NBS

Technical Note No. 126

MUTUAL INTERFERENCE BETWEEN SURFACE AND SATELLITE COMMUNICATION SYSTEMS

WILLIAM J. HARTMAN AND MARTIN T. DECKER

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

Functions and Activities

The functions of the National Bureau of Standards are set forth in the Act of Congress, March 3, 1901, as amended by Congress in Public Law 619, 1950. These include the development and maintenance of the national standards of measurement and the provision of means and methods for making measurements consistent with these standards; the determination of physical constants and properties of materials; the development of methods and instruments for testing materials, devices, and structures; advisory services to government agencies on scientific and technical problems; invention and development of devices to serve special needs of the Government; and the development of standard practices, codes, and specifications. The work includes basic and applied research, development, engineering, instrumentation, testing, evaluation, calibration services, and various consultation and information services. Research projects are also performed for other government agencies when the work relates to and supplements the basic program of the Bureau or when the Bureau's unique competence is required. The scope of activities is suggested by the listing of divisions and sections on the inside of the back cover.

Publications

The results of the Bureau's research are published either in the Bureau's own series of publications or in the journals of professional and scientific societies. The Bureau publishes three periodicals available from the Government Printing Office: The Journal of Research, published in four separate sections, presents complete scientific and technical papers; the Technical News Bulletin presents summary and preliminary reports on work in progress; and the Central Radio Propagation Laboratory Ionospheric Predictions provides data for determining the best frequencies to use for radio communications throughout the world. There are also five series of nonperiodical publications: Monographs, Applied Mathematics Series, Handbooks, Miscellaneous Publications, and Technical Notes.

A complete listing of the Bureau's publications can be found in National Bureau of Standards Circular 460, Publications of the National Bureau of Standards, 1901 to June 1947 ($1.25), and the Supplement to National Bureau of Standards Circular 460, July 1947 to June 1957 ($1.50), and Miscellaneous Publication 240, July 1957 to June 1960 (includes Titles of Papers Published in Outside Journals 1950 to 1959) ($2.25); available from the Superintendent of Documents, Government Printing Office, Washington D.C. 20402.

NATIONAL BUREAU OF STANDARDS

Technical Note 126

August 1, 1963

MUTUAL INTERFERENCE BETWEEN SURFACE AND SATELLITE COMMUNICATION SYSTEMS

(November, 1961)

by

William J. Hartman and Martin T. Decker

NBS Technical Notes are designed to supplement the Bureau's regular publications program. They provide a means for making available scientific data that are of transient or limited interest. Technical Notes may be listed or referred to in the open literature.

For sale by the Superintendent of Documents, U. S. Government Printing Office
Washington, D.C. 20402

Price 35 cents

TABLE OF CONTENTS

MUTUAL INTERFERENCE BETWEEN
SURFACE AND SATELLITE COMMUNICATION SYSTEMS *

William J. Hartman and Martin T. Decker

Estimates of the mutual interference expected to occur between the ground terminals of space communications systems and surface point-to-point systems are presented in a fashion suitable for engineering applications. These estimates are obtained from recently developed methods for predicting the transmission loss over tropospheric paths in terms of parameters such as geographic separation, elevation angle of the antenna, antenna patterns, and frequency. It is concluded that these systems can share the same frequency assignment under suitable conditions.

1. INTRODUCTION

Many problems of mutual interference between proposed satellite communication systems and surface communication systems can be investigated in terms of available theories. The primary purpose of this paper is to predict the conditions under which a service will be interference-free for a given percent of the time. The prediction methods that are developed are intended to have a wide range of applicability. Examples are used to illustrate the use of the method for specific systems.

In general, the effects of an interfering signal must be determined for each system. Tolerable interference will depend not only on the relative levels of the desired and undesired signals, but also on the type of modulation used in both signals. In most

* This work was sponsored by the Joint Technical Advisory Committee of E.I.A. and I.R.E.

cases it must be determined experimentally, in some cases subjectively (for example, subjective rating of television pictures). Further, neither desired nor interfering signals will be steady signals, but will be subject to fading; hence the ratio of desired to interfering signal will be represented by a distribution of values. Because of this, satisfactory operation should usually be specified in terms of an hourly median desired signal to an hourly median undesired signal ratio required to provide a given grade of service or better for some percentage of the hours. A further discussion of this problem is given by Norton [1959]. However, in view of the many unknowns, the problem has been somewhat simplified for the purposes of this paper by simply relating the hourly median interfering signal to the noise power of the receiver under consideration. Thus, the question answered here is: What separation distances and antenna elevation angles are required so that the interfering hourly median signals are equal to or less than the receiver noise power for a given percent of the hours?

All of the calculations in this paper are presented with the following assumptions: (1) The main beam of the ground terminal antennas will not be pointed below about 5° above the horizon, because of the increased atmospheric absorption and antenna noise from ground reflections [Pierce and Kompfner, 1959]; and (2) the frequency band most suitable for space communication systems is the band from about 1 Gc/s, (thousand million c/s), to above 10 Gc/s [Haydon, 1960].

The use of a particular value or assumption will be justified where necessary and possible. In cases where the state-of-the-art limits the ability to predict with accuracy, values will be used that will predict the larger interference.

2. TRANSMISSION LOSS

The usual concept of transmission loss [Norton, 1959; Rice, Longley, and Norton, 1959] will be used here to predict the mutual interference between surface systems and space communication systems. The median transmission loss in decibels,

$$L = 10 \log_{10} P_r / P_a , \tag{1}$$

is given in terms of the ratio of the power radiated from the transmitting antenna, P_r, to the available power at the receiving antenna, P_a. No distinction will be made here between system loss and transmission loss. The method used to predict L is a modification of the method published by Rice, et al.[1959], which makes use of basic median transmission loss,

$$L_b = L + G_p , \tag{2}$$

where G_p is the path antenna gain in decibels. The loss L that is predicted here is the hourly median for typical winter afternoon hours. Variation for other times of the year will be discussed in a later section.

As a point of reference, we first calculate the basic median transmission loss for various frequencies and distances over a smooth spherical earth. This gives the loss expected if nondirectional isotropic radiators are used at both the transmitter and receiver. If care is taken in locating the interfering systems, the assumption of a smooth earth will correspond to a lower path loss, and therefore to potentially more interference than would be encountered over a rough earth. L_b is shown in figure 1 plotted versus distance (or angle). The minimum distance shown here is 100 miles. At distances of less than 100 miles, diffraction becomes more important and eventually becomes dominant. This can be calculated using the methods given by Rice, et al, [1959].

For the purposes of calculation, it has been assumed that the receiver antenna beam is being tilted upward through an angle ψ (see figure 2) in the great-circle plane determined by the location of the transmitting antenna, T, and receiving antenna, R. This designation of T and R is not a restriction on the problem, however, because the reciprocity theorem holds for tropospheric propagation. In order to reduce the number of parameters, it has been assumed that the antennas are 30 feet above a smooth spherical earth. The results will not be essentially different for antenna heights up to 60 feet when the antenna is tilted 5° or more above the horizon. Varying this height will change α_o (see figure 2), the angle between the line connecting transmitter and receiver, $\overline{TR}$, and the horizon ray from the transmitter in the great-circle plane; and will change β_o, the angle between $\overline{TR}$ and the horizon ray from the receiver, also in the great-circle plane. The change and, hence, the total effect will be small. The main and side lobe of both transmitter and receiver beams will be centered about the great-circle plane; for the minimum values of α_o and β_o, the main beams of the antennas will be centered on their respective horizons.

The path antenna gain, G_p, is given in terms of the free-space gains of the transmitter and receiver,

$$G_p = G_t + G_r - G_L, \tag{3}$$

where G_L is the loss in antenna gain [Hartman and Wilkerson, 1959]. Here, parabolic dishes are assumed for the calculation of G_p. However, since the parameter used for predicting G_p is actually the half-power beamwidth, and since the calculations are not done using the entire antenna pattern, but only one part (such as the main lobe or one side lobe), the calculations can be used for arbitrary patterns that have the same half-power beamwidths. (The method actually restricts the patterns to be symmetric although good approximations can be made for asymmetric patterns.)

Figures 3 through 23 show the transmission loss for the combinations of antennas shown in table 1.

TABLE 1

Transmitter	Receiver	Transmitter	Receiver
10' dish	60' dish	10' dish	6' dish
6' dish	60' dish	6' dish	6' dish
Isotropic	60' dish	Isotropic	6' dish

Table 2 gives, for frequencies of 1, 2, 6.5, and 10 Gc/s, the gain in decibels above an isotropic antenna; the half-power beamwidths; and, for the 60-foot dish, the location of the first and second side lobes relative to the main beam axis.

The antenna pattern assumed here will consist of the main beam, one side lobe, and the remaining portion of the pattern isotropic. However, this may be modified to conform to an actual antenna pattern by adding the contributions from additional side lobes. For the assumed pattern the total power available at the receiver will be approximately

$$P'_a = P_r\left(10^{-L_1/10} + 10^{-L_2/10} + 10^{-L_3/10}\right) \qquad (4)$$

or in terms of transmission loss,

$$L' = -10 \log_{10}\left(10^{-L_1/10} + 10^{-L_2/10} + 10^{-L_3/10}\right), \qquad (5)$$

TABLE 2

Frequency (Gc)	Diameter of Dish (ft)	Half-Power Beamwidth (mr)*	Free-Space Gain Relative to an Isotropic Antenna (db) (56% efficiency)	Location of First Side Lobe (mr)	Location of Second Side Lobe (mr)
1	60	20	43.1	33	50.6
	10	119.8	27.6		
	6	199.7	23.1		
2	60	10.0	49.2	16.3	25.4
	10	59.9	33.6		
	6	99.8	29.2		
6.5	60	3.1	59.4	5.0	7.8
	10	18.4	43.8		
	6	30.7	39.4		
10	60	2.0	63.1	3.3	5.1
	10	12.0	47.6		
	6	20.0	43.1		

* Milliradians

where L_1 is the transmission loss for the main beam, L_2 is the transmission loss for the side lobe, and L_3 is the transmission loss for an isotropic antenna. (In a given antenna, L_3 may be above or below an isotropic antenna by 10 or even 20 db. The exact amount depends on the design and construction of the specific antenna.) The loss for a beam with several side lobes could be accounted for in the same way. Considering only one side lobe, this loss could have a variety of forms, two of which will be discussed here. Assuming that the side lobe is 20 db down from the main beam, the side lobe could be a broader beam, like that of a 6-foot dish compared to a 60-foot dish with the same power, or it could have the same half-power beamwidth with less power. The former case is covered by the curves for the 6-foot dish; the latter case is covered by adding 20 db to the transmission loss curves for the 60-foot dish.

It will become apparent later in the paper that the use in these examples of a 60-foot dish at the receiver is not a critical assumption, and that the conclusions reached concerning the interference will not be changed significantly if the 60-foot dish is replaced by a 30-foot dish or by a 120-foot dish. However, the use of a 10-foot dish at the transmitter does place some limitations on the types of systems that can be assumed.

The curves shown in figure 24 (transmission loss versus frequency for 100 and 350 miles) have been prepared to show only the effect of frequency by using a constant beamwidth of 5 mr at the receiver end and an isotropic antenna at the transmitter end. This corresponds approximately to a 240-foot dish at 1 Gc/s and to a 24-foot dish at 10 Gc/s.

3. VARIABILITY

The values of transmission loss described in section 2, and shown in figures 3 through 23, are median values of hourly medians for typical winter afternoons. In order to account for the variability of the hourly medians from this median value, empirically derived curves from Rice, et al.[1959] are used. These curves, shown in figure 25, are the best available estimates of the variability, although most of the data from which these were derived are for frequencies below 1 Gc/ s and for broad-beamed antennas. However, the trend in the data indicates that the largest variability occurs near 400 Mc/ s and decreases with frequency to 1 Gc/ s. In general, it is expected that the variability will be less for the frequencies from 1 Gc/ s to 10 Gc/ s than is indicated on these curves. The largest variability in these curves occurs at about 10 mr,which is approximately where the diffracted and scattered components are equal. The possibility that the path antenna gain, G_p, varies with high fields might be the cause for some concern. For the portion of the antenna pattern directed at the horizon, the loss in antenna gain will be small and therefore any variation of G_p will be small, and is included in the total variation by use of the curves in figure 25. The loss in antenna gain for the main beam can be large, but since in this report the very narrow main beams are directed above the horizon, all of the following mechanisms normally responsible for the high fields are not very effectual. High fields due to ducting of the main beam will not occur, since the maximum observed angle at which the radio waves can be trapped is 5.8 mr [Bean, 1959], while the antenna beam is elevated above 50 mr. Superrefraction, causing bending of radio waves, can cause only a very small percent of change in θ when the original main beam elevation angle is above 3° [Bean and Thayer, 1959]. Here θ is the angle between the rays in the great circle plane at the lower edges of the common volume of the antenna beams. Moreover, terrain effects that are emphasized by refraction when the main beams are near the horizon would have little effect at the higher elevation angles. Fields associated with reflection by elevated layers will be smaller at the high angles and high frequencies for two reasons: (1) The gradient required for reflection is directly proportional to frequency; and (2) by examining Rayleigh's criterion for the roughness of the reflecting surface we see that the reflecting stratum must be increasingly smoother at the higher frequencies. Thus we conclude that if any variations in G_p exist they must be very small in the problem under consideration.

It would be desirable to obtain experimental variability curves more directly applicable to the specific conditions of this problem. Preliminary measurements over a 165-mile path from Table Mesa to Haswell, Colorado, at 409.9 Mc/s using a 14-foot dish for a transmitter and a 60-foot dish for the receiver, are shown plotted together with the predicted median transmission loss in figure 26. These experimental values are medians for five-minute periods during which the receiving antenna is tilted above the horizon at the angle indicated.

The value of hourly median transmission loss of concern here is that value which will be exceeded p percent of the hours, and is given by

$$L(p) = L - V(100 - p, \theta). \qquad (6)$$

The actual transmission loss is less than the transmission loss for only the main beam, or for only a side lobe, or for only an isotropic antenna; furthermore, because of the nature of the approximation made in (5), it is greater than the transmission loss L'. Thus, in the following sections, the smallest of the three values of transmission loss (L_1, L_2, L_3) will be assumed to be the pertinent value of L'.

The following value of the parameters will be assumed:

Frequency	=	1 Gc/s
d	=	100 miles, d = 150 miles,
α_o	=	β_o = 8 mr
p	=	99.9%
Receiver	=	60-foot dish with one side lobe 20 db below the main beam and located 33 mr from the main beam axis, and isotropic radiation otherwise.
Transmitter	=	10-foot dish.

Figure 27 shows the transmission loss, L(99.9), plotted versus the angle ψ, the elevation angle for the main beam. This figure shows values of transmission loss that will be exceeded by 99.9 percent of the hourly medians for each of the following combinations:

T	R
10' dish	60' dish--main beam only
10' dish	60' dish--first side lobe only
10' dish	Isotropic
Isotropic	Isotropic

Similar curves for different frequencies are shown in figures 28, 29, and 30. Figure 31 shows the 1 Gc/s curves at the 99 percent level.

All of the previous curves have been prepared using a value for the surface refractivity, N_s, of 301. N_s varies with geographic location and this will have a small effect on the values of L and L(p). Figure 32 shows a map of the United States with contours of N_s for February [Bean, Horn, and Ozanich, 1960]. For the largest value N_s = 335, L will be decreased by approximately 5 db, and for the smallest value, N_s = 245, L will be increased by approximately 5 db with a corresponding change in L(p).

4. RESULTS

The following procedure is used to determine the separation distances and antenna elevations necessary to make the interfering hourly median signals less than or equal to the receiver noise power for a given percent of hours.

1. Select the separation distance, the frequency, and the antennas to be considered, together with the required percent of the hours, p, for which the interfering signal must be less than the receiver noise.

2. Plot curves of $L(p) = L - V(100 - p, \theta)$ versus antenna elevation angle where L is taken from the appropriate curves of figures 3 through 23, and $V(100 - p, \theta)$ is taken from figure 25. These curves are plotted for any portion of the antenna patterns which may be of interest. Here we plot curves for the main beam, lower side lobe, and isotropic side lobes. Note that for isotropic side lobes the value of $L - V(100 - p, \theta)$ will not be a function of the antenna elevation angle since this portion of the antenna pattern will always extend to the horizon.

3. Determine the noise power, P_n, in decibels, for the receiver being considered. This may be either

$$P_n = NF + 10 \log KTb = NF + 10 \log b - 204 \tag{7}$$

or

$$P_n = 10 \log KT_e b = 10 \log T_e b - 228.6, \tag{8}$$

where NF is the effective noise figure [Norton, 1959] of the receiving system,

K is Boltzmann's constant,
b is the noise bandwidth of the receiver in cps,
T is a reference temperature, for a conventional receiver 288.48° K,

and

T_e is the effective noise temperature of the receiver and antenna combination.

4. Compute the value of transmission loss required to make the interfering signal equal to the noise power. This value is

$$L_{req} = P_t - L_c - M - P_n \quad (9)$$

where P_t is the power, in decibels, of the interfering transmitter.

L_c represents coupling losses in the system and may include transmission line losses, cross polariation losses, etc.

M is a term to allow for the situation in which the transmitted energy is spread over a frequency band different from that which will be accepted by the receiver. It will depend on the type of modulation as well as the bandwidths, but an estimate is made here by letting $M = 10 \log b_t/b_r$ where b_t and b_r are the transmitter and receiver bandwidths, respectively.

5. The value found in step 4 is then compared with the curves of step 2 in order to determine if $L_{req} \leq L'$, where L' is the smallest of the values of the transmission losses for the main beam or the side lobe or the isotropic part of the antenna pattern. If this requirement is satisfied, no interference will be encountered for the conditions assumed in step 1.

5. EXAMPLES

As an example of the use of the transmission loss curves consider systems operating on the same frequency assignment and with the main beams centered in the great-circle plane connecting the two terminals. At one end of the path a 10-foot dish is pointed at the horizon and here represents one terminal of a surface point-to-point microwave relay system. At the other end of the path a 60-foot dish represents the earth terminal of a satellite communication system and may be elevated above the horizon by an angle ψ.

It has characteristics as in table 2 with the first side lobe 20 db below the main beam. The radiation pattern, for the purpose of this example, is assumed to be isotropic outside the main beam and first side lobe. It is assumed that the interfering signal must be less than the receiver noise power for at least 99.9 percent of the hours. The curves of L(p) in figures 28 through 31 are plotted for the above conditions using the method given in section 4, step 2.

5.1. Example 1

Consider first the case of interference from the earth terminal transmitter to a point-to-point relay receiver. The receiver noise power is determined as in step 3 assuming a bandwidth of 20 Mc/s and a noise figure of 10 db. Then

$$P_n = NF + 10 \log b - 204$$

$$= 10 + \left[10 \log \left(20 \times 10^6\right)\right] - 204$$

$$= -121 \text{ dbw}.$$

The transmission loss required to make the interfering signal equal to the noise power is found as in step 4. Assume a transmitter power of 1 kw, coupling losses of 4 db, including line and polarization losses, and a transmitted bandwidth of 20 Mc/s. Then

$$L_{req} = P_t - L_c - M - P_n$$

$$= 30 - 4 - 0 - (-121)$$

$$= 147 \text{ db}.$$

This transmission loss value is now used with figures 28 through 31 to determine whether the condition of step 5 can be met. It is clear that for a separation distance of 100 miles and for all four frequencies the transmission loss from the isotropic portion of the transmitting antenna is less than the 147 db required loss. For a separation of 150 miles the energy transmitted by way of the main beam becomes significant and the required conditions can be met at all frequencies if the main beam of the 60-foot antenna is elevated above the horizon by approximately 5°. At 2, 6.5, and 10 Gc/s lower elevation angles could be tolerated.

A number of changes can be made in the system parameters assumed for this case. The analysis assumes that the antenna of the surface point-to-point system is directed toward the earth terminal. Rotating this antenna so that the main beam does not point directly toward the earth terminal would increase the transmission loss. When the pattern of the 10-foot dish is at the isotropic level in the direction of the earth terminal, the "isotropic-isotropic" curves of figures 28 through 31 will apply rather than the "10-foot dish isotropic" curves. The transmission loss via main and side lobes will, of course, increase by approximately the same amount. Therefore, the 99.9-percent time requirement could be met at 100 miles and at all frequencies by orienting the 10-foot dish to reduce the interfering signal by 19 db at 1 Gc/s and by lesser amounts at the other frequencies.

Other earth-terminal-to-satellite systems might require more or less transmitter power. Suggested systems [FCC, 1960] range from approximately 3 to 36 dbw. The effect of changing this parameter in the above example would give a range of L_{req} from 120 to 153 db at the 99.9-percent level.

If, instead of a 60-foot dish, a 120-foot or a 30-foot dish were used for the transmitter, the only noticeable effect would be in the calculations for L(p) for the main beam. In the former case, L(p) for the main beam would be decreased by less than 6 db and in the latter case, L(p) would be increased by approximately 6 db. This can alter the conclusions only by increasing (or decreasing) the required elevation angle of the transmitter by at most 2°.

A reduction in the percentage of hours for which the interfering signal must be less than the receiver noise is illustrated in figure 31. The conditions are the same as in figure 28 except that the time requirement has been reduced from 99.9 to 99 percent. Similar curves can be drawn for any percent value using step 2.

5.2. Example 2

Consider next the case of interference from a point-to-point microwave relay transmitter to the earth-terminal receiver of a satellite system. Figures 27 through 31 again apply. It is assumed that a wide-deviation FM system is used in the satellite-to-earth link, so that the earth terminal receiver has an RF bandwidth of 100 Mc/s. With the use of a low-noise antenna and maser amplifier, we assume that the effective noise temperature of the receiver is reduced to 30°K.

By step 3,

$$P_n = 10 \log T_e b - 228.6$$

$$= 10 \log 30 + 10 \log 100 \times 10^6 - 228.6$$

$$= 14.8 + 80 - 228.6$$

Compute the transmission loss, L_{req}, as in step 4, assuming a transmitter power of 1 w, coupling losses of 4 db, and a transmitted bandwidth of 20 Mc/s. Then

$$L_{req} = P_t - L_c - M - P_n$$

$$= 0 - 4 - 10 \log 20/100 - (-134)$$

$$= 137 \text{ db.}$$

This value of L_{req} is compared with figures 27 through 31 to determine whether the requirement of step 5 can be met. It is seen that under these assumptions the point-to-point antenna could not be directed toward the earth terminal at a distance of 100 miles. As in the previous example, the curves indicate that the requirements could be met by not allowing the 10-foot dish to be directed toward the earth terminal.

The effects of varying the transmitter antenna size and the transmitted power were noted in example 1. Similar statements can be made about varying the receiver antenna size and transmitted power in this example. Values of the power used for typical point-to-point microwave relays range from -3 dbw to +7 dbw.

6. CONCLUSIONS

Our theoretical analysis indicates that space communication systems and surface systems of the conventional microwave relay type can share the same frequencies if care is used in locating the possible interfering sources. As seen in the examples, separation distances of from 100 to 150 miles will usually suffice, and under ideal conditions, distances of less than 100 miles could give adequate protection. Estimates for other systems, such as radar using large antennas and power outputs, can be found using the curves in this paper. Some authors [Bond, Cahn, and Meyer, 1960] have concluded that these high-powered radar systems will cause intolerable interference at the satellite, and this may be the limiting factor rather than the interference to (or from) the earth terminals.

If the radar antenna is directed toward the earth terminal, and away from the satellite, harmful interference should not be experienced if the radar and earth terminal are separated by distances of 500 miles or more. In many systems shorter separations may suffice.

It is important that some of the basic assumptions made in this theoretical analysis be checked experimentally over long periods of time. However, it is expected that such experiments will only substantiate some of the estimated values and will not be likely to contradict the broad general conclusions reached.

The authors wish to acknowledge the contribution of A. F. Barghausen who supervised the measurements reported here.

7. REFERENCES

Bean, B. R., Climatology of ground-based radio ducts, J. Res. NBS 63D, (Radio Prop.), No. 1, 29-34, (July-Aug., 1959).

Bean, B. R., J. D. Horn, and A. M. Ozanich, Jr., Climatic charts and data of the radio refractive index for the United States and the world, NBS Monograph 22, (November 1960).

Bean, B. R., and G. D. Thayer, CRPL exponential reference atmosphere, NBS Monograph 4, (October 1959).

Bond, F. E., C. R. Cahn, and H. F. Meyer, Interference and channel allocation problems associated with orbiting satellite communication relays, Proc. IRE 48, No. 4, 608-612, (Apr., 1960).

Federal Communications Commission, Allocation of frequencies in the bands above 890 mc, FCC Docket 11866, (1960).

Hartman, W. J., and R. E. Wilkerson, Path antenna gain in an exponential atmosphere, J. Res. NBS 63D, (Radio Prop.), No. 3, 273-286, (Nov. - Dec., 1959).

Haydon, G. W., Optimum frequencies for outer space communication, J. Res. NBS 64D, (Radio Prop.), No. 2, 105-109, (Mar. - Apr., 1960).

Norton, K. A., System loss in radio wave propagation, J. Res. NBS 63D, (Radio Prop.), No. 1, 53-73, (July - Aug., 1959).

Pierce, J. R., and R. Kompfner, Transoceanic communication by means of satellites, Proc. IRE 47, No. 3, 372-380, (Mar., 1959).

Rice, P. L., A. G. Longley, and K. A. Norton, Prediction of the cumulative distribution of ground wave and tropospheric wave transmission loss (Part I), NBS Technical Note 15, PB 151374, (July 1959). Order by PB number from the Office of Technical Services, U. S. Department of Commerce, Washington 25, D. C. Foreign remittances must be in U. S. exchange and must include one-fourth of the publication price to cover mailing costs. $1.50.

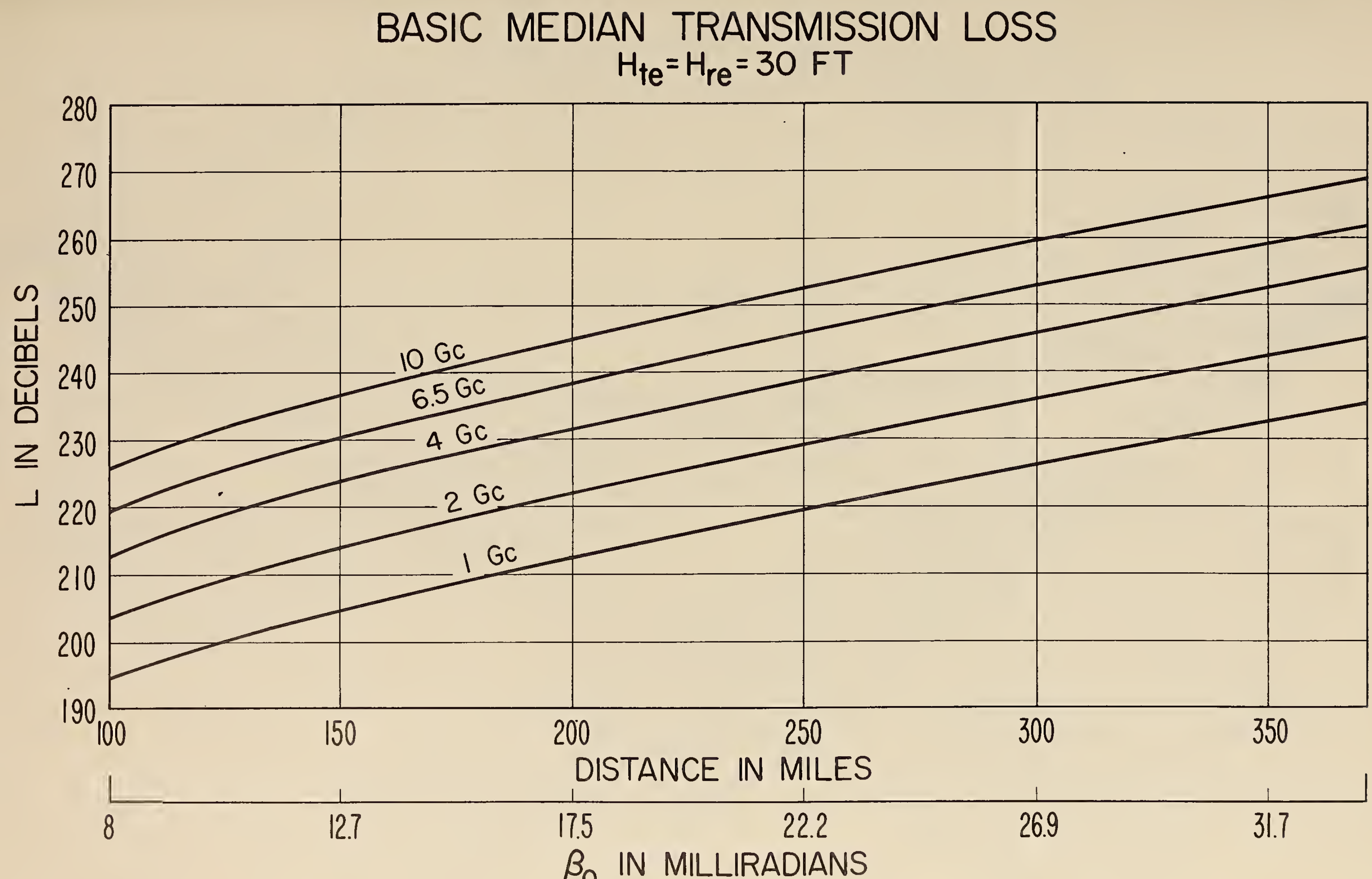
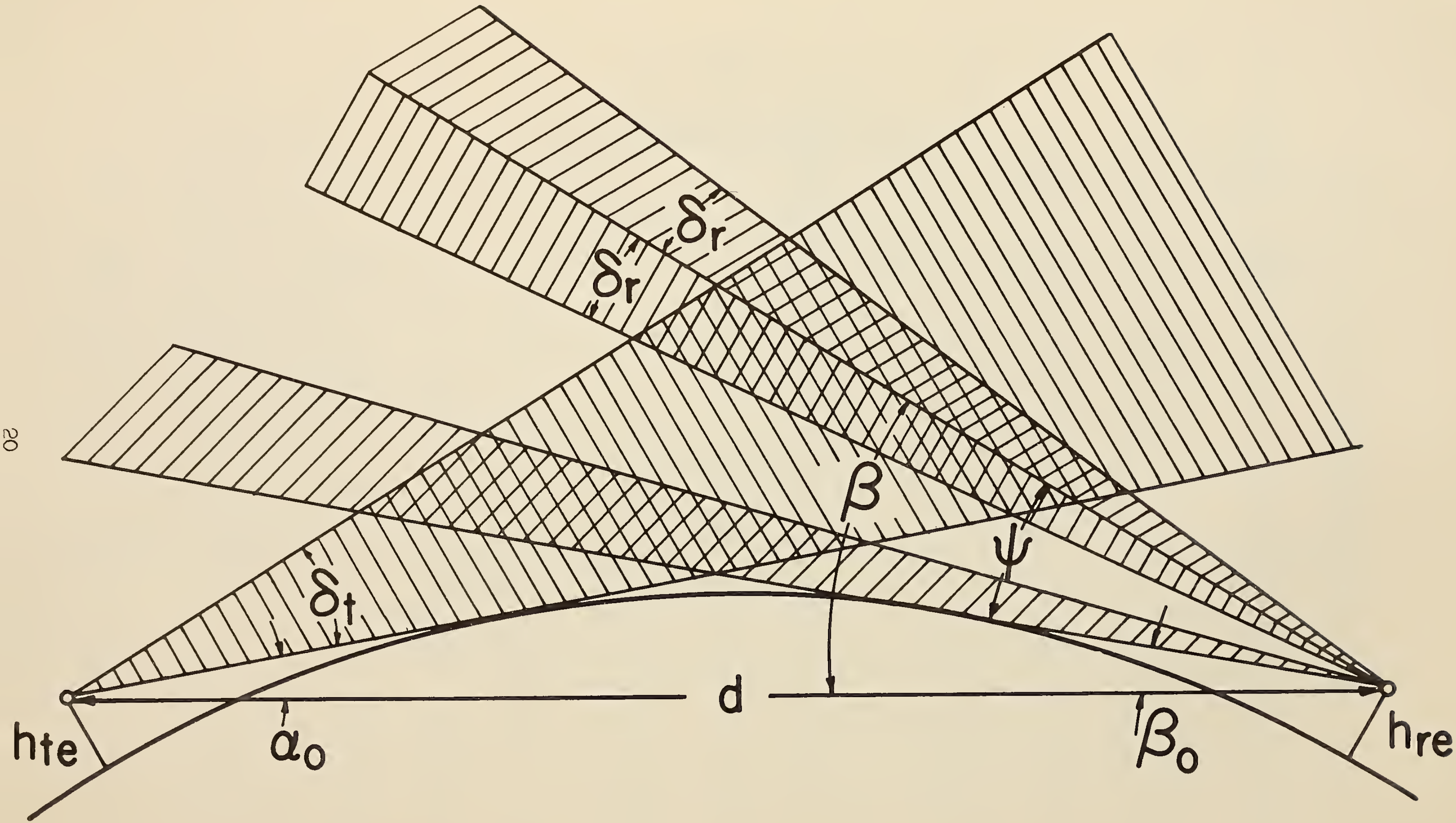

BASIC MEDIAN TRANSMISSION LOSS
$H_{te} = H_{re} = 30$ FT
L IN DECIBELS
280
270
260
250
240
230
220
210
200
190
10 Gc
6.5 Gc
4 Gc
2 Gc
1 Gc
100
150
200
250
300
350
DISTANCE IN MILES
8
12.7
17.5
22.2
26.9
31.7
β_o IN MILLIRADIANS

Figure 1



GEOMETRY FOR CALCULATION OF TRANSMISSION LOSS

Figure 2

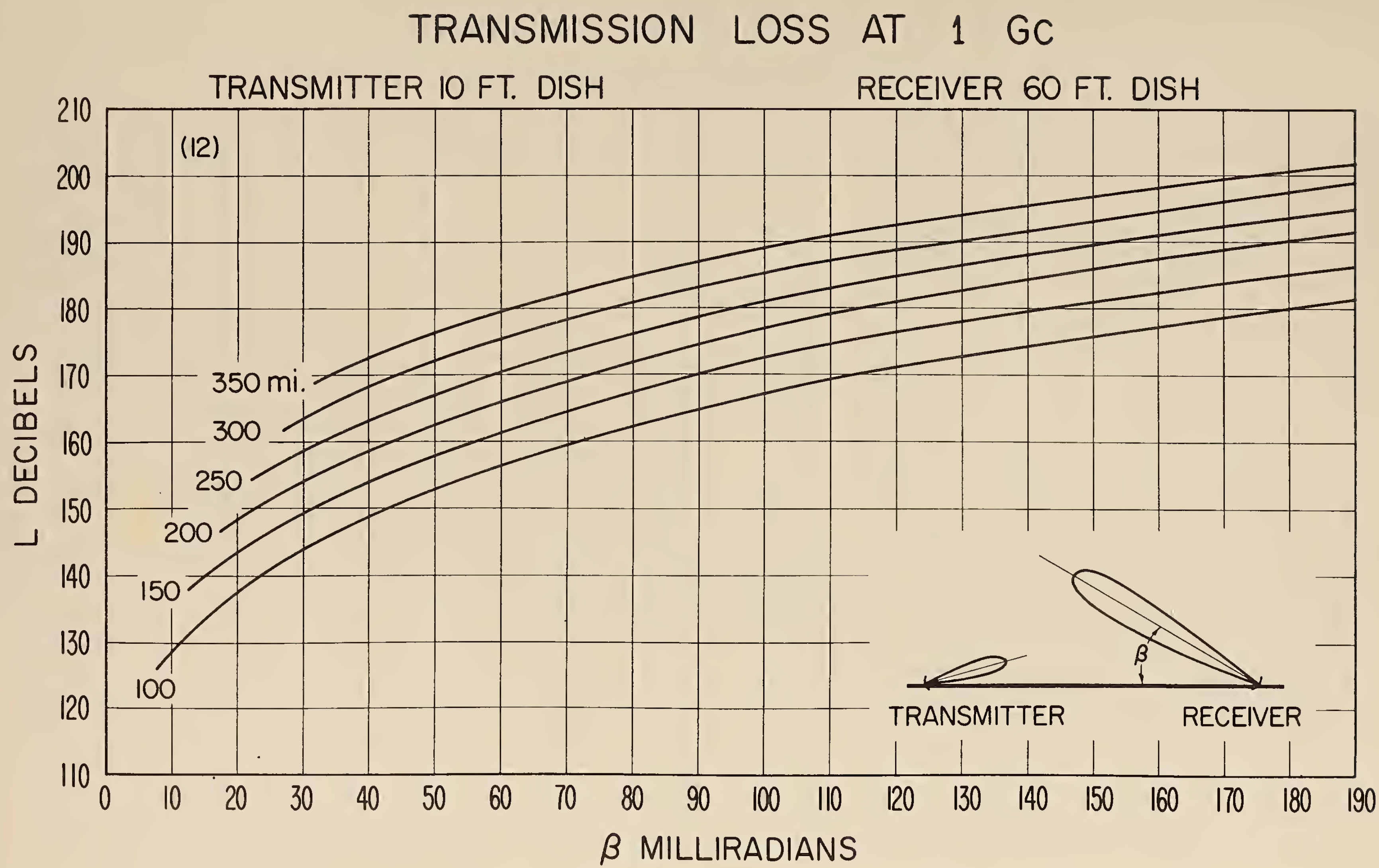

TRANSMISSION LOSS AT 1 Gc
TRANSMITTER 10 FT. DISH
RECEIVER 60 FT. DISH
(12)
350 mi.
300
250
200
150
100
L DECIBELS
210
200
190
180
170
160
150
140
130
120
110
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
β MILLIRADIANS
TRANSMITTER
RECEIVER
β

Figure 3

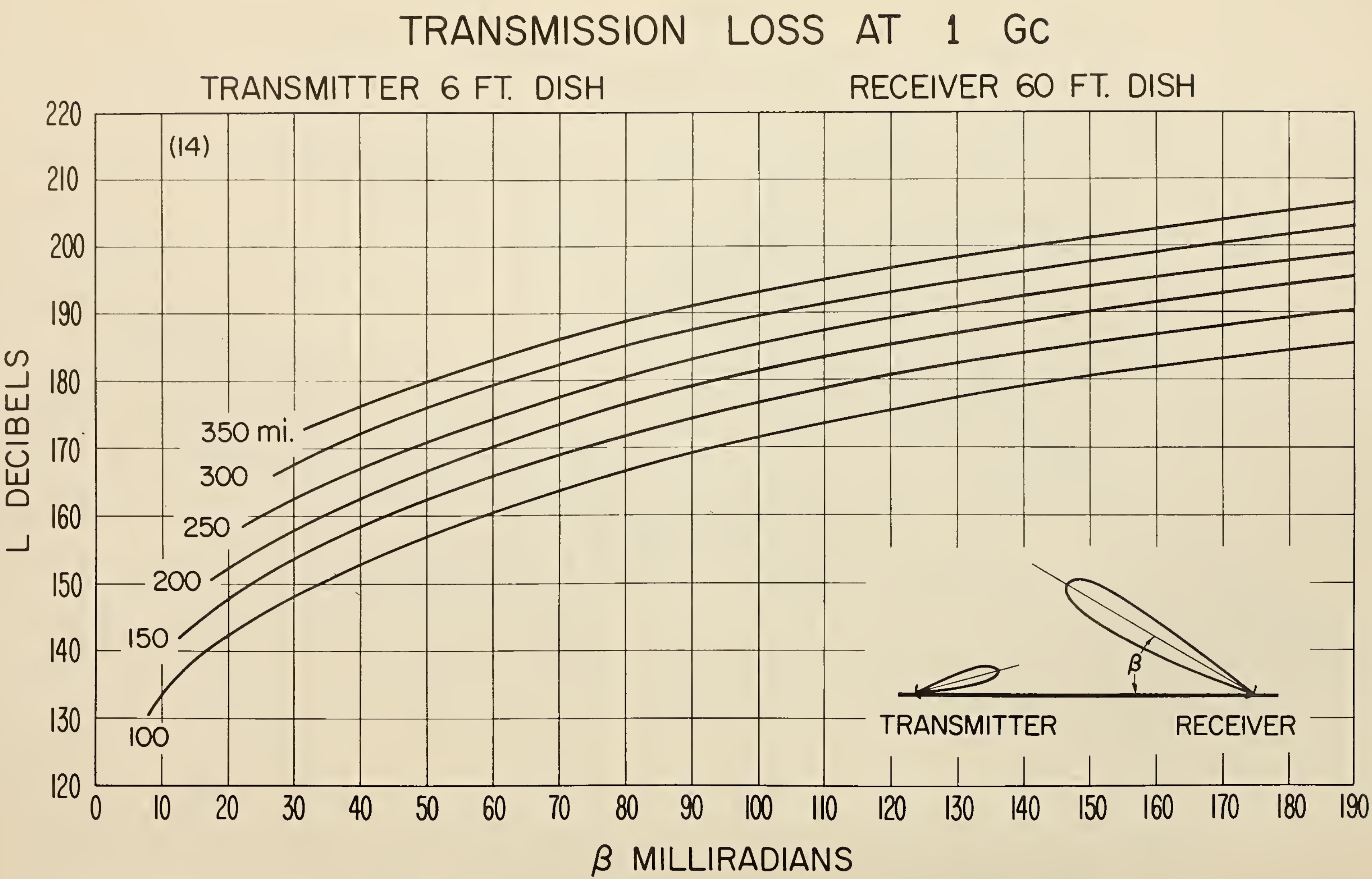

TRANSMISSION LOSS AT 1 Gc
TRANSMITTER 6 FT. DISH
RECEIVER 60 FT. DISH
(14)
L DECIBELS
220
210
200
190
180
170
160
150
140
130
120
350 mi.
300
250
200
150
100
TRANSMITTER
RECEIVER
β
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
β MILLIRADIANS

Figure 4

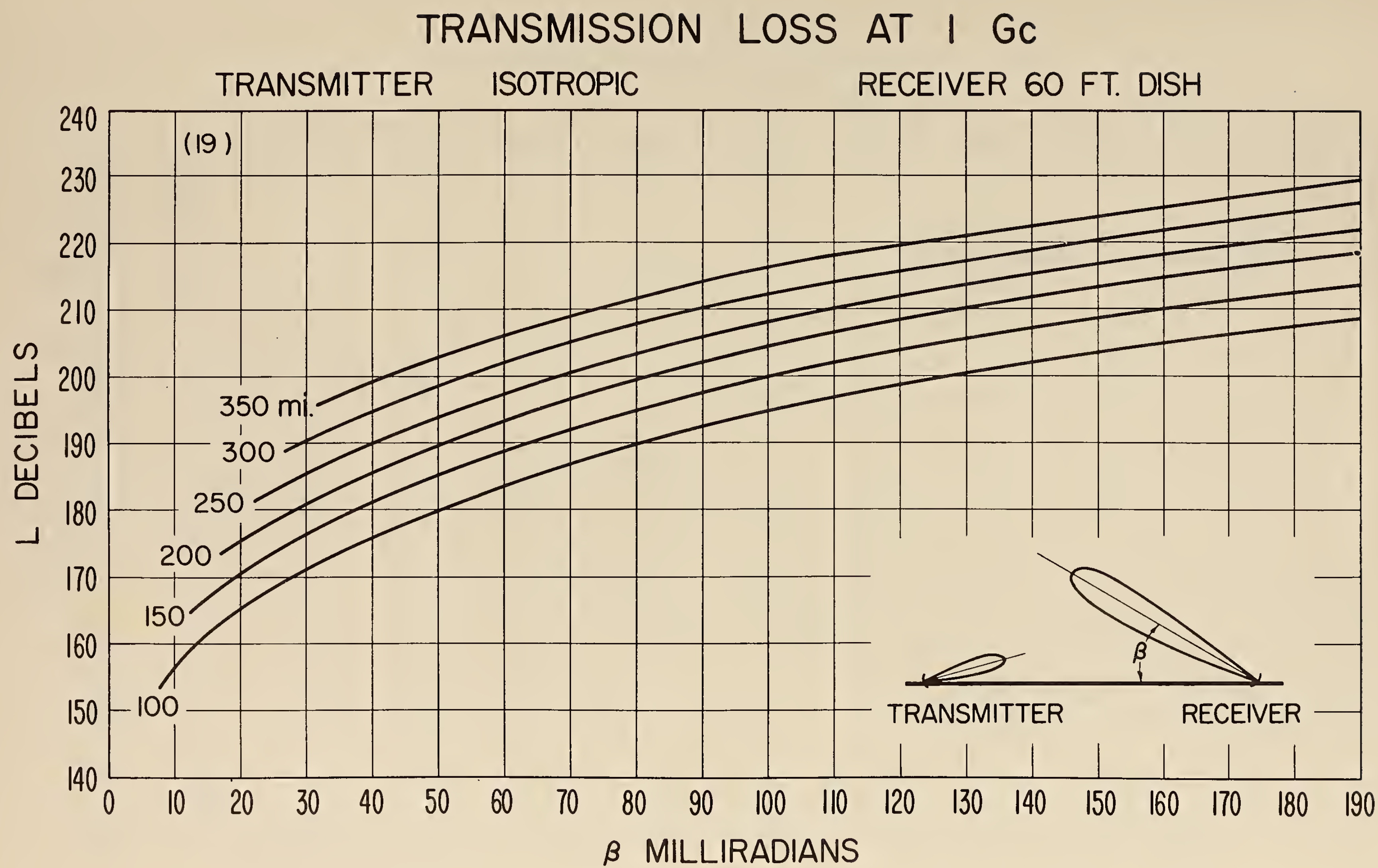

TRANSMISSION LOSS AT 1 Gc
TRANSMITTER ISOTROPIC
RECEIVER 60 FT. DISH
(19)
L DECIBELS
240
230
220
210
200
190
180
170
160
150
140
350 mi.
300
250
200
150
100
TRANSMITTER
RECEIVER
β
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
β MILLIRADIANS

Figure 5

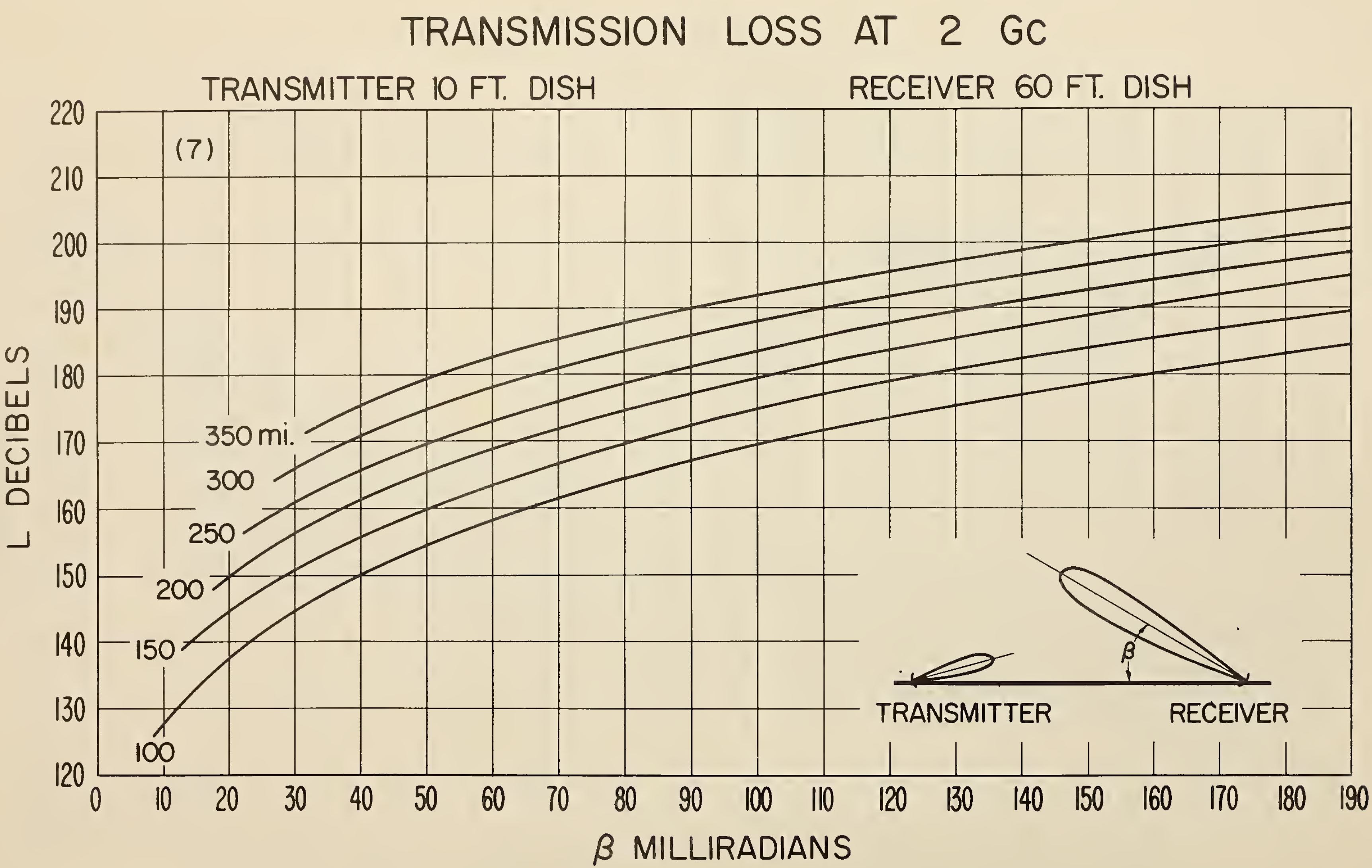

TRANSMISSION LOSS AT 2 Gc
TRANSMITTER 10 FT. DISH
RECEIVER 60 FT. DISH
(7)
L DECIBELS
β MILLIRADIANS
220
210
200
190
180
170
160
150
140
130
120
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
350 mi.
300
250
200
150
100
β
TRANSMITTER
RECEIVER

Figure 6

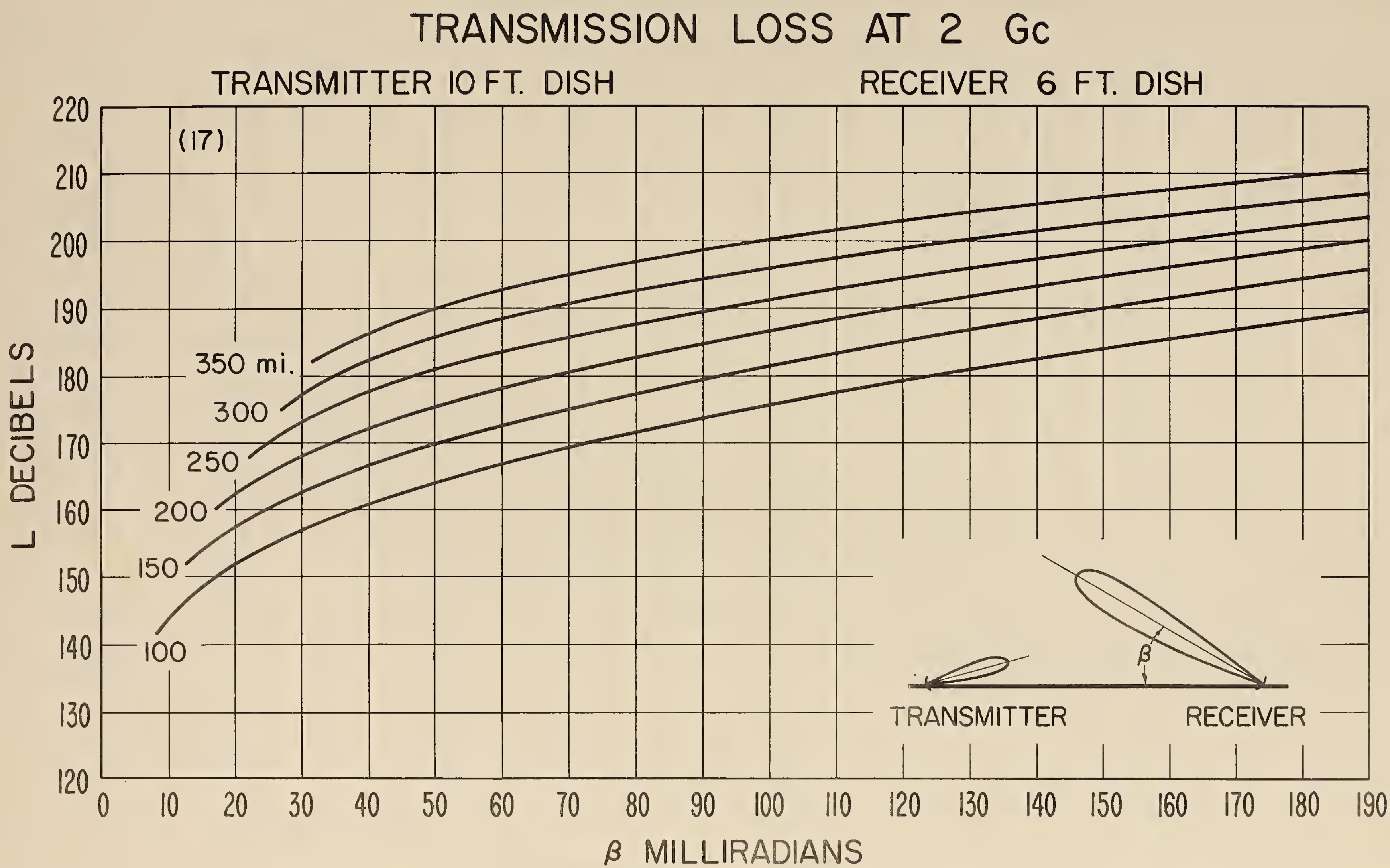
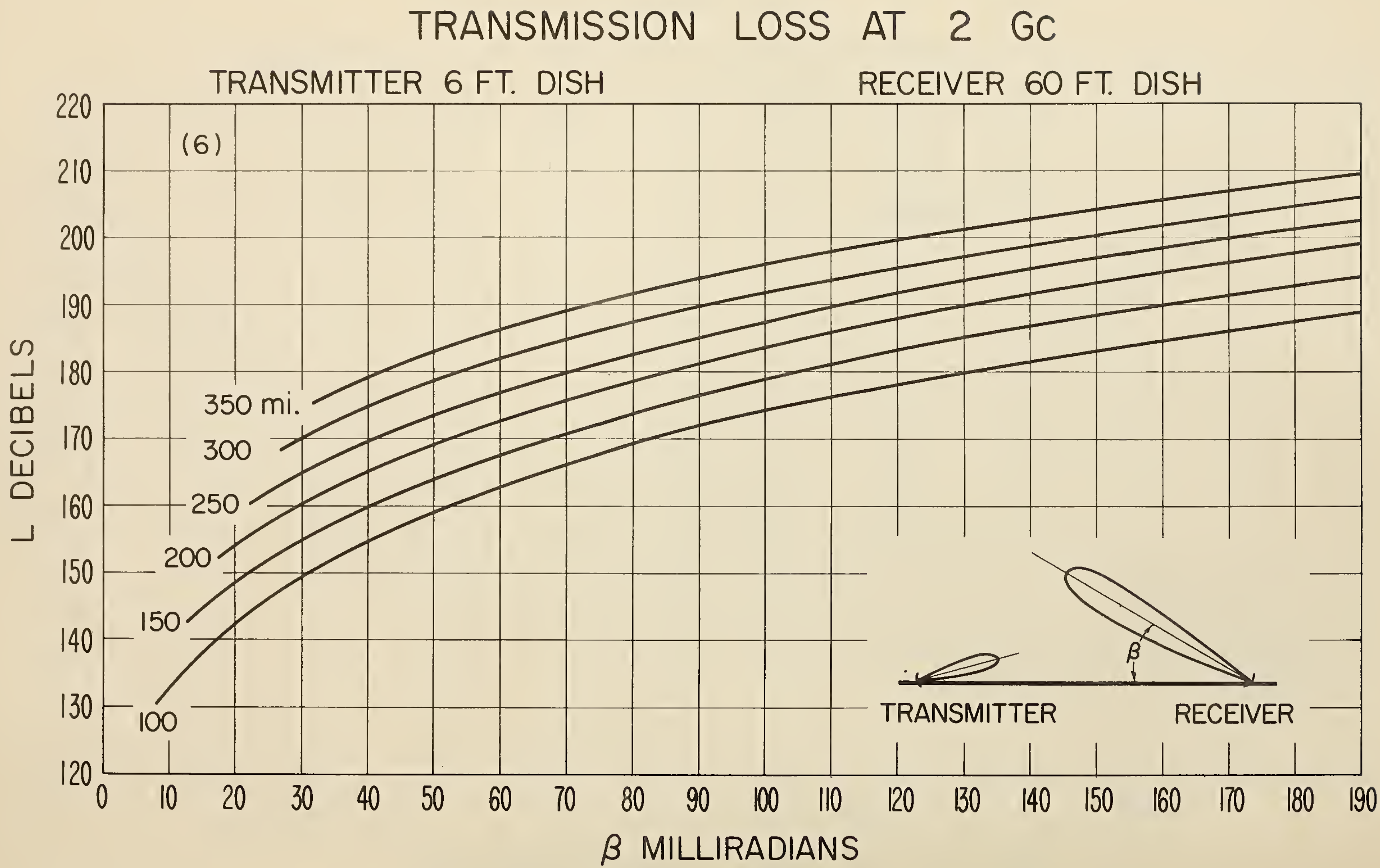

TRANSMISSION LOSS AT 2 Gc
TRANSMITTER 10 FT. DISH
RECEIVER 6 FT. DISH
(17)
350 mi.
300
250
200
150
100
L DECIBELS
220
210
200
190
180
170
160
150
140
130
120
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
β MILLIRADIANS
β
TRANSMITTER
RECEIVER

Figure 7



TRANSMISSION LOSS AT 2 Gc
TRANSMITTER 6 FT. DISH
RECEIVER 60 FT. DISH
(6)
350 mi.
300
250
200
150
100
L DECIBELS
220
210
200
190
180
170
160
150
140
130
120
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
β
TRANSMITTER
RECEIVER
β MILLIRADIANS

Figure 8

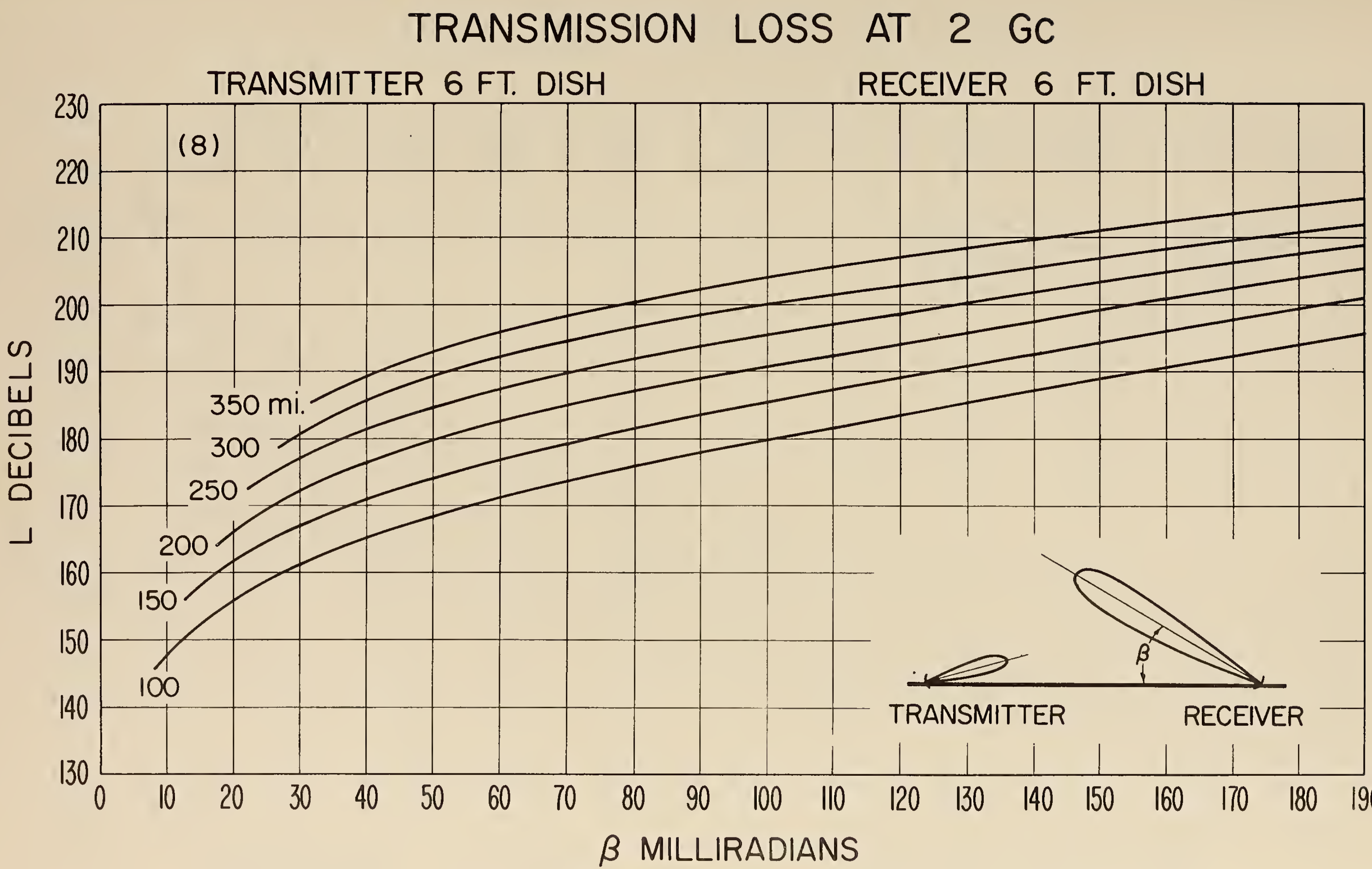

TRANSMISSION LOSS AT 2 Gc
TRANSMITTER 6 FT. DISH
RECEIVER 6 FT. DISH
(8)
350 mi.
300
250
200
150
100
L DECIBELS
230
220
210
200
190
180
170
160
150
140
130
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
β
TRANSMITTER
RECEIVER
β MILLIRADIANS

Figure 9

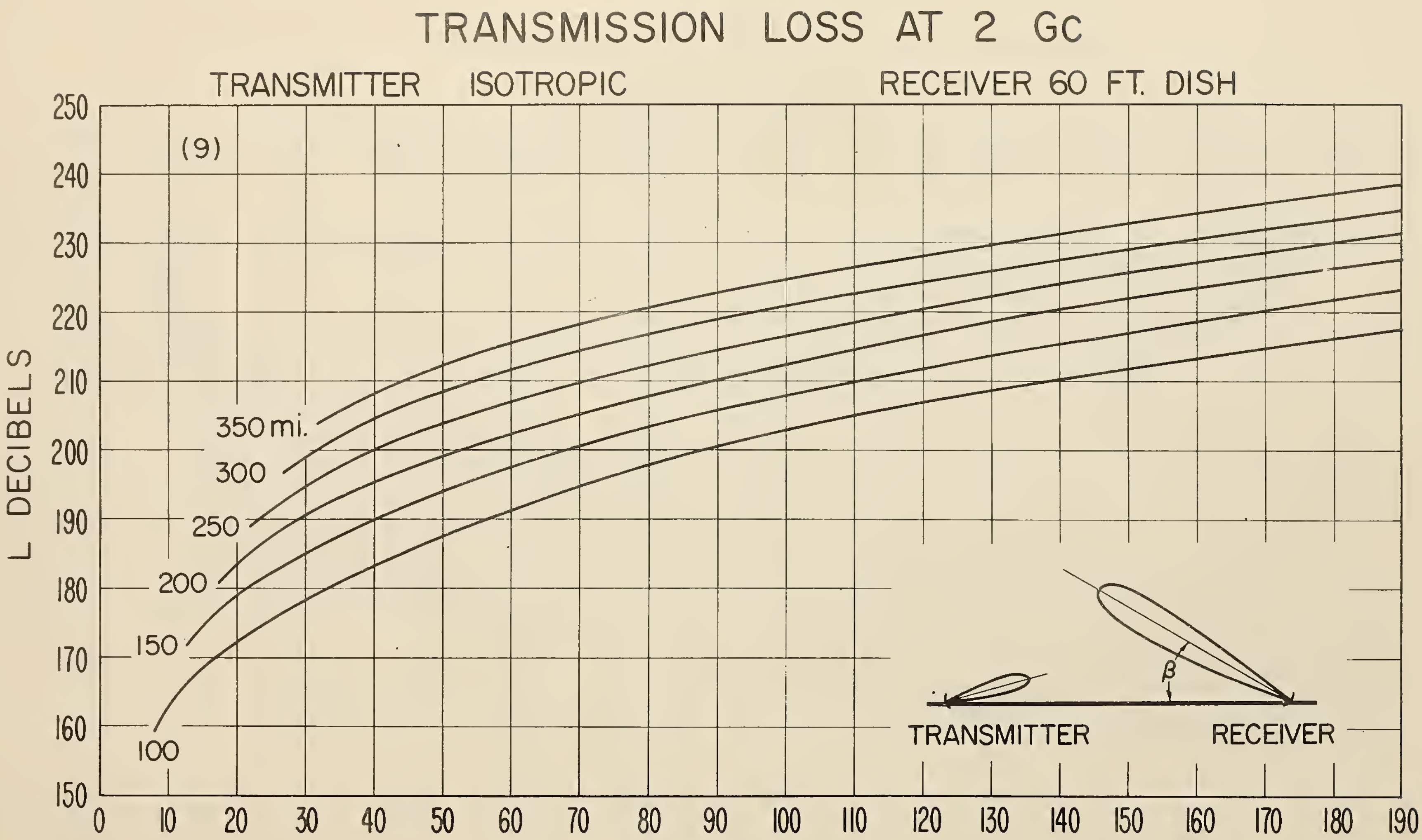

TRANSMISSION LOSS AT 2 Gc
TRANSMITTER ISOTROPIC
RECEIVER 60 FT. DISH
(9)
L DECIBELS
250
240
230
220
210
200
190
180
170
160
150
350 mi.
300
250
200
150
100
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
β MILLIRADIANS
β
TRANSMITTER
RECEIVER

Figure 10

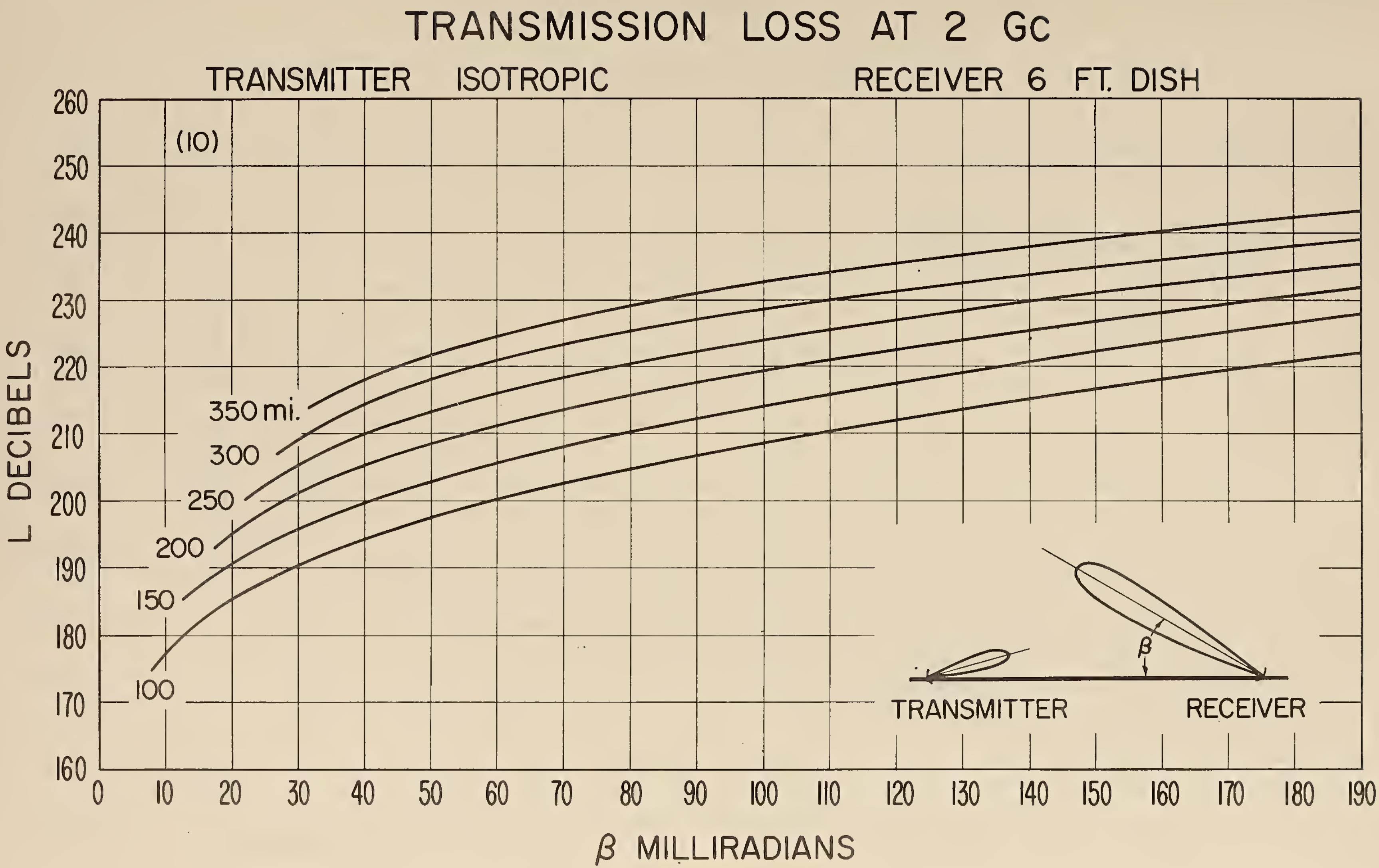
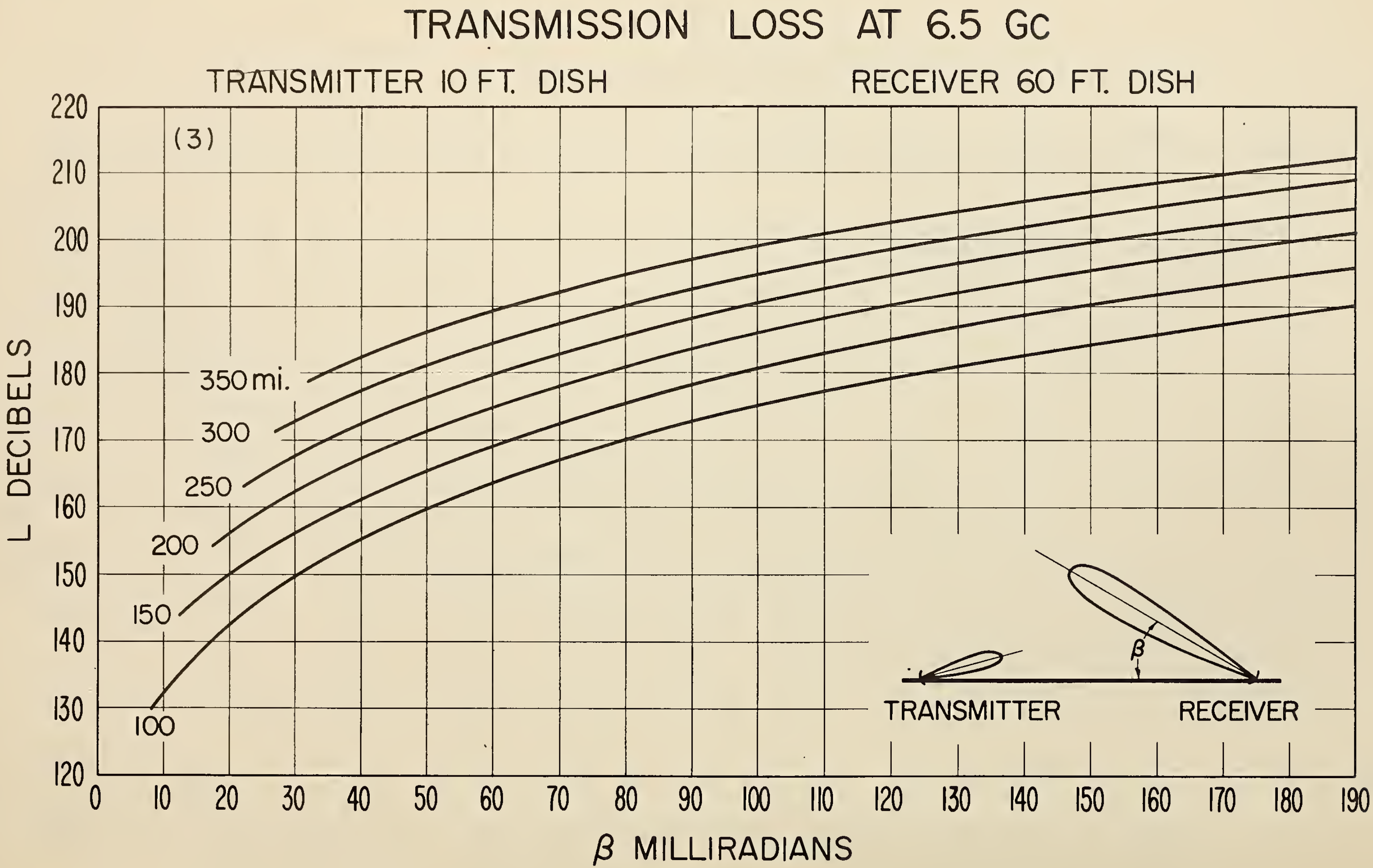

TRANSMISSION LOSS AT 2 Gc
TRANSMITTER ISOTROPIC
RECEIVER 6 FT. DISH
(10)
L DECIBELS
260
250
240
230
220
210
200
190
180
170
160
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
350 mi.
300
250
200
150
100
β
TRANSMITTER
RECEIVER
β MILLIRADIANS

Figure 11



TRANSMISSION LOSS AT 6.5 Gc
TRANSMITTER 10 FT. DISH
RECEIVER 60 FT. DISH
(3)
L DECIBELS
220
210
200
190
180
170
160
150
140
130
120
350 mi.
300
250
200
150
100
β
TRANSMITTER
RECEIVER
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
β MILLIRADIANS

Figure 12

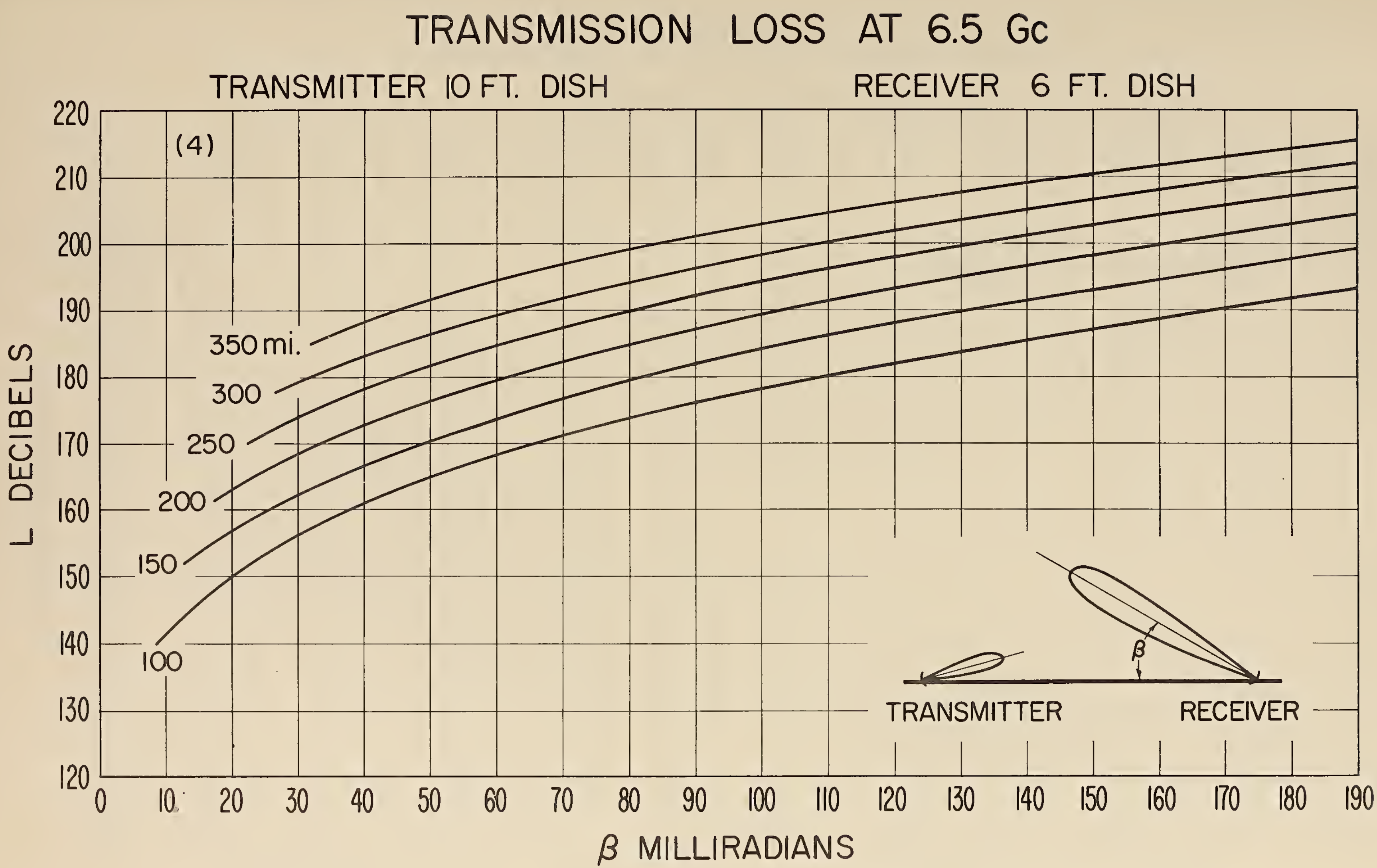
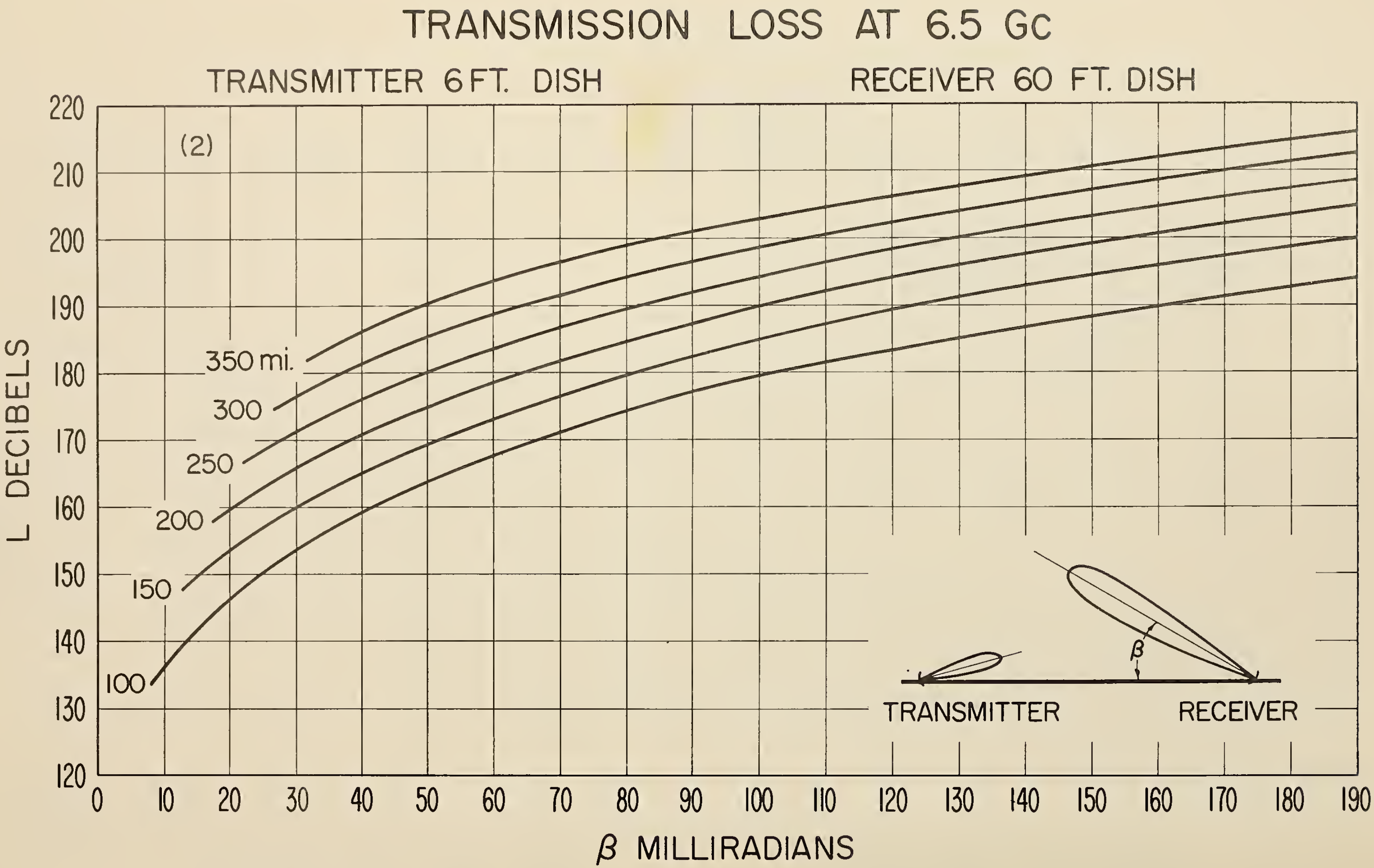

TRANSMISSION LOSS AT 6.5 Gc
TRANSMITTER 10 FT. DISH
RECEIVER 6 FT. DISH
(4)
350 mi.
300
250
200
150
100
L DECIBELS
220
210
200
190
180
170
160
150
140
130
120
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
β MILLIRADIANS
β
TRANSMITTER
RECEIVER

Figure 13



TRANSMISSION LOSS AT 6.5 Gc
TRANSMITTER 6 FT. DISH
RECEIVER 60 FT. DISH
(2)
350 mi.
300
250
200
150
100
L DECIBELS
220
210
200
190
180
170
160
150
140
130
120
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
β MILLIRADIANS
β
TRANSMITTER
RECEIVER

Figure 14

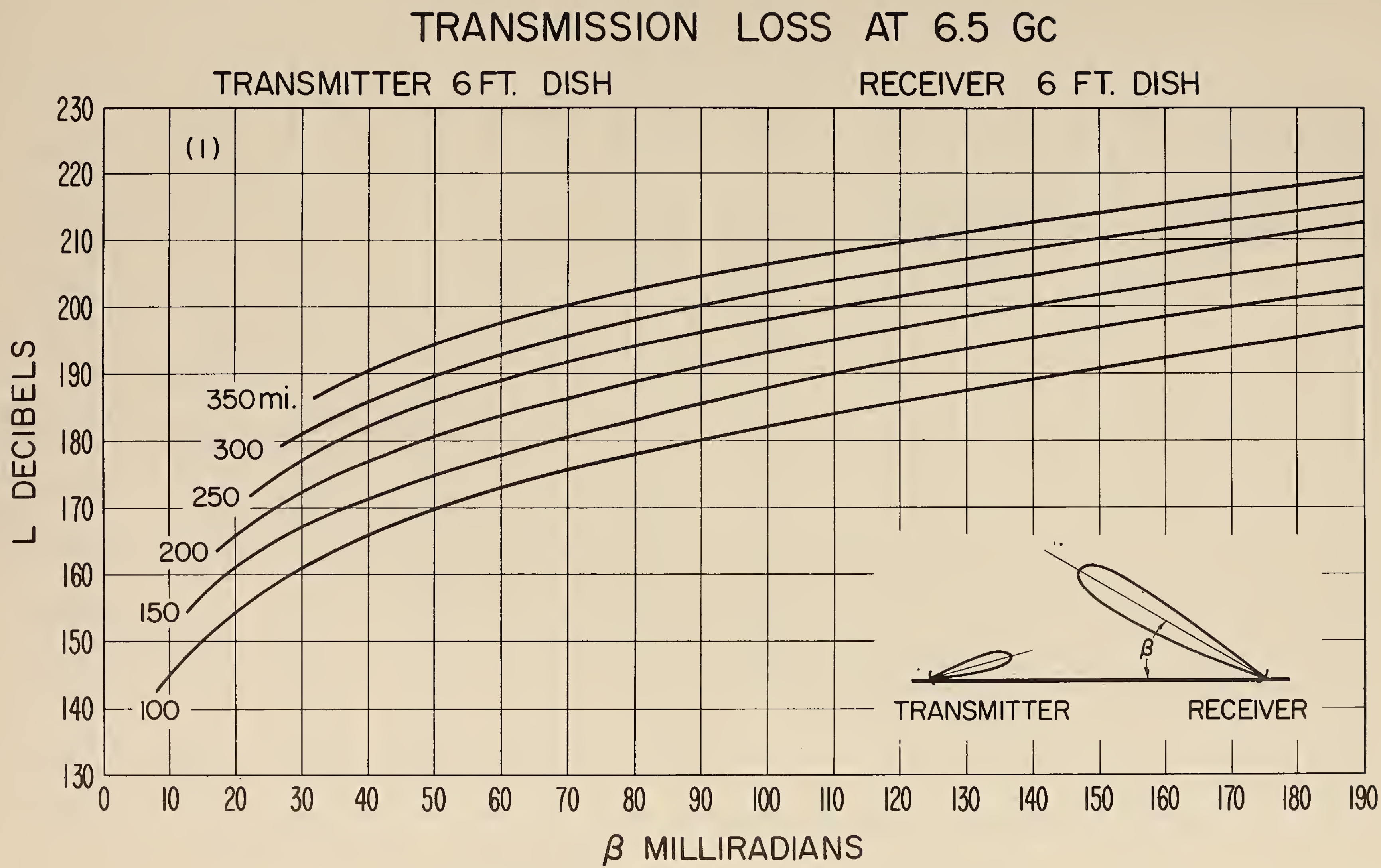

TRANSMISSION LOSS AT 6.5 Gc
TRANSMITTER 6 FT. DISH
RECEIVER 6 FT. DISH
(1)
L DECIBELS
230
220
210
200
190
180
170
160
150
140
130
350 mi.
300
250
200
150
100
TRANSMITTER
RECEIVER
β
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
β MILLIRADIANS

Figure 15

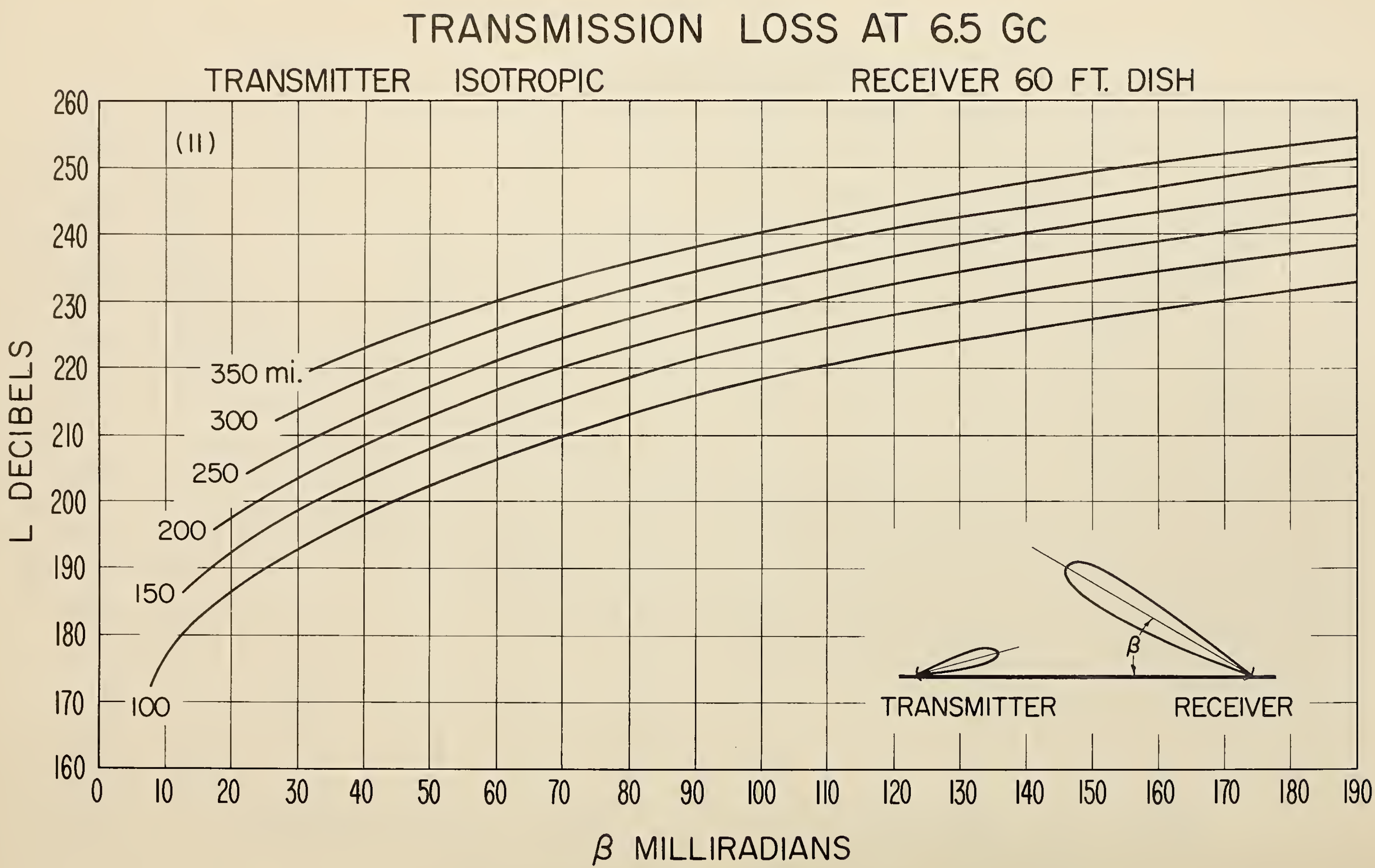

TRANSMISSION LOSS AT 6.5 Gc
TRANSMITTER ISOTROPIC
RECEIVER 60 FT. DISH
(11)
L DECIBELS
260
250
240
230
220
210
200
190
180
170
160
350 mi.
300
250
200
150
100
β
TRANSMITTER
RECEIVER
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
β MILLIRADIANS

Figure 16

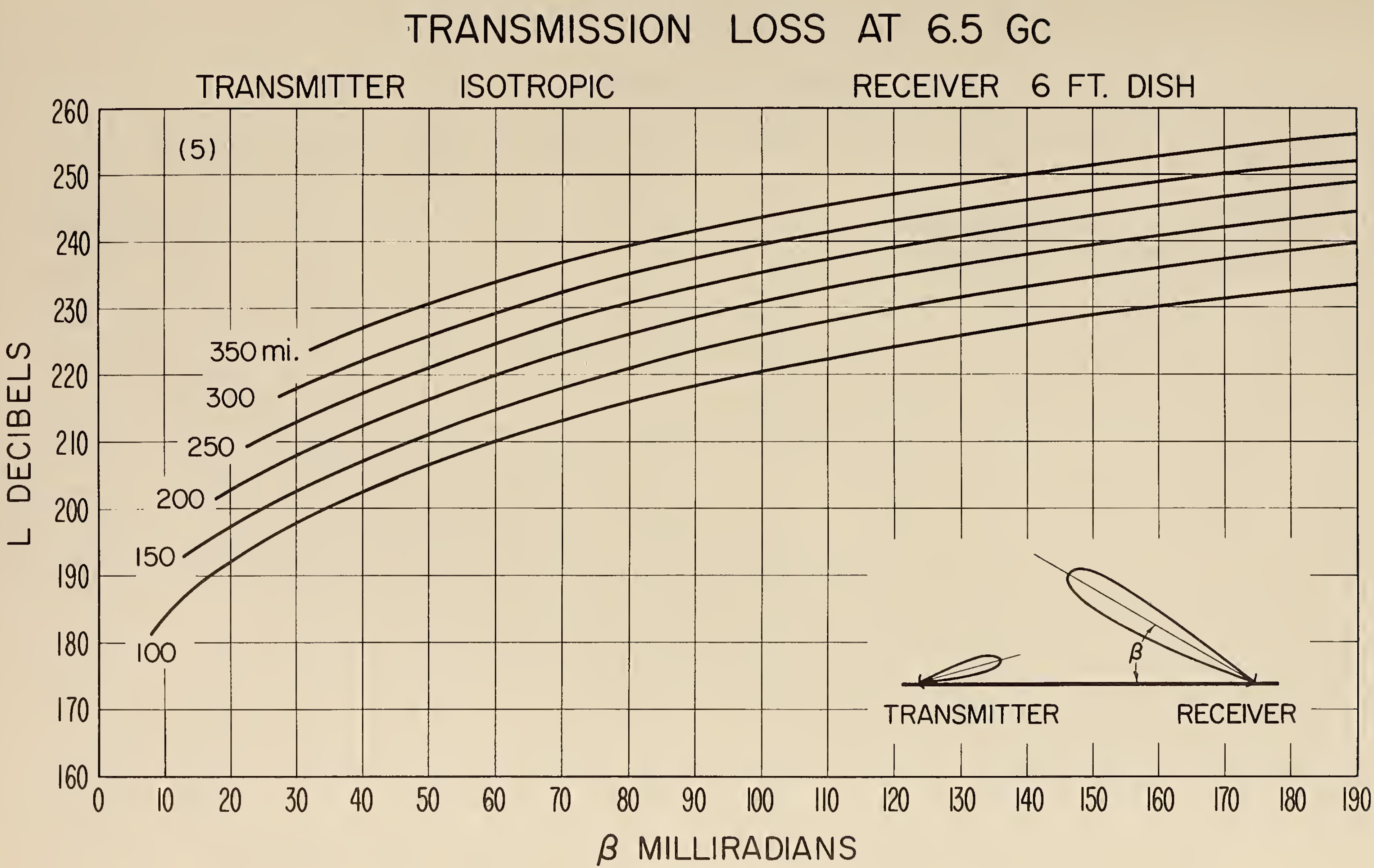
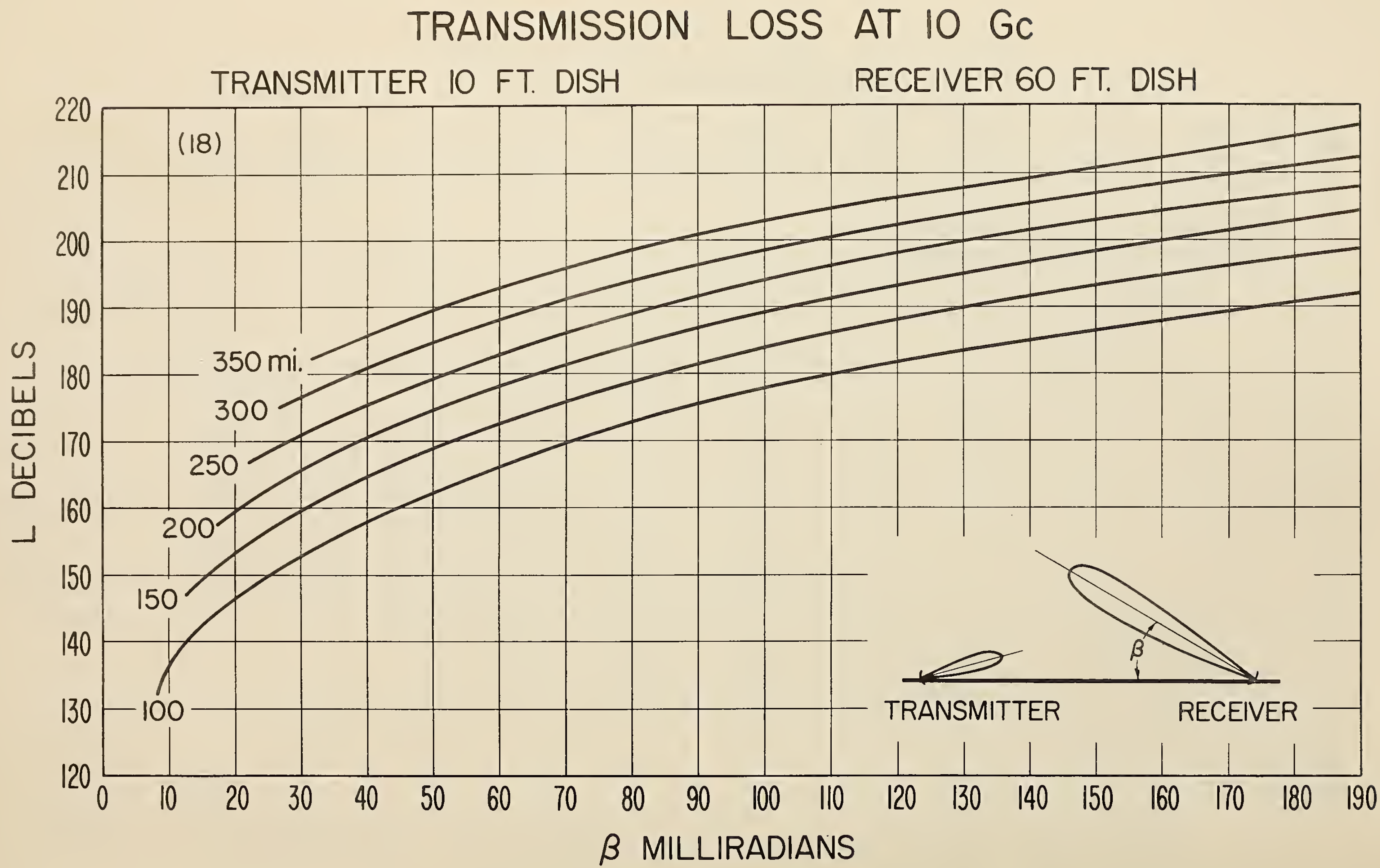

TRANSMISSION LOSS AT 6.5 Gc
TRANSMITTER ISOTROPIC
RECEIVER 6 FT. DISH
(5)
350 mi.
300
250
200
150
100
L DECIBELS
260
250
240
230
220
210
200
190
180
170
160
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
β MILLIRADIANS
β
TRANSMITTER
RECEIVER

Figure 17



TRANSMISSION LOSS AT 10 Gc
TRANSMITTER 10 FT. DISH
RECEIVER 60 FT. DISH
(18)
350 mi.
300
250
200
150
100
L DECIBELS
β MILLIRADIANS
TRANSMITTER
RECEIVER
β

Figure 18

TRANSMISSION LOSS AT 10 Gc

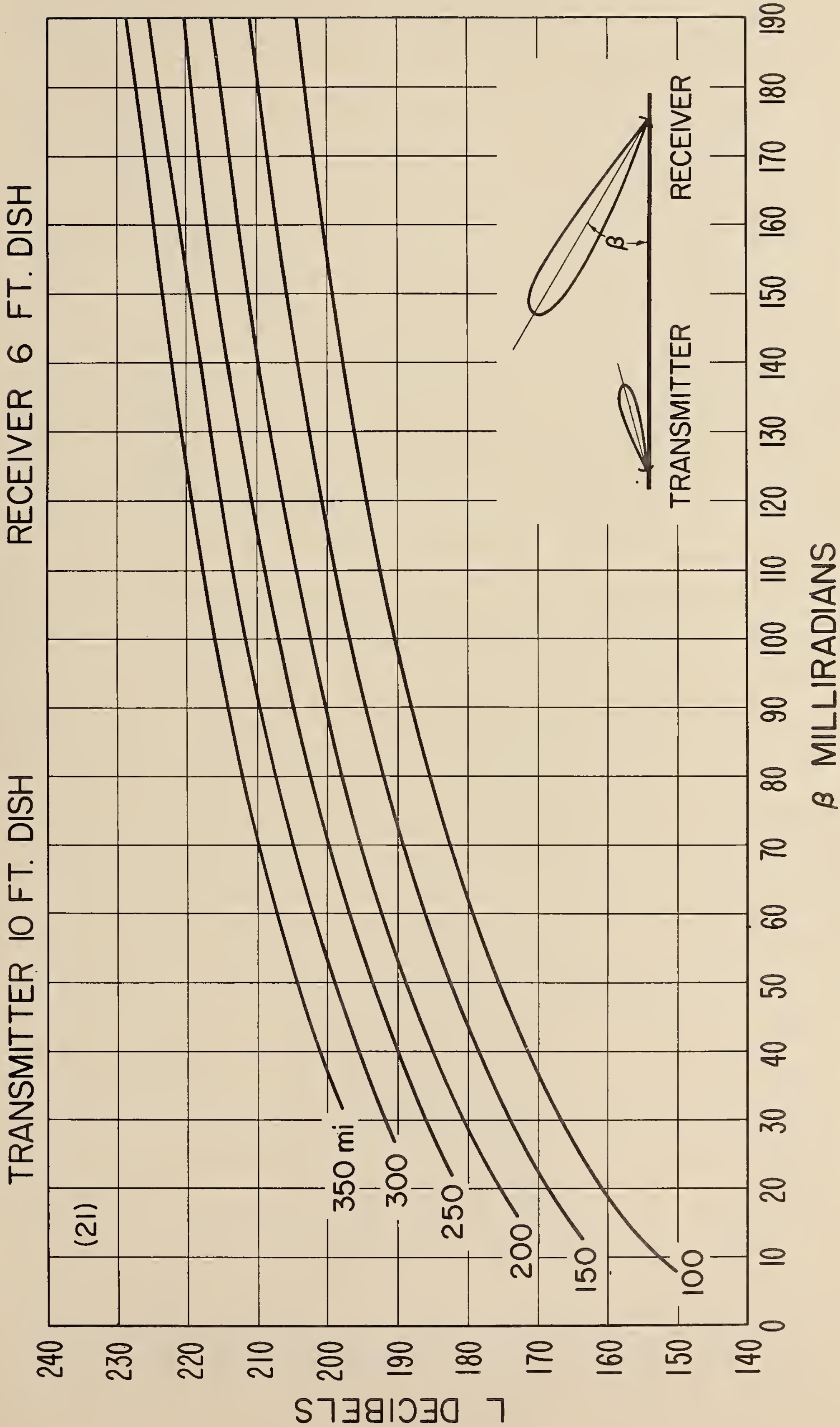


Figure 19

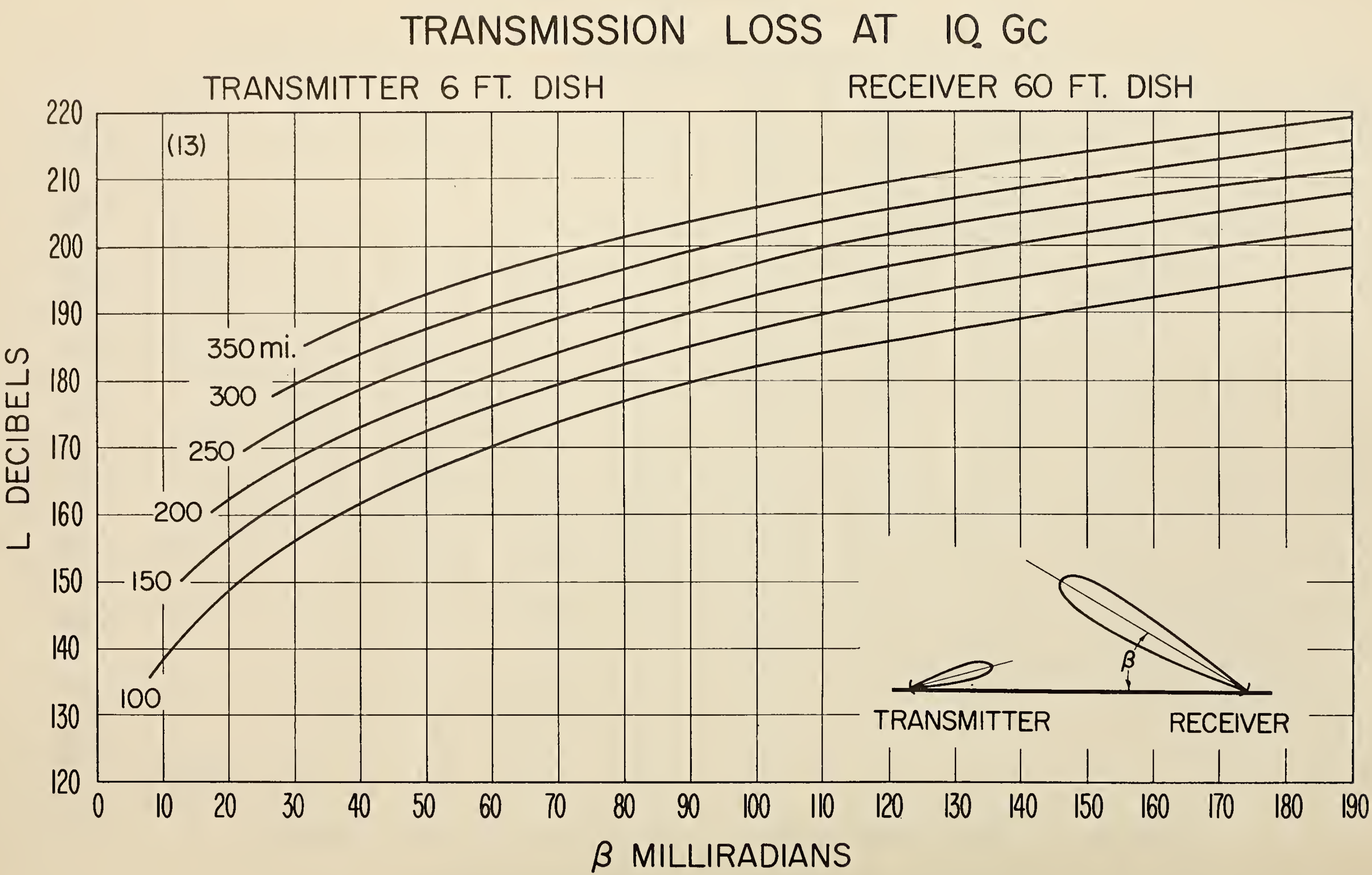
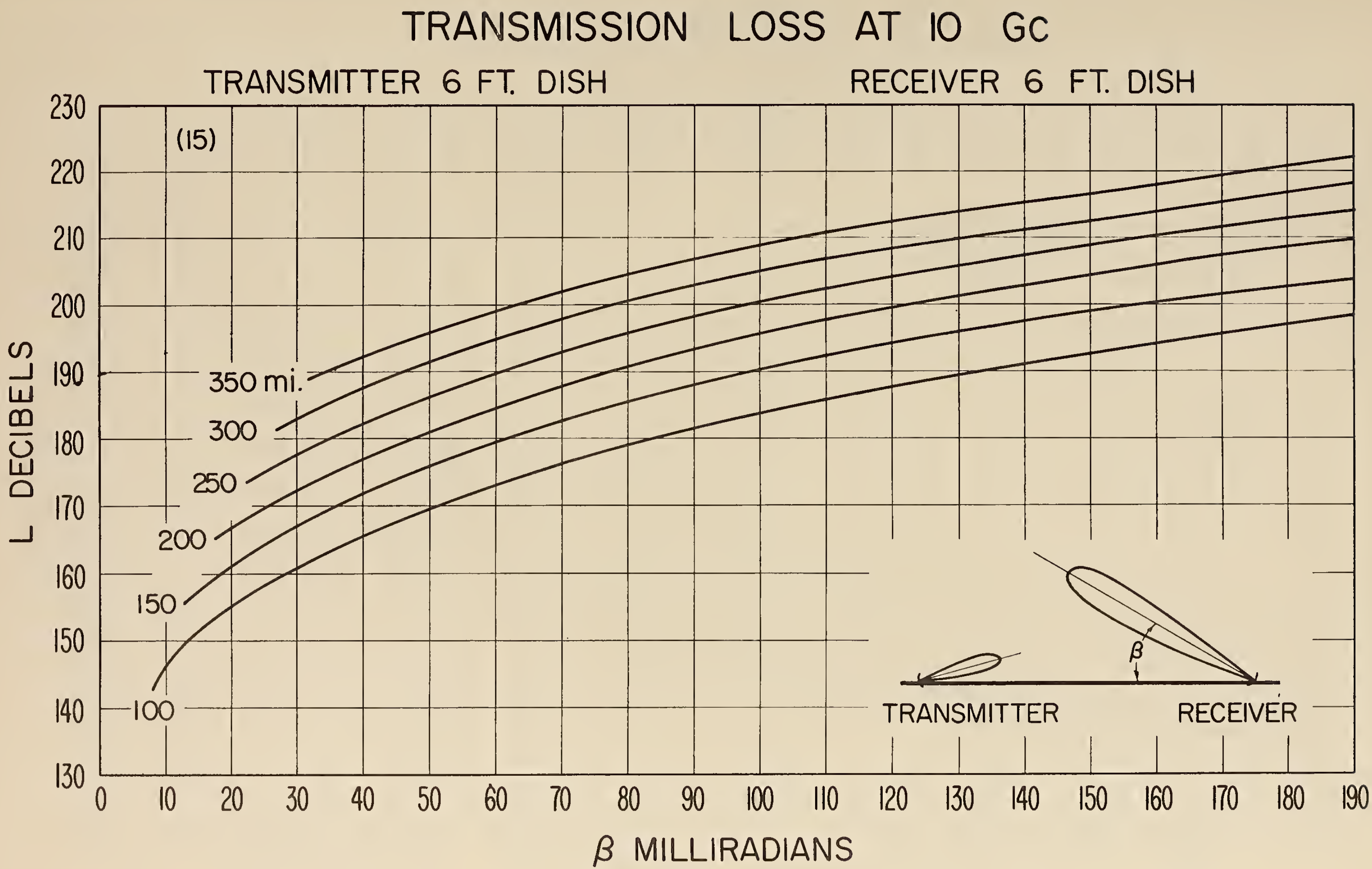

TRANSMISSION LOSS AT 10 Gc
TRANSMITTER 6 FT. DISH
RECEIVER 60 FT. DISH
(13)
L DECIBELS
220
210
200
190
180
170
160
150
140
130
120
350 mi.
300
250
200
150
100
β
TRANSMITTER
RECEIVER
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
β MILLIRADIANS

Figure 20



TRANSMISSION LOSS AT 10 Gc
TRANSMITTER 6 FT. DISH
RECEIVER 6 FT. DISH
(15)
350 mi.
300
250
200
150
100
L DECIBELS
230
220
210
200
190
180
170
160
150
140
130
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
β MILLIRADIANS
β
TRANSMITTER
RECEIVER

Figure 21

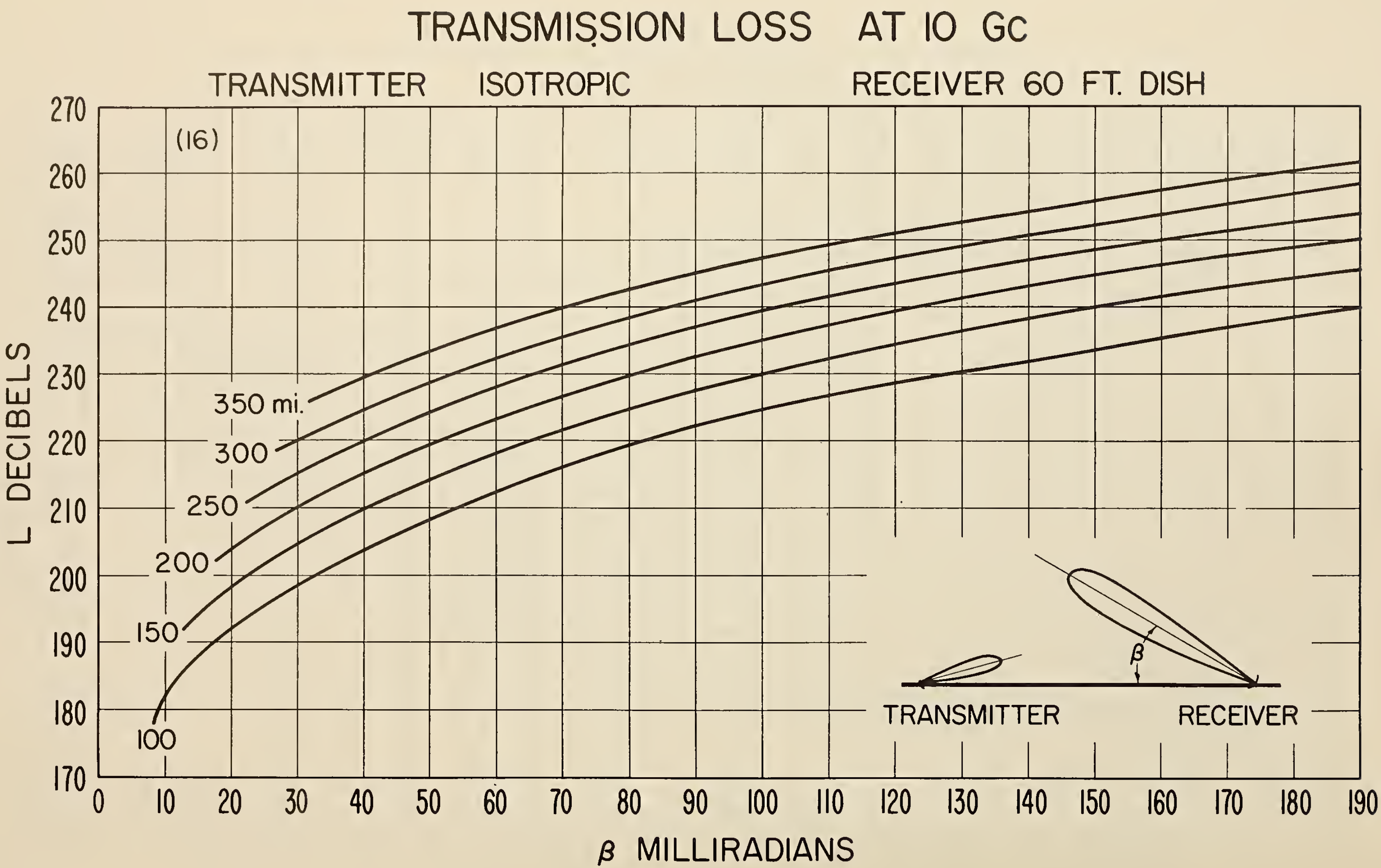

TRANSMISSION LOSS AT 10 Gc
TRANSMITTER ISOTROPIC
RECEIVER 60 FT. DISH
(16)
L DECIBELS
270
260
250
240
230
220
210
200
190
180
170
350 mi.
300
250
200
150
100
β
TRANSMITTER
RECEIVER
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
β MILLIRADIANS

Figure 22

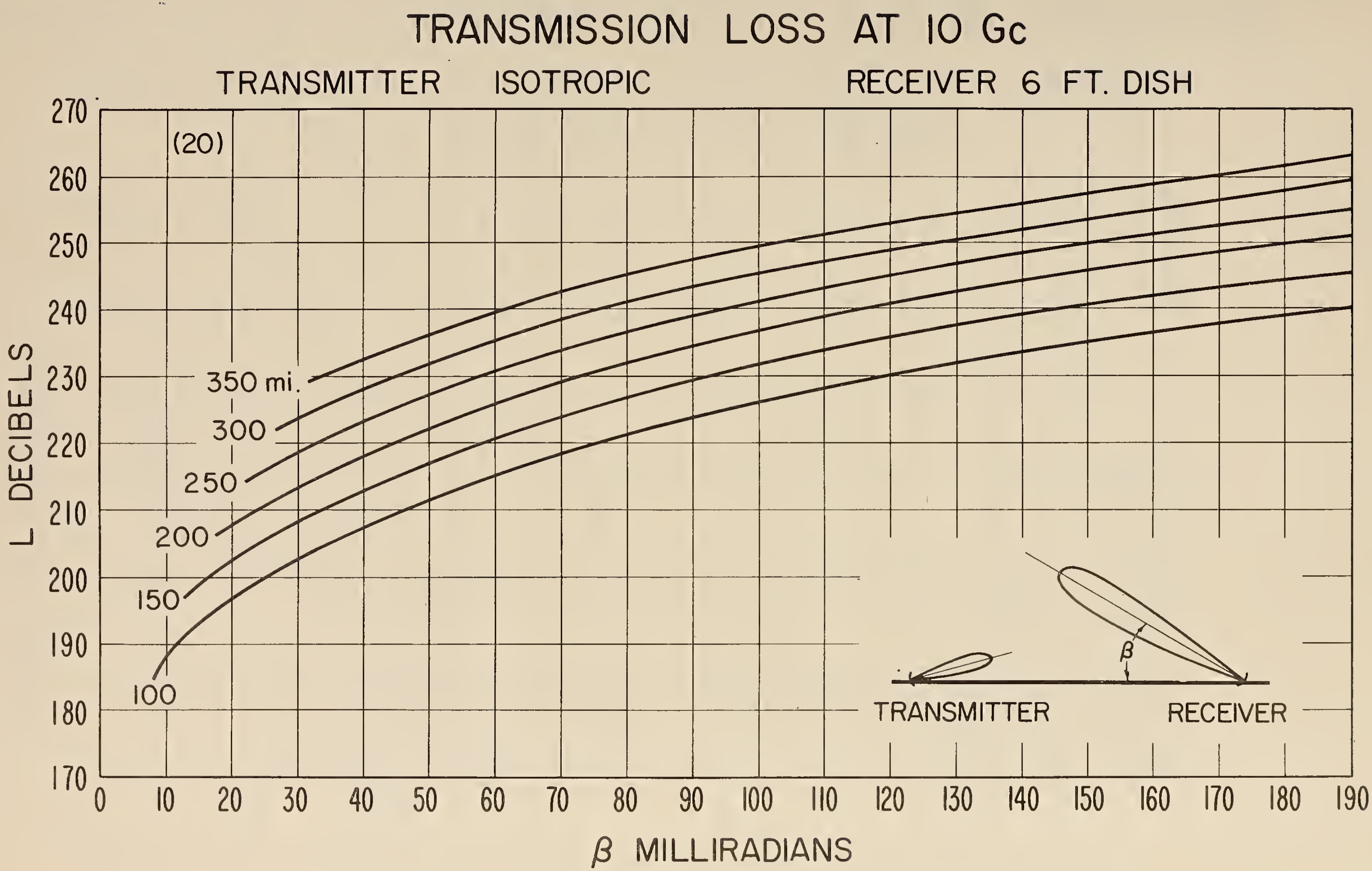

TRANSMISSION LOSS AT 10 Gc
TRANSMITTER ISOTROPIC
RECEIVER 6 FT. DISH
(20)
350 mi.
300
250
200
150
100
L DECIBELS
β MILLIRADIANS
TRANSMITTER
RECEIVER
β

Figure 23

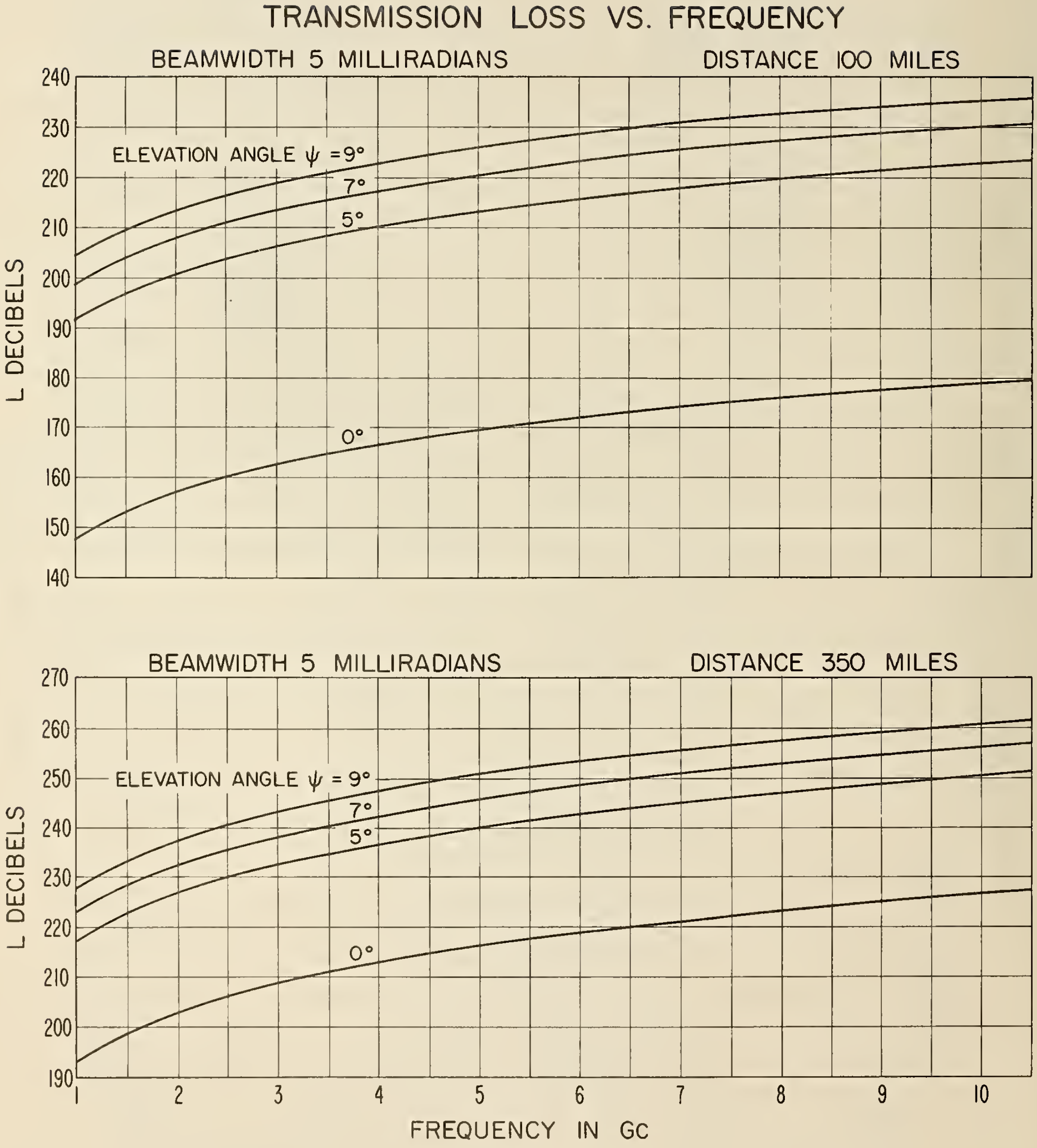
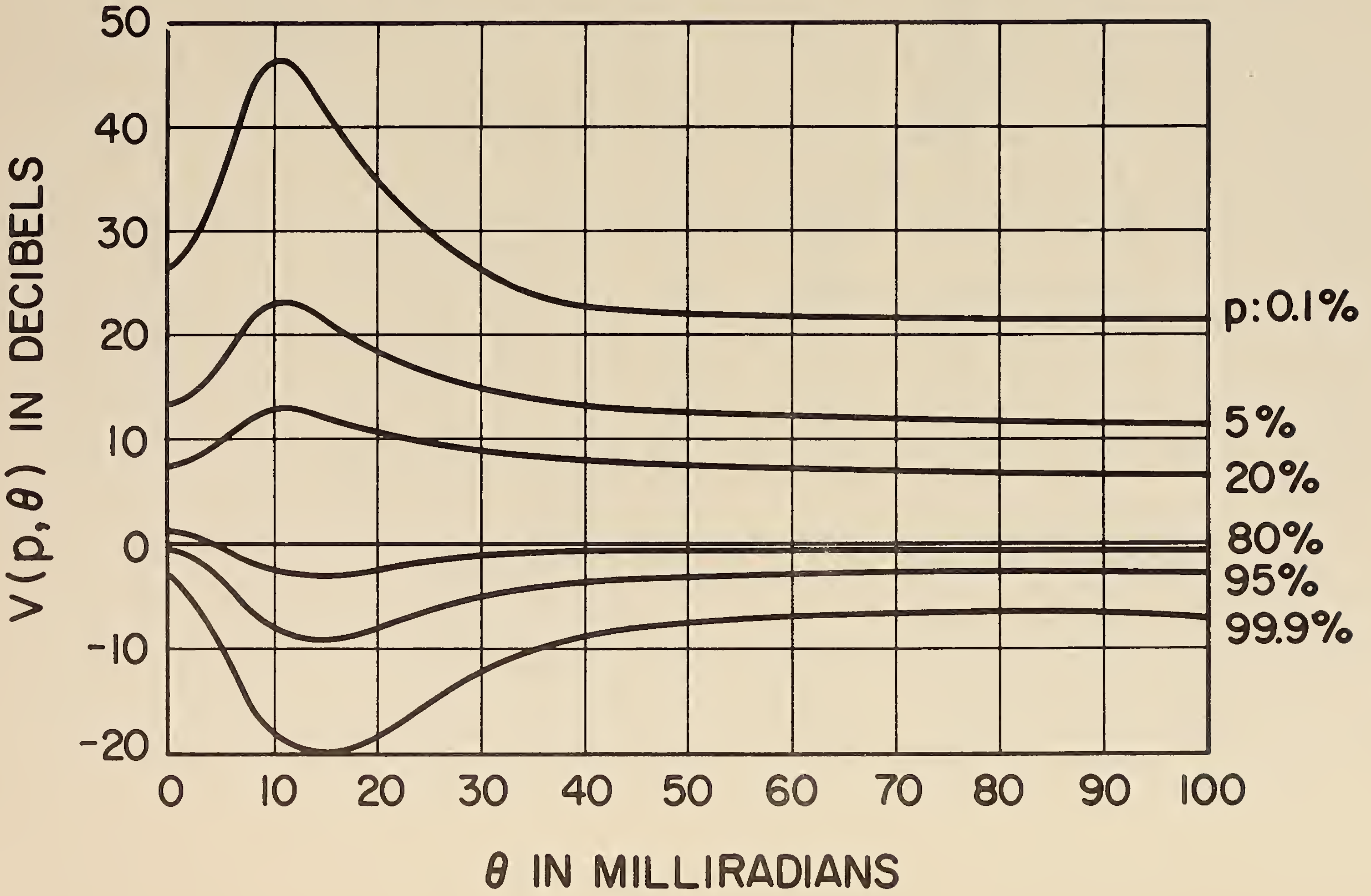

TRANSMISSION LOSS VS. FREQUENCY
BEAMWIDTH 5 MILLIRADIANS
DISTANCE 100 MILES
ELEVATION ANGLE ψ =9°
7°
5°
0°
L DECIBELS
240
230
220
210
200
190
180
170
160
150
140
BEAMWIDTH 5 MILLIRADIANS
DISTANCE 350 MILES
ELEVATION ANGLE ψ = 9°
7°
5°
0°
L DECIBELS
270
260
250
240
230
220
210
200
190
1
2
3
4
5
6
7
8
9
10
FREQUENCY IN Gc

Figure 24

EXPECTED SIGNAL LEVEL, $V(p,\theta)$ EXCEEDED BY p PERCENT OF ALL HOURLY MEDIANS OBSERVED AT ANGULAR DISTANCE θ DURING ALL HOURS OF THE YEAR



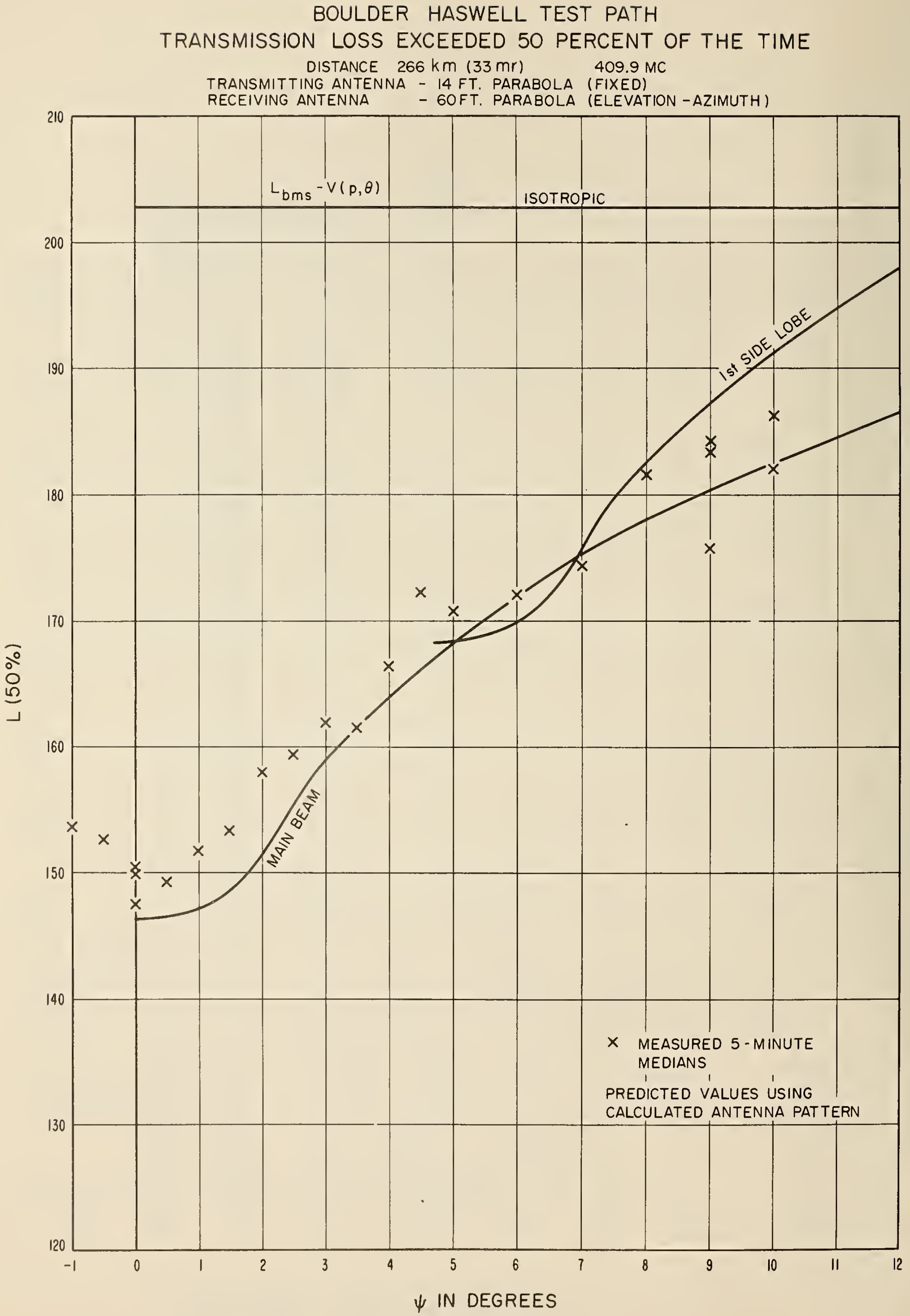

BOULDER HASWELL TEST PATH
TRANSMISSION LOSS EXCEEDED 50 PERCENT OF THE TIME
DISTANCE 266 km (33 mr) 409.9 MC
TRANSMITTING ANTENNA - 14 FT. PARABOLA (FIXED)
RECEIVING ANTENNA - 60 FT. PARABOLA (ELEVATION - AZIMUTH)
L(50%)
ψ IN DEGREES
$L_{bms} - V(p, \theta)$
ISOTROPIC
1st SIDE LOBE
MAIN BEAM
× MEASURED 5-MINUTE MEDIANS
PREDICTED VALUES USING CALCULATED ANTENNA PATTERN
210
200
190
180
170
160
150
140
130
120
-1
0
1
2
3
4
5
6
7
8
9
10
11
12

Figure 26

TRANSMISSION LOSS EXCEEDED 99.9 % OF THE TIME
FREQUENCY 1 Gc

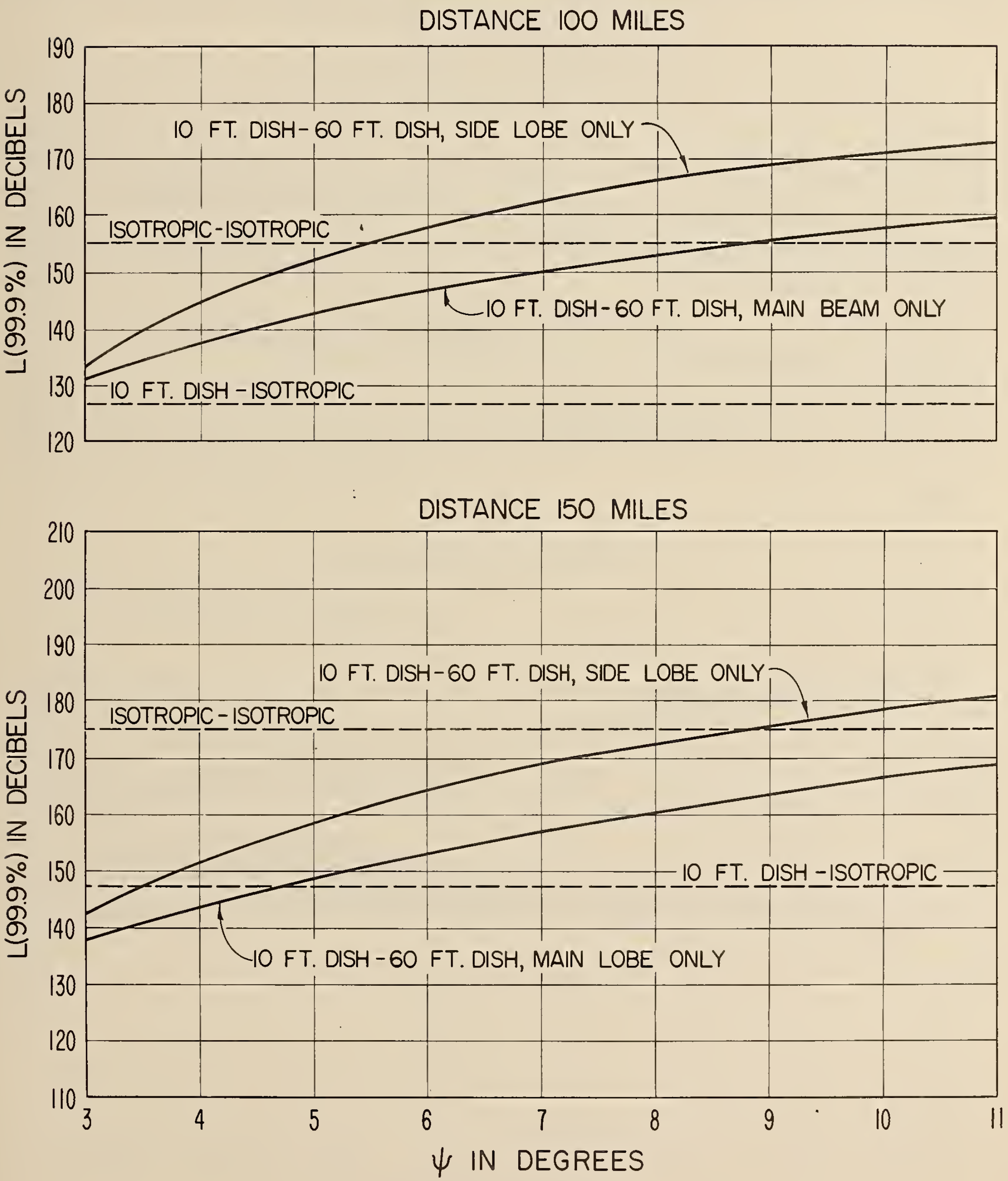


Figure 27

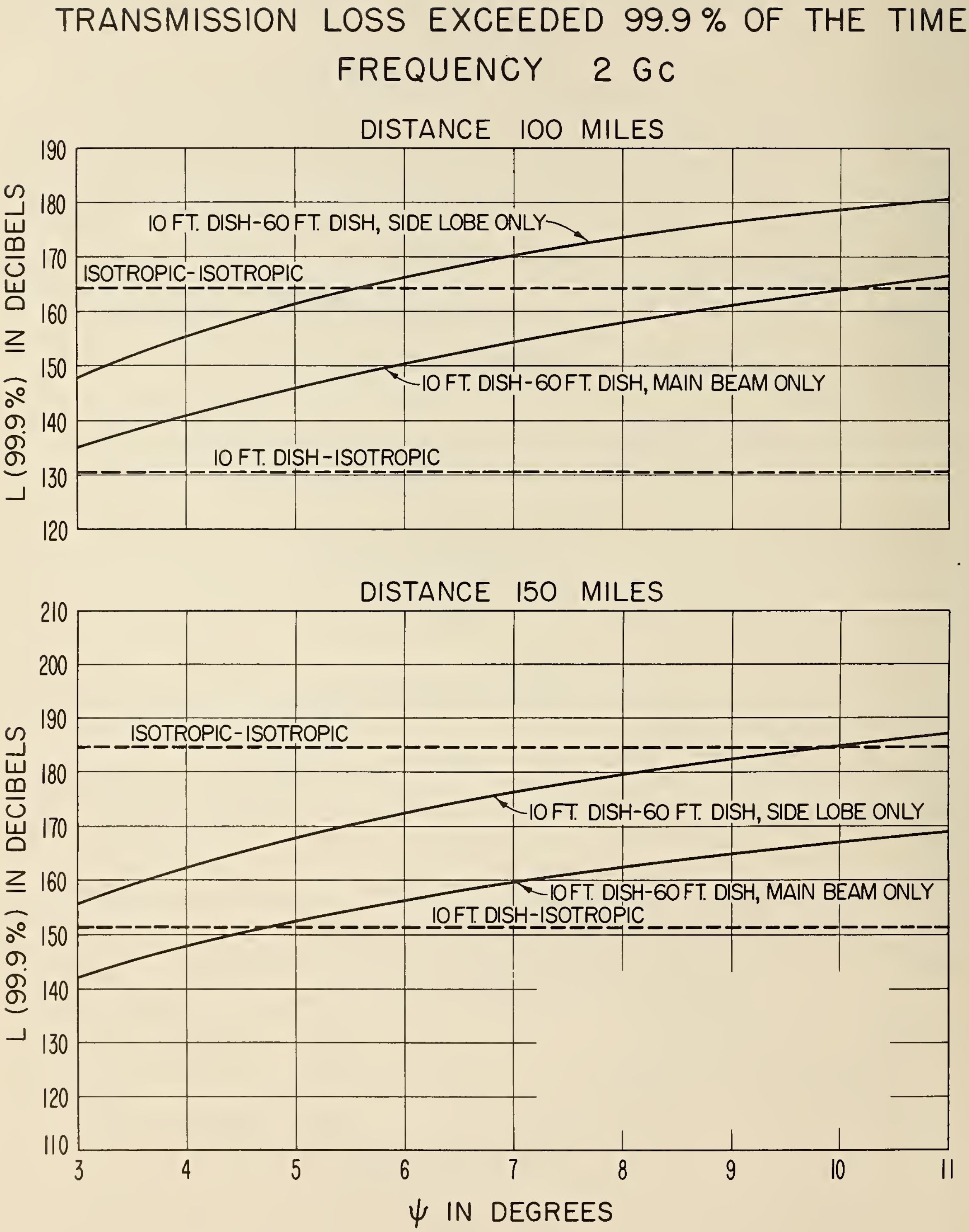

TRANSMISSION LOSS EXCEEDED 99.9 % OF THE TIME
FREQUENCY 2 Gc
DISTANCE 100 MILES
10 FT. DISH-60 FT. DISH, SIDE LOBE ONLY
ISOTROPIC-ISOTROPIC
10 FT. DISH-60 FT. DISH, MAIN BEAM ONLY
10 FT. DISH-ISOTROPIC
L (99.9%) IN DECIBELS
190
180
170
160
150
140
130
120
DISTANCE 150 MILES
ISOTROPIC-ISOTROPIC
10 FT. DISH-60 FT. DISH, SIDE LOBE ONLY
10 FT. DISH-60 FT. DISH, MAIN BEAM ONLY
10 FT. DISH-ISOTROPIC
L (99.9%) IN DECIBELS
210
200
190
180
170
160
150
140
130
120
110
3
4
5
6
7
8
9
10
11
ψ IN DEGREES

Figure 28

TRANSMISSION LOSS EXCEEDED 99.9 % OF THE TIME
FREQUENCY 6.5 Gc

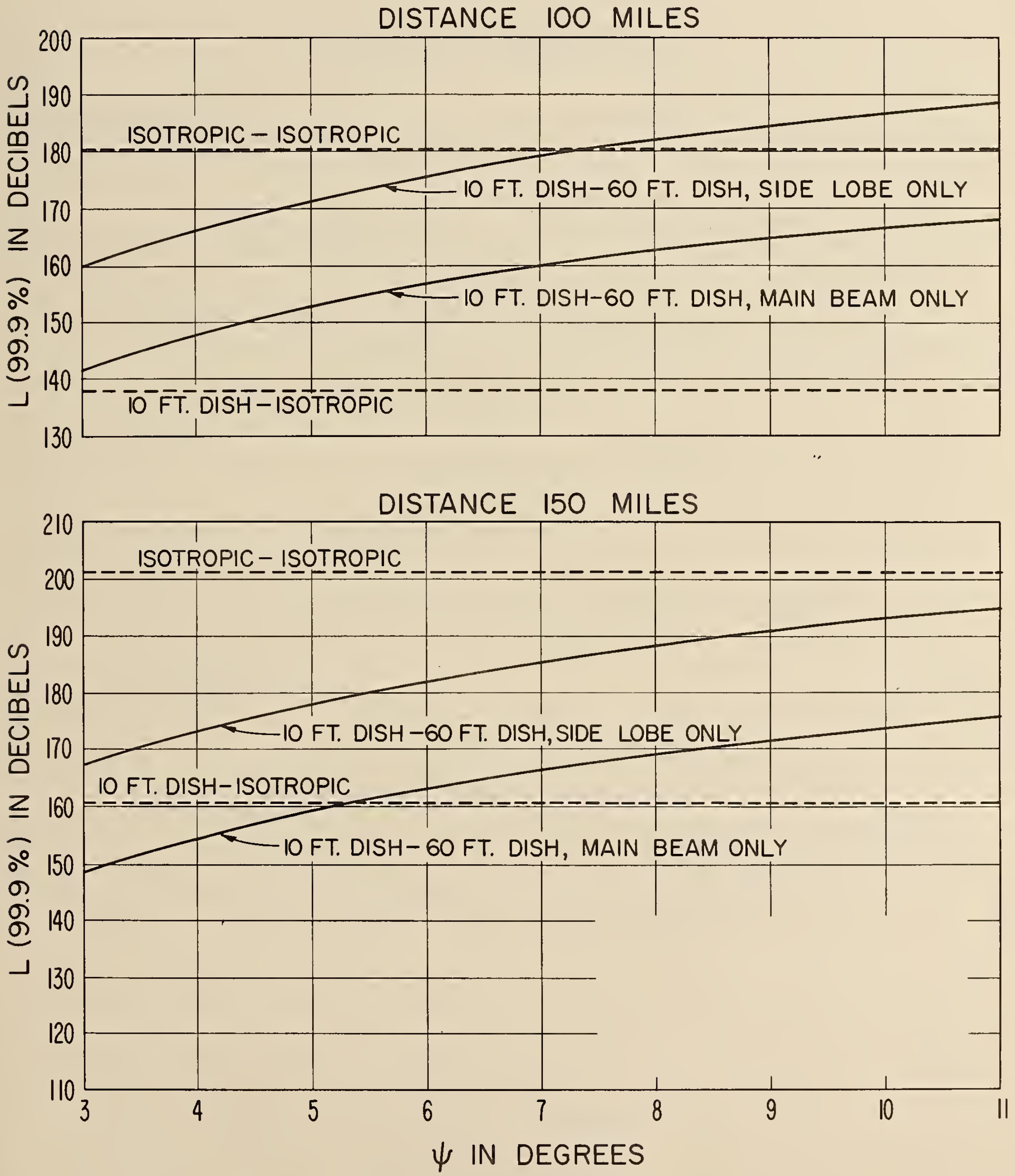
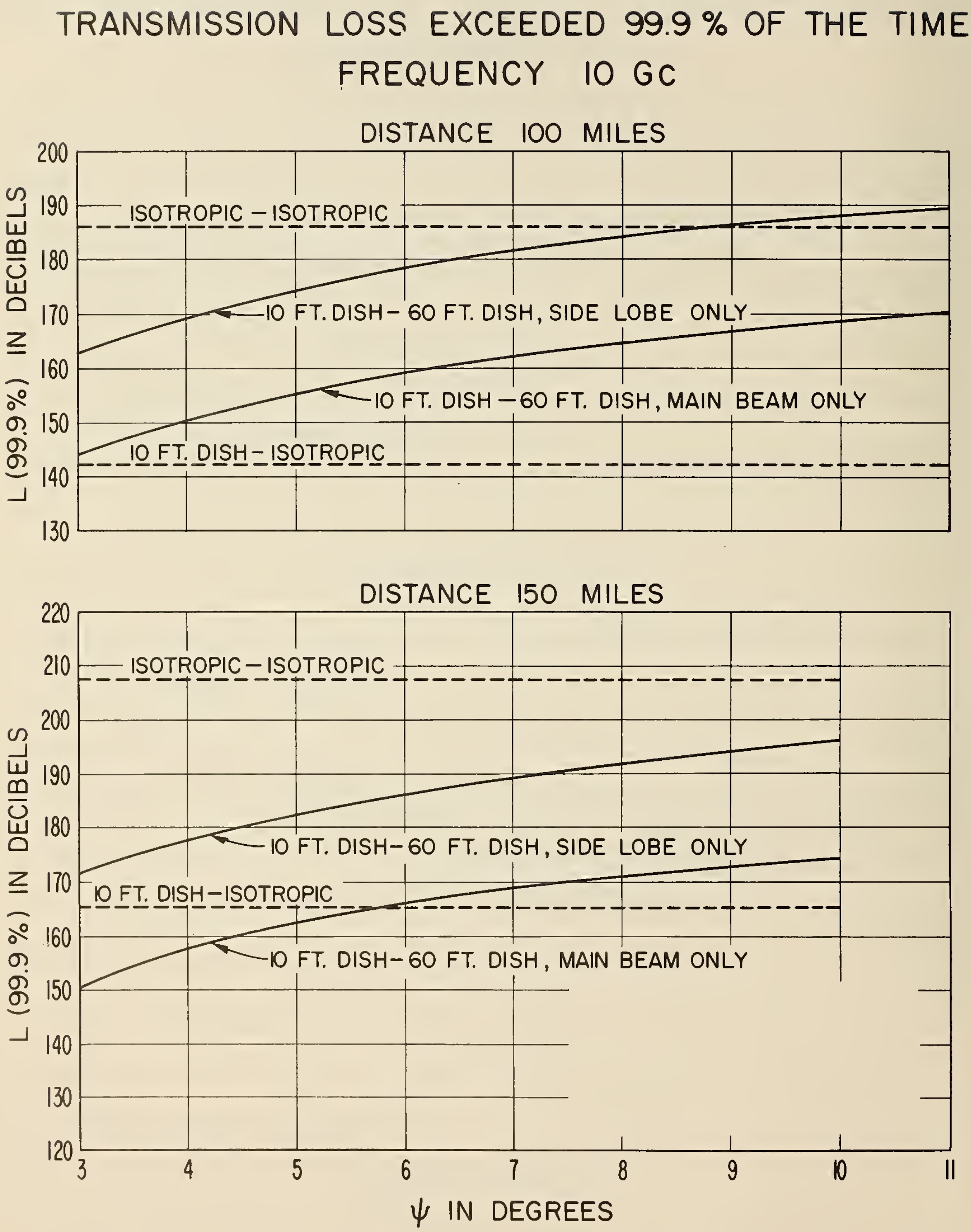


Figure 29



TRANSMISSION LOSS EXCEEDED 99.9 % OF THE TIME
FREQUENCY 10 Gc
DISTANCE 100 MILES
ISOTROPIC – ISOTROPIC
10 FT. DISH – 60 FT. DISH, SIDE LOBE ONLY
10 FT. DISH – 60 FT. DISH, MAIN BEAM ONLY
10 FT. DISH – ISOTROPIC
DISTANCE 150 MILES
ISOTROPIC – ISOTROPIC
10 FT. DISH – 60 FT. DISH, SIDE LOBE ONLY
10 FT. DISH – ISOTROPIC
10 FT. DISH – 60 FT. DISH, MAIN BEAM ONLY
L (99.9%) IN DECIBELS
ψ IN DEGREES

Figure 30

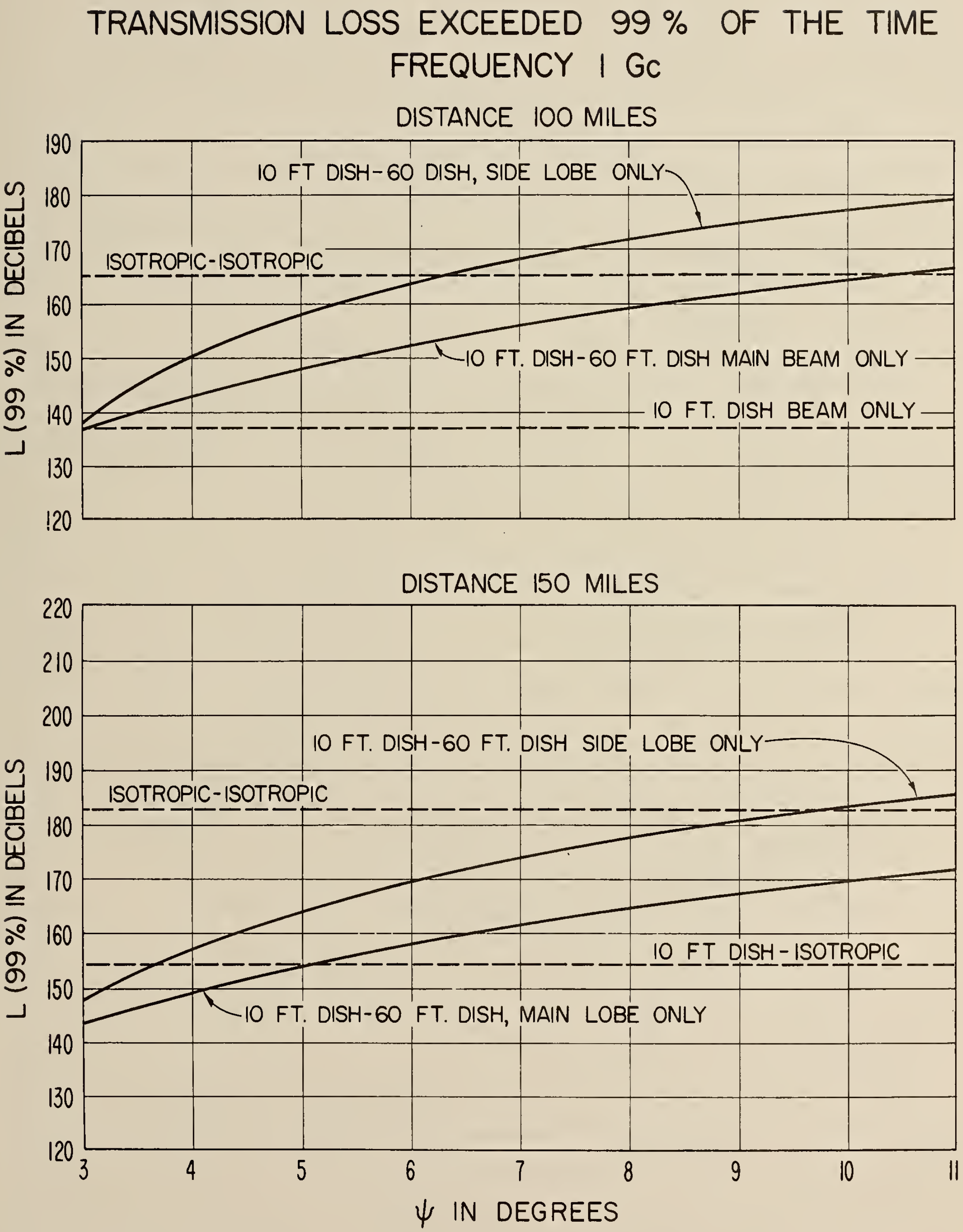
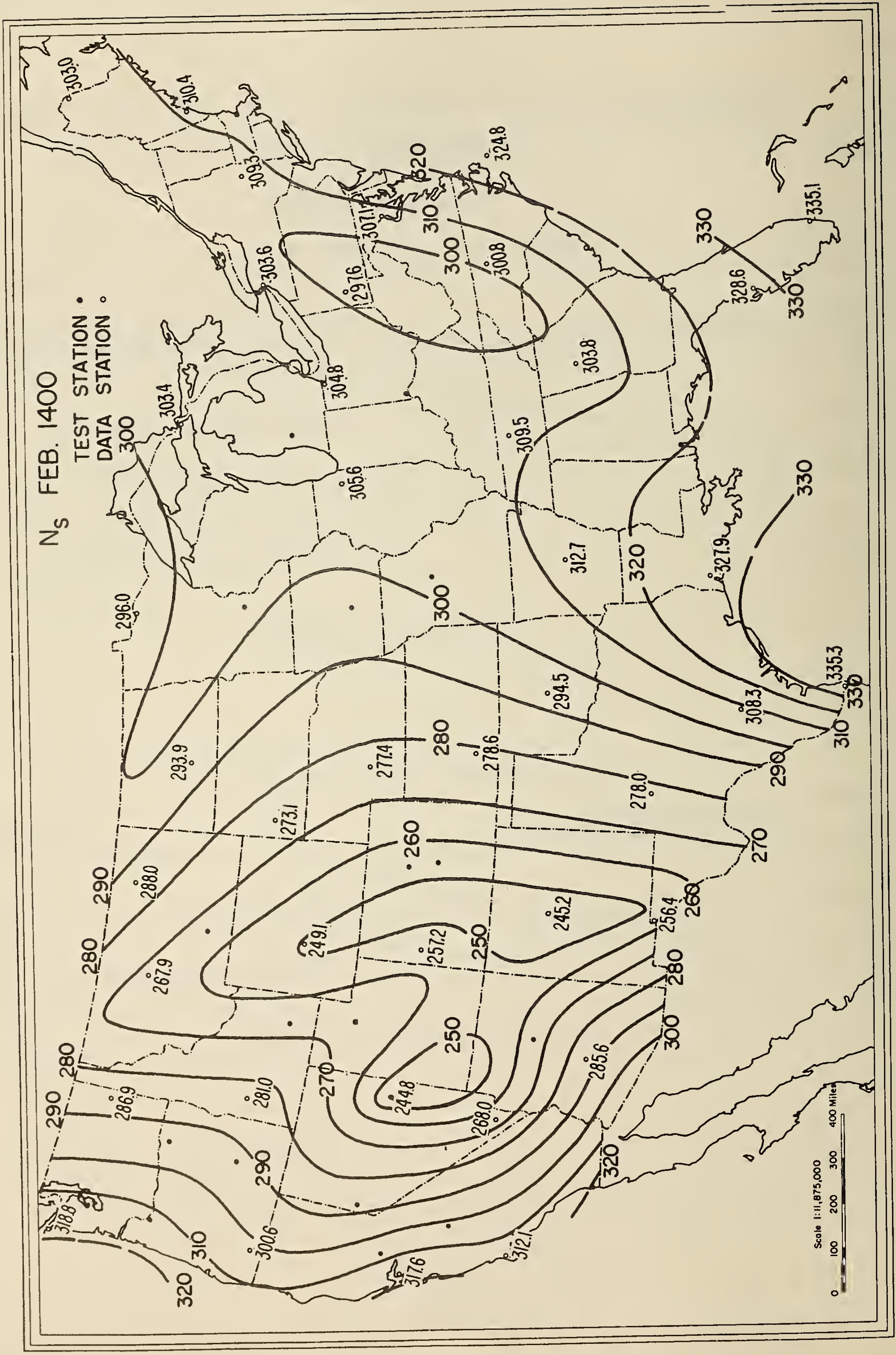

TRANSMISSION LOSS EXCEEDED 99 % OF THE TIME
FREQUENCY 1 Gc
DISTANCE 100 MILES
10 FT DISH-60 DISH, SIDE LOBE ONLY
ISOTROPIC-ISOTROPIC
10 FT. DISH-60 FT. DISH MAIN BEAM ONLY
10 FT. DISH BEAM ONLY
L (99 %) IN DECIBELS
190
180
170
160
150
140
130
120
DISTANCE 150 MILES
10 FT. DISH-60 FT. DISH SIDE LOBE ONLY
ISOTROPIC-ISOTROPIC
10 FT DISH-ISOTROPIC
10 FT. DISH-60 FT. DISH, MAIN LOBE ONLY
L (99%) IN DECIBELS
220
210
200
190
180
170
160
150
140
130
120
3
4
5
6
7
8
9
10
11
ψ IN DEGREES

Figure 31


N_S FEB. 1400
TEST STATION •
DATA STATION ∘
Scale 1:11,875,000
0 100 200 300 400 Miles

U. S. DEPARTMENT OF COMMERCE
Luther H. Hodges, *Secretary*

NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards at its major laboratories in Washington, D.C., and Boulder, Colorado, is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section carries out specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant publications, appears on the inside of the front cover.

WASHINGTON, D. C.

Electricity. Resistance and Reactance. Electrochemistry. Electrical Instruments. Magnetic Measurements. Dielectrics. High Voltage.

Metrology. Photometry and Colorimetry. Refractometry. Photographic Research. Length. Engineering Metrology. Mass and Scale. Volumetry and Densimetry.

Heat. Temperature Physics. Heat Measurements. Cryogenic Physics. Equation of State. Statistical Physics.

Radiation Physics. X-ray. Radioactivity. Radiation Theory. High Energy Radiation. Radiological Equipment. Nucleonic Instrumentation. Neutron Physics.

Analytical and Inorganic Chemistry. Pure Substances. Spectrochemistry. Solution Chemistry. Standard Reference Materials. Applied Analytical Research. Crystal Chemistry.

Mechanics. Sound. Pressure and Vacuum. Fluid Mechanics. Engineering Mechanics. Rheology. Combustion Controls.

Polymers. Macromolecules: Synthesis and Structure. Polymer Chemistry. Polymer Physics. Polymer Characterization. Polymer Evaluation and Testing. Applied Polymer Standards and Research. Dental Research.

Metallurgy. Engineering Metallurgy. Microscopy and Diffraction. Metal Reactions. Metal Physics. Electrolysis and Metal Deposition.

Inorganic Solids. Engineering Ceramics. Glass. Solid State Chemistry. Crystal Growth. Physical Properties. Crystallography.

Building Research. Structural Engineering. Fire Research. Mechanical Systems. Organic Building Materials. Codes and Safety Standards. Heat Transfer. Inorganic Building Materials. Metallic Building Materials.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics. Operations Research.

Data Processing Systems. Components and Techniques. Computer Technology. Measurements Automation. Engineering Applications. Systems Analysis.

Atomic Physics. Spectroscopy. Infrared Spectroscopy. Far Ultraviolet Physics. Solid State Physics. Electron Physics. Atomic Physics. Plasma Spectroscopy.

Instrumentation. Engineering Electronics. Electron Devices. Electronic Instrumentation. Mechanical Instruments. Basic Instrumentation.

Physical Chemistry. Thermochemistry. Surface Chemistry. Organic Chemistry. Molecular Spectroscopy. Elementary Processes. Mass Spectrometry. Photochemistry and Radiation Chemistry.

Office of Weights and Measures.

BOULDER, COLO.

Cryogenic Engineering Laboratory. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Cryogenic Technical Services.

CENTRAL RADIO PROPAGATION LABORATORY

Ionosphere Research and Propagation. Low Frequency and Very Low Frequency Research. Ionosphere Research. Prediction Services. Sun-Earth Relationships. Field Engineering. Radio Warning Services. Vertical Soundings Research.

Radio Propagation Engineering. Data Reduction Instrumentation. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation-Terrain Effects. Radio-Meteorology. Lower Atmosphere Physics.

Radio Systems. Applied Electromagnetic Theory. High Frequency and Very High Frequency Research. Frequency Utilization. Modulation Research. Antenna Research. Radiodetermination.

Upper Atmosphere and Space Physics. Upper Atmosphere and Plasma Physics. High Latitude Ionosphere Physics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.

RADIO STANDARDS LABORATORY

Radio Physics. Radio Broadcast Service. Radio and Microwave Materials. Atomic Frequency and Time-Interval Standards. Radio Plasma. Millimeter-Wave Research.

Circuit Standards. High Frequency Electrical Standards. High Frequency Calibration Services. High Frequency Impedance Standards. Microwave Calibration Services. Microwave Circuit Standards. Low Frequency Calibration Services.

NBS