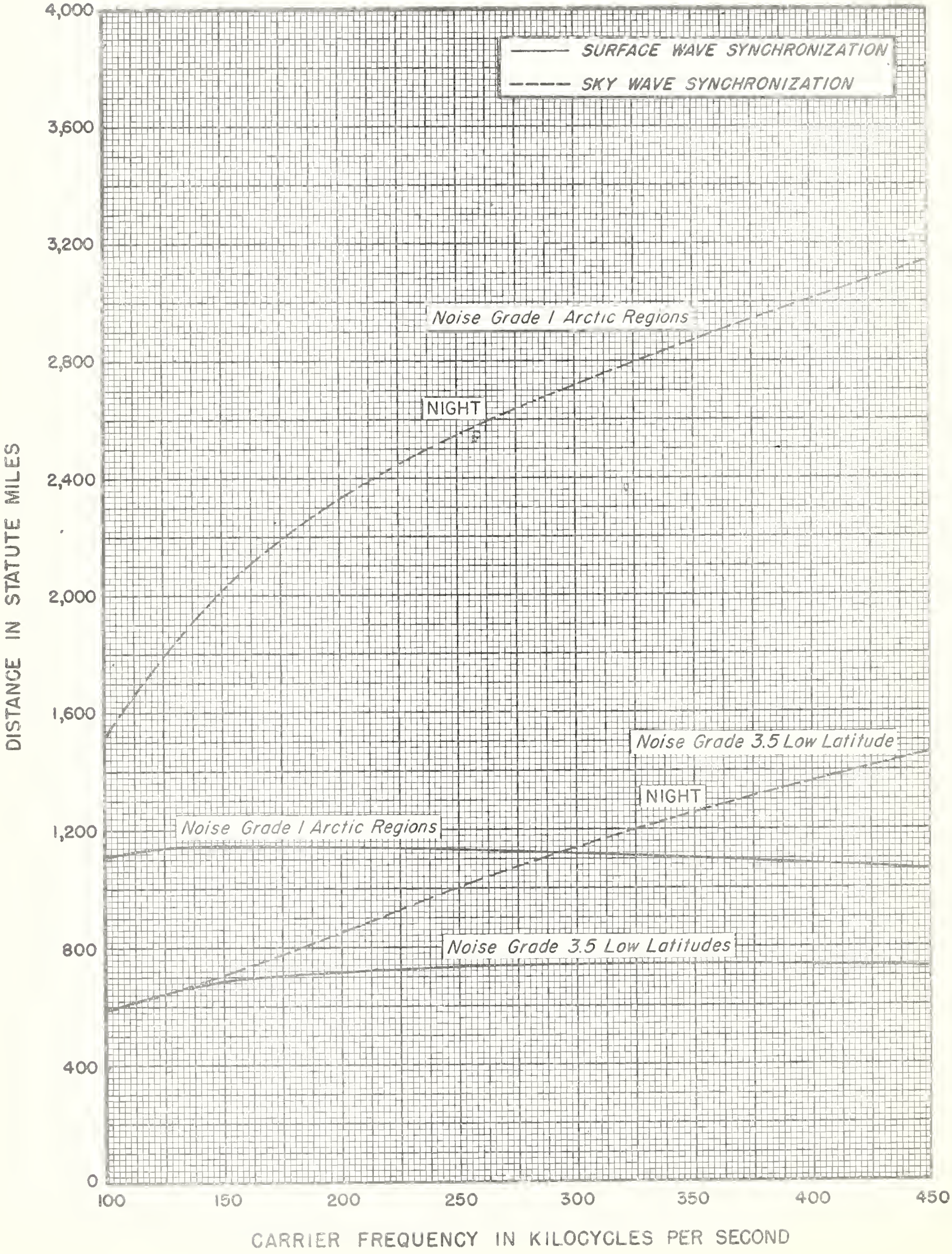
$\sigma = 5 \times 10^{-14}$ E.M.U $\quad \varepsilon = 15$



THE MAXIMUM DISTANCE AT WHICH L.F. LORAN TRANSMITTERS MAY BE SYNCHRONIZED FOR 99% OF THE TIME WITH THE TRANSMISSION PATH OVER THE SEA

TRANSMITTER POWER 1,000 KW DELIVERED TO A 625 FOOT STEEL TOWER WITH UMBRELLA LOADING

$\sigma = 5 \times 10^{-11}$ E.M.U. $\epsilon = 80$



EXPECTED ACCURACY OF L. F. LORAN FOR THE PRESENT EXPERIMENTAL SYSTEM OPERATING ON 200 KC INVOLVING CONTAMINATED PULSES COMPARED WITH A SKY WAVE SYNCHRONIZATION SYSTEM OPERATING ON 400 KC

(PULSES OCCUPYING A NARROW BAND HAVE A TIME OF RISING SO LONG THAT SKY WAVES ARRIVE AT THE RECEIVER BEFORE THE SURFACE WAVE ATTAINS ITS FULL AMPLITUDE; THE DISTANCE ERROR TO BE EXPECTED IN THIS CASE WILL BE LESS THAN THE VALUES FOR WHICH THE CONTOURS ARE LABELLED FOR 99% OF THE FIXES; THE SYSTEM IS ASSUMED TO CONSIST OF THE IDEAL L. F. LORAN ARRANGEMENT OF FOUR STATIONS ON THE FOUR CORNERS OF A SQUARE)

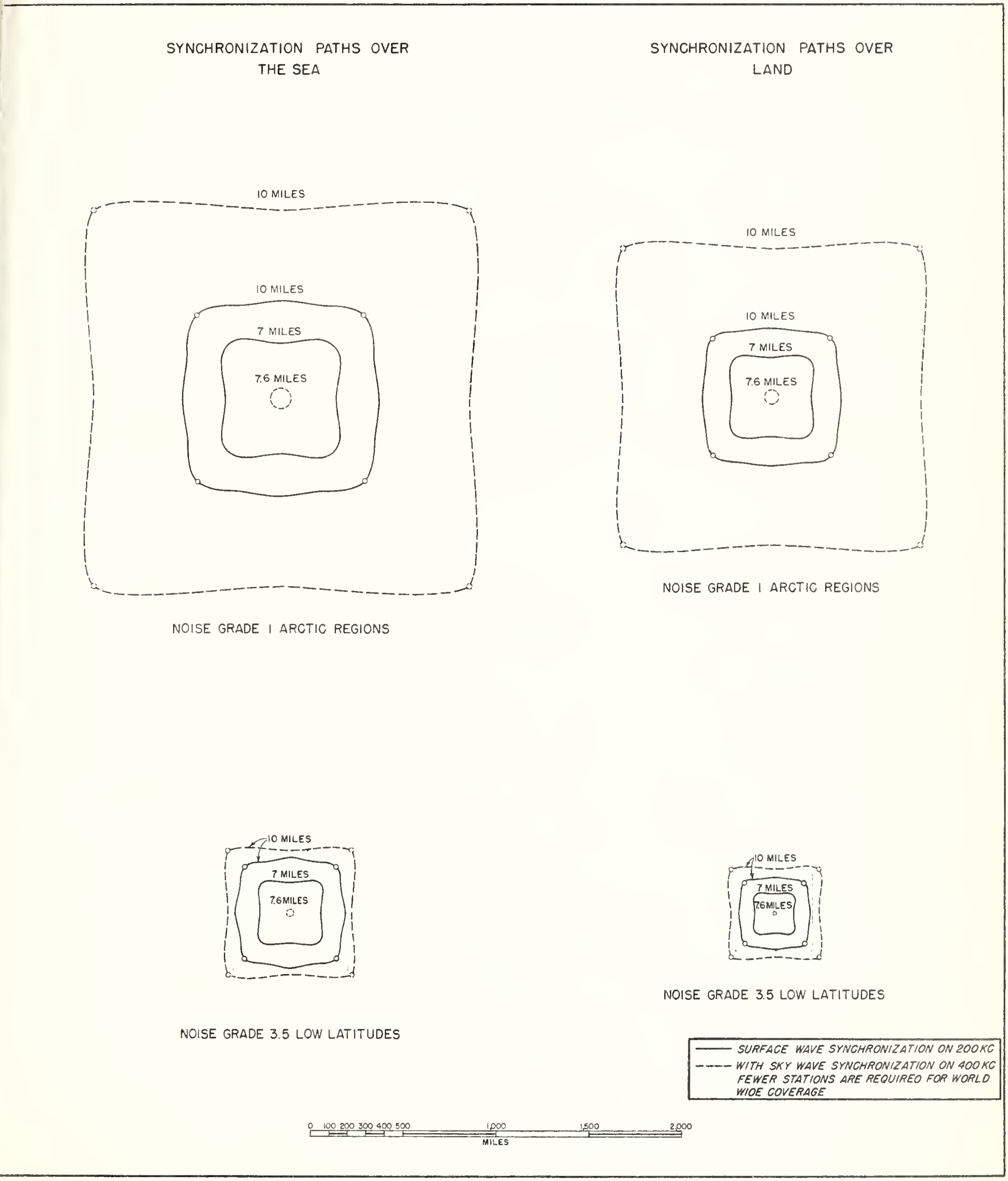


FIG. 8