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# WIND TURBINE GENERATOR SITING HANDBOOK

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# NOTICE

## ABSTRACT

The rotating blades of a horizontal axis wind turbine generator (WTG) can distort the video portion of a TV signal and thereby interfere with TV reception in the vicinity of the WTG. The nature of this interference is discussed and methods are described for calculating the zone within which the interference is judged severe. All necessary information is provided for predicting the interference zones about MOD-0, MOD-0A and MOD-1 machines for any given TV transmitter using graphical procedures.

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# WIND TURBINE GENERATOR SITING HANDBOOK

## 1. INTRODUCTION

The purpose of this Handbook is to show how to predict the region where a horizontal axis wind turbine generator (WTG) can significantly effect the reception of television (TV) signals. Such information can assist in the selection of a site for a WTG facility and in the analysis of the interference under a variety of circumstances. The results of a detailed theoretical and experimental investigation into the nature of the interference are given in [1,2].

The electromagnetic interference is intimately connected with the characteristics of radiowave propagation over the earth and in the presence of the WTG. It is assumed that the waves propagate over a homogeneous smooth spherical earth having a radius 6.34 x $10^3$ km, with relative permittivity $\varepsilon_r = 15$ and conductivity $\sigma = 0.01$ siemens/m. The medium above the earth is assumed to be free space and the effects of any terrain inhomogeneity or irregularity are ignored.

## 2. INTERFERENCE PHENOMENA

It has been found [1] that the rotating blades of a horizontal axis WTG can interfere with TV reception by producing video distortion. At a given distance from a given WTG the interference increases with increasing frequency and is therefore worst on the upper UHF channels. It also decreases with increasing distance from the machine, but in the worst cases can still produce objectionable video distortion at distances up to a few kilometers. For ambient (primary) signals above the noise level of the receiver, there is in general no significant dependence on the ambient field strength, and no audio distortion has been observed.

The interference is caused by the time-varying amplitude modulation (AM) of the received signal produced by the rotating blades. In a neighborhood of a WTG the signals scattered by the blades combine with the primary signal to create a form of time-varying multipath, thereby amplitude modulating the total received signal. The amplitude modulation waveform consists of sync pulses repeating at the rotation frequency of the blades. The width of the pulses is inversely proportional to the electrical length of a blade. If sufficiently strong, these extraneous pulses can distort the received picture, whereas the audio information, being transmitted by frequency modulation, remains unaffected.

When the blades are stationary the scattered signal may appear on the TV screen as a ghost whose position (separation) depends on the difference between the time delays suffered by the primary and scattered signals. A rotation of the blades then causes the ghost to fluctuate, and if the ghost is sufficiently strong, the resulting interference can be objectionable. In such cases the received picture displays a horizontal jitter in synchronism with the blade rotation. As the interference increases, the entire (fuzzy) picture shows a pulsed brightening, and still larger interference can disrupt the TV receiver's vertical sync, producing complete picture break-up. This type of interference occurs when the interfering signal reaches the receiver as a result of scattering, primarily specular, off the broad faces of the blades. In the forward scattering region when the WTG is almost in-line between the TV transmitter and the receiver, there may be little or no difference in the times of arrival of the primary and scattered signals, and the video interference then appears as an intensity (brightness) fluctuation of the picture in synchronism with the blade rotation. In both cases, however, the amount of interference depends on the strength of the scattered signal relative to the primary one, and this decreases with increasing distance from the WTG.

## 3. MODULATION THRESHOLD AND THE INTERFERENCE ZONE

The modulation threshold $m_0$ is defined as the largest value of the extraneous amplitude modulation index m of the received signal for which the video distortion is still judged to be acceptable. The threshold is obviously somewhat subjective, but as a result of detailed laboratory simulations and field tests we have established it as $m_0 = 0.15$ for all TV channels except the two lowest (Channels 2 and 4) for which $m_0 \simeq 0.20$. However, since the interference increases with increasing frequency (and therefore channel number), it is recommended that the threshold $m_0 = 0.15$ be used in all calculations of interference regions. The threshold is independent of the signal strength at the receiver and, for a given WTG, determines the maximum distance from the WTG at which the interference can still be objectionable.

On the assumption that the WTG is so oriented (in azimuth) as to direct the maximum scattered signal to the receiver, the region where $m > m_0$ is defined as the interference zone [1]. That portion of the region which is produced by specular reflection off the blades is a cardioid centered at the WTG with its maximum pointing towards the TV transmitter. There is also a narrow lobe directed away from the transmitter resulting from forward scattering off the blades, and this generally provides the maximum distance from the WTG at which objectionable interference can occur. In the forward region the interference appears weakly dependent on the ambient or primary signal strength, being strongest in fringe areas of reception where the signal strength is low. This effect is ignored in the calculation of the interference zones. Though the shapes of these zones are independent of the TV channel number, their size increases with increasing number.

## 4. THEORETICAL CONSIDERATIONS

The calculation of the interference zone of a WTG is based on the theoretical expressions for the fields derived in [1], and we shall only summarize them here.

At a receiving point R in the presence of a WTG the amplitude modulation index m of the total field is

$$m = E^B(R)/E^T(R) \tag{1}$$

where $E^T(R)$ is the amplitude of the direct (primary) field of the TV transmitter (T) at the receiver (R) and $E^B(R)$ is the amplitude of the secondary field which reaches the receiver after reflection from a rotating blade (B) of the WTG. The latter field is itself the product of the direct field of amplitude $E^T(B)$ illuminating the WTG and the field at the receiver of a transmitter of effective strength N located at the blade. We can therefore write

$$E^B(R) = E^T(B) N \, E^{BT}(R) \; , \qquad (2)$$

giving

$$m = N \frac{E^T(B)}{E^T(R)} E^{BT}(R) \qquad (3)$$

where $E^{BT}(R)$ is the amplitude of the field produced by a transmitter at the blade radiating the same power as the primary TV transmitter.

The parameter N is determined by the scattering characteristics of the blades. Laboratory and full scale tests and analyses indicate [1,2] that the blade scattering is predominantly in the specular and forward directions with each blade contributing individually, and that the rotation of the blades produces a periodic impulsive type of amplitude modulation. For blades whose electrical size is sufficiently large, the scattering can be estimated using the physical optics approximation, and the calculation can be further simplified by treating each blade as a rectangular metal plate whose equivalent (scattering) area is $A_e$ [2].

Figure 1 shows the locations of the distant TV transmitter, the receiver and the scattering center of a blade, all assumed to lie in a horizontal plane, i.e., the plane of the paper. It is also assumed that the blade rotates in a vertical plane through M-M (see Figure 1), and that this plane is so oriented as to direct the specularly reflected field to the receiver. The parameter N characterizing a blade as a re-radiator is then

$$N = \frac{A_e f}{4.5 \times 10^4 \sqrt{P}} \begin{cases} \cos \frac{\phi}{2} & \text{for } 0 \leq |\phi| \lesssim \pi - \lambda/L \\ \text{sinc}\left(\frac{L}{\lambda} \sin \phi\right) & \text{for } \pi - \lambda/L < |\phi| \leq \pi \end{cases} \qquad (4)$$

where $A_e$ is the equivalent scattering area of a blade (in $m^2$)

$L$ is the physical length of a blade (in m)

$\lambda$ is the wavelength (in m)

$f$ is the frequency (in MHz)

$P$ is the effective power radiated by the TV transmitter (in Kw)

and

$$\text{sinc } x = \frac{\sin \pi x}{\pi x} \quad .$$

Note that $A_e \cos \phi/2$ is the projection of $A_e$ perpendicular to the direction of incidence.

Since P plays no role in the interference calculations, we shall therefore take $P = 1$.

If the plane of the blade rotation is always chosen so as to direct the maximum reflected or forward scattered field to the receiver regardless of its position, N achieves its maximum value

$$N_o = \frac{A_e f}{4.5 \times 10^4} \tag{5}$$

when $\phi = 0$ and $\pi$, corresponding respectively to backscattering (R in line between T and B) and forward scattering (R on the extension of TB). For a given level of interference, the distances from B at which this is achieved are largest in the directions $\phi = 0$ and $\pi$, and these distances can be estimated in the following manner. If $E^{BT}(R)$ is assumed inversely proportional to the distance r from the WTG, i.e., $E^{BT}(R) = K/r$ where K is some constant, the distances $r_1$ and $r_2$ in the back and forward directions at which the modulation index equals its threshold value $m_o$ are

$$r_1 = \frac{KN_o}{m_o} \frac{E^T(B)}{E^T(R_1)} \quad , \qquad r_2 = \frac{KN_o}{m_o} \frac{E^T(B)}{E^T(R_2)} \tag{7}$$

where $R_1 = (r_1, 0)$ and $R_2 = (r_2, \pi)$. In general $E^T(R_2) < E^T(R_1)$, implying $r_2 > r_1$. Using $r_1$ and $r_2$ in conjunction with (3) and (4), the boundary of the backward (specular) portion of the interference zone is

$$r(\phi) = r_1 \cos \phi/2 \qquad (0 \leq |\phi| \lesssim \pi - \lambda/L) \tag{8}$$

which is a cardioid centered on the WTG with its maximum directed towards the transmitter. For the forward portion

$$r(\phi) = r_2 \operatorname{sinc} \left(\frac{L}{\lambda} \operatorname{sinc} \phi\right) \qquad (\pi - \lambda/L < |\phi| \leq \pi) \tag{9}$$

which is a narrow lobe directed away from the transmitter.

For general siting purposes it is sometimes convenient to regard the interference zone as a circle centered on the WTG with radius

$$r_0 = \frac{1}{2}(r_1 + r_2) , \tag{10}$$

i.e., the average of the distances in the back and forward directions. Since the blade scattering increases with frequency, it may also be sufficient to calculate $r_0$ only for the highest TV channel frequency of interest, but even this still requires the determination of the fields using the theoretical expressions in [1]. To facilitate the task, a computer program has been written as described in the next section.

## 5. COMPUTER METHOD FOR INTERFERENCE ZONE CALCULATIONS

The computer program [1] used is itself an extension of one which was developed [3] for calculating ground wave propagation over a homogeneous spherical earth. The transmitting and receiving antennas are assumed omnidirectional and horizontally polarized and located at heights $h_1$ and $h_2$ respectively above the earth's surface. The height of the scattering or phase center of the blade is $h_3$. At a given frequency and for given $h_1$, $h_2$ and $h_3$, the program computes the field quantities $E^T(R)$ and $E^T(B)$ as functions of the great circle distance from the transmitter and $E^{TB}(R)$ as a function of the distance r from the WTG. The output is in the form of field strength (in mV/m), linear and dB, and relative phase (in radians). Though the program can handle any specified values for the relative permittivity $\varepsilon_r$ and conductivity $\sigma$ of the earth, and any earth radius correction factor $\alpha$ to account for atmospheric refraction, the computations were performed for the values listed in Section 1 with $\alpha = 1$. For all of the calculations discussed here, $h_1 = 300$ m, $h_2 = 10$ m and $h_3 = 30$ m, typical of the heights encountered in practice.

With the frequency f and distance d as inputs, the quantites $E^B(R)$ and $E^T(R)$ are obtained at a sequence of distances from the WTG along the same great circle path from the transmitter. From a manual comparison of the two sets of values, the farthest points on either side of the WTG at which $m = m_0 = 0.15$ are located. These specify the two distances $r_1$ and $r_2$, the average of which then constitutes the circular interference zone radius $r_0$. If desired, the actual interference zone can be found by solving (1) with $m = m_0$, or estimated using (8) and (9). As is evident, however, the process requires the computation of a whole new series of field strength values for every TV transmitter and its distance from the WTG. It is therefore costly and inefficient, and a simpler graphical method which makes use of a general set of computed data was developed in its place.

## 6. GRAPHICAL METHOD FOR INTERFERENCE ZONE CALCULATIONS

For any $h_1$, $h_2$ and f, the field strength as a function of the distance d (in km) from the transmitter is typically as shown in Figure 2. The distance $\overline{d}$ to the radio horizon is

$$\overline{d} = 3.57 \left\{h_1^{1/2} + h_2^{1/2}\right\} \tag{11}$$

where $h_1$ and $h_2$ are measured in meters, and the horizon is marked in Figure 2. Well within the horizon distance, the field strength oscillates as a result of interference between the free space and ground-reflected waves and here a change in d of less than 1 km can produce a field strength variation of more than 30 dB. Since our concern is to calculate the maximum distance from a WTG at which a given level of video distortion can occur, it is sufficient to ignore the oscillations and confine attention to the peak values of the field. This provides a major simplification. As evident from (3) of [3], the peak values are such that

$$E \simeq 0.3/d \quad \text{mV/m} \tag{12}$$

independent of $h_1$, $h_2$ and f, though the locations of the peaks do, of course, depend on all three parameters. From (12) it now follows that throughout the interference region

$$20 \log E = -(10.46 + 20 \log d) \tag{13}$$

and the corresponding straight line is indicated in Figure 2.

The graphical method for predicting the interference zone of a WTG is based on the following. From (3)

$$20 \log E^{BT}(R) = 20 \log \frac{E^T(R)}{E^T(B)} + 20 \log \frac{m}{N} \tag{14}$$

and the maximum interference distances $r_1$ and $r_2$ can be obtained by solving (14) for R located at $(r_1, 0)$ and $(r_2, \pi)$ with $m = m_0 = 0.15$ and $N = N_0$. From (6)

$$20 \log \frac{m_0}{N_0} = 76.58 - 20 \log A_e - 20 \log f \tag{15}$$

with $A_e$ in $m^2$ and f in MHz and Figure 3 shows $20 \log m_0/N_0$ as a function of f, $50 \leq f \leq 900$ MHz, for three values of the equivalent scattering area $A_e$ of a blade. For 9 specific frequencies in this range, $20 \log E^{BT}(R)$ is plotted as a function of the distance r of a receiver ($h_2$ = 10 m) from the WTG ($h_3$ = 30 m) in Figure 4, and we observe that with decreasing r each curve becomes tangent to the straight line given by (13).

The only remaining quantity in (14) is the ratio of the direct (primary) fields at the receiver and the blade. To find this the computer program was again used to obtain the field of a transmitter of height $h_1$ = 300 m at selected frequencies f, $50 \leq f \leq 900$ MHz, and at all necessary increments in range d from a few kilometers out to 200 km. Throughout the interference region, the actual field strength values were replaced by those deduced from (13). A value of d was then chosen and at each frequency $E^T(R)/E^T(B)$ was determined as a function of the distance r of the receiver from the WTG. Locations towards ($\phi = 0$) and away ($\phi = \pi$) from the transmitter were considered with $1 \leq r \leq 20$ km. The process was then repeated at other ranges so as to develop the curves in Figure 5a through 5i. Whereas for small ranges the curves change quite rapidly with increasing d, for d $\gtrsim$ 100 km there is very little change, and we therefore selected the specific values d = 10(10)60, 80, 120 and 200 km. The resulting plots of 20 log $E^T(R)/E^T(B)$ versus r (in km) are given in Figures 5 a through 5i, with the solid curves for $\phi = \pi$ and the dashed ones for $\phi = 0$. For values of d and/or f intermediate to those shown, adequate accuracy can be obtained by linear interpolation. With the aid of Figures 3, 4 and 5, it is now possible to solve (14) graphically (see Section 7) to find $r_1$ and $r_2$ for any TV channel.

Knowing $r_1$ and $r_2$, the complete interference zone can be approximated using (9) and (10), but a more accurate determination requires the solution of (14) for receivers located off the great circle path through the transmitter and the WTG. For $\phi \neq 0, \pi$, the projection of the blade area perpendicular to the direction of incidence is less, and $N_0$ is then reduced by the factor cos $\phi/2$. In Figure 6, 20 log cos $\phi/2$ is plotted as a function of $\phi$, $0 \leq \phi < \pi$ and this can be used in conjunction with Figure 3 to give the required value of 20 log $m_0/N_0$. However, this is not the entire story. For R within the backward portion of the interference zone, the reduced scattering by the blade is partially offset by the increased distance of the receiver from the transmitter, and for all practical purposes, this distance can be taken as

$$d' = d - r \cos \phi \ .$$

The manner in which this affects the use of the data in Figures 4 through 6 is explained in the next section (steps 10 and 11).

## 7. INTERFERENCE ZONE CALCULATIONS

We now present a systematic method for calculating the interference zone around a WTG in a fixed location with respect to a TV transmitter. A listing of the symbols used is as follows:

| | | |
|---|---|---|
| T,B,R | | denote the TV transmitter, WTG blade and TV receiver, respectively, |
| $f$ | = | TV Channel video carrier frequency (in MHz) (see Appendix A), |
| $\lambda$ | = | $299.8/f$ : wavelength (in m), |
| $d$ | = | TV transmitter to WTG distance (in Km), |
| $r$ | = | WTG to receiver distance (in Km), |
| $h_1$ | = | height (in m) above earth of the phase center of the TV transmitting antenna, |
| $h_2$ | = | height (in m) above earth of the phase center of the receiving antenna, |
| $h_3$ | = | height (in m) above earth of the phase (scattering) center of the WTG blade (can be taken as the WTG tower height), |
| $\phi$ | = | angle between the lines BR and BT, |
| $\phi'$ | = | angle between the lines RT and RB, |
| $A_p$ | = | projected (geometrical) area (in $m^2$) of a WTG blade, |
| $A_e$ | = | equivalent scattering area (in $m^2$) of a WTG blade, |
| $\eta$ | = | $A_e/A_p$ : scattering efficiency of a WTG blade, |
| $L$ | = | length (in m) of a WTG blade, |
| $m$ | = | amplitude modulation index, |
| $m_0$ | = | threshold of amplitude modulation index, |
| $N$ | = | effective strength of the fictitious transmitter located at the phase center of a WTG blade, |
| $N_0$ | = | maximum value of $N$, |

$E^{BT}(R)$ = amplitude of the field at R of a transmitter at B,
$E^{T}(B)$ = amplitude of the direct field at B of the transmitter at T,
$E^{T}(R)$ = amplitude of the direct field at R of the transmitter at T,
$r_1$, $r_2$ = backward and forward interference distances (in Km),
$r_o$ = $1/2(r_1 + r_2)$ : radius (in Km) of equivalent circular interference zone.

The following graphical results are required for the determination of the interference zone:

(i) 20 log $m_o/N_o$ vs f , $50 \leq f \leq 900$ , for various $A_e$ (Figure 3)

(ii) 20 log $E^{BT}(R)$ vs r for various f, $50 \leq f \leq 900$ (Figure 4)

(iii) 20 log $E^{T}(R)/E^{T}(B)$ vs r for various f, $50 \leq f \leq 900$ and selected d (Figure 5)

(iv) 20 log cos $\phi/2$ vs $\phi$, $0 \leq \phi < \pi$ (Figure 6).

The above field strength curves were computed for $h_1$ = 300 m, $h_2$ = 10 m and $h_3$ = 30 m, typical of the values encountered in practice. The antennas were assumed omnidirectional and horizontally polarized, with the transmitters radiating 1 Kw effective power.

The equivalent scattering area $A_e$ of the WTG blade is also required. This is related to the projected (geometrical) area $A_p$ via the scattering efficiency $\eta$, and the projected areas of the MOD-0, MOD-0A and MOD-1 blades are 18, 18 and 62.5 $m^2$ respectively. From laboratory scale model and full scale scattering tests [2], the corresponding scattering efficiencies of the three blades are found to be 0.67, 0.27 and 0.63 respectively, where the MOD-0A (fiberglas) blade has been assumed to have a minimal configuration (stage #2: see [2]) of lightning arrestor strips. For all practical purposes it is sufficient to use $A_e$ = 12 $m^2$, 5 $m^2$ and 40 $m^2$ for the three blades, and these values were employed in the construction of Figure 3. The lengths of the blades are approximately 18, 18 and 28 m respectively.

To determine the interference zone in any given case:

1. Identify f (from the TV Channel number: see Appendix A), d and $A_e$
2. From Figure 3 obtain the appropriate dB level $y_1$
3. Choose the Figure 5(x) for the distance d closest to the desired one
4. Overlay Figures 4 and 5(x), positioning the $y_1$ dB level of Figure 4 at the 0 dB level of Figure 5(x)
5. Note the curves for f in Figure 5(x) and read the intercepts to obtain

   $r_1$ for $\phi = 0$ (dashed curve)

   $r_2$ for $\phi = \pi$ (solid curve)

   This gives the maximum interference distances in the backward and forward directions.
6. Average $r_1$ and $r_2$ to give the radius $r_0$ of the equivalent circular interference zone.

An approximation to the actual shape of the interference zone involves two additional steps.

7. Compute $r(\phi) = r_1 \cos \phi/2$ , $0 \leq \phi \lesssim \pi - \lambda/L$
8. Compute $r(\phi) = r_2 \operatorname{sinc} (L/\lambda \sin \phi)$ , $\pi - \lambda/L < \phi \leq \pi$

Steps 1 through 8 complete the determination of the interference zone to an accuracy that is adequate for most purposes.

In the backward region $0 \leq \phi \lesssim \pi - \lambda/L$ the zone shape differs somewhat from that computed above, and for a more precise determination, the following additional steps are necessary.

9. Select a value of $\phi$ in the range $0 \leq \phi \lesssim \pi - \lambda/L$. From Figure 6, obtain the dB level $y_2$ corresponding to the chosen $\phi$. Subtract $y_2$ from $y_1$ (see step 2) to find the modified dB level $y_3 = y_1 - y_2$.

10. Choose the appropriate Figure 5(x) and interpret the abscissa as $r' = r|\cos\phi|$, using the dashed curves if $\phi < \pi/2$ and the solid ones if $\phi > \pi/2$.

11. Overlay Figures 4 and 5(x), positioning the dB level $y_3$ of Figure 4 at the 0 dB level of Figure 5, with the r = 1 of Figure 4 at the r = r' of Figure 5(x).

12. Having selected the required f curve, read the abscissa in Figure 4 at which the intercept occurs. This is the interference distance in the direction $\phi$.

13. Repeat steps 9 through 12 at a sequence of $\phi$ in the range $0 \leq \phi \lesssim \pi - \lambda/L$.

If the receiving antenna has different gains as regards the primary and secondary fields, i.e., is not omnidirectional, the interference zone will differ from that computed above. To illustrate, assume that the main beam of the antenna is always directed at the TV transmitter. If $f(\phi')$ is the pattern factor of the antenna in the plane of observation with $f(0) = 1$, the required modification is to

14. multiply the interference distances in steps 5, 7, 8, 12 and 13 by $f(\phi')$.

This completes the calculation of the interference zone for a given TV transmitter. All relevant steps must be repeated for each transmitter frequency and/or location.

## 8. SAMPLE CALCULATIONS

We illustrate the procedure by computing the interference zones for TV Channel 52 whose transmitter is 120 Km from a MOD-1 or a MOD-0 WTG.

The following parameters are identified

$$f = 699.25 \text{ MHz}, \quad \lambda = 0.429 \text{ m}, \quad d = 120 \text{ Km}$$

The blade parameters are:

| Blade | $A_e$ | L | $\lambda/L$ |
|---|---|---|---|
| MOD-1 | 40 $m^2$ | 28 m | 0.0153 |
| MOD-0 | 12 $m^2$ | 18 m | 0.0238 |

The required graphs are Figures 3, 4, 5h and 6. We show the details of the calculations only for the MOD-1 blade.

<u>Step 2</u>

From Figure 3, $y_1 = -12.4$ dB .

<u>Steps 3-5</u>

Overlay Figures 4 and 5h such that the -12.4 dB level of Figure 4 coincides with the 0 dB level of Figure 5h. Noting which curves are for 700 MHz, read off from Figure 4 the values of r corresponding to the intercepts of the curves:

$r_1 = 3.1$ Km for $\phi = 0$ (dashed curve)

$r_2 = 6.9$ Km for $\phi = \pi$ (solid curve) , Step 6

The equivalent circular interference zone radius is

$$r_o = \frac{1}{2}(3.1 + 6.9) = 5.0 \text{ Km} ,$$

Step 7

An approximation to the backward portion of the interference zone is obtained by computing

$$r(\phi) = 3.1 \cos \phi/2 \qquad (0 \leq \phi \lesssim \pi - \lambda/L)$$

leading to the result shown in Figure 7.

Step 8

The forward portion of the interference zone is given by

$$r(\phi) = 6.9 \text{ sinc} \left(\frac{\sin\phi}{0.0153}\right) \qquad (\pi - \lambda/L < \phi \lesssim \pi) .$$

The (half) width of the forward lobe is $\sin^{-1} 0.0153 = 0.88$ degrees, and the lobe is sketched in Figure 7.

If a more precise description of the backward portion of the interference zone is required, proceed as follows:

Step 9

Choose some value of $\phi$, $0 < \phi < \pi - \lambda/L$: $\phi = 30$ degrees (say). From Figure 6, $y_2 = -0.4$ dB. Hence $y_3 = y_1 - y_2 = -12.4 -(-0.4) = -12.0$ dB.

Step 10

$$r' = r|\cos 30°| = 0.866\ r\ .$$

Steps 11 and 12

Overlay Figures 4 and 5h such that the -12.0 dB level of Figure 4 is at the 0 dB level of Figure 5h, with the r = 1 of Figure 4 at the r = 0.866 point of Figure 5h. Read off from Figure 4 the value of r corresponding to the intercept of the dashed curve for f = 700 MHz to obtain

$$r(30°) = 3.1\ \text{Km}.$$

Step 13

Repeat steps 9-12 for a sequence of values of $\phi$ in the range $0 < \phi < \pi - \lambda/L$. Some of the values of $r(\phi)$ obtained are listed in Table 1 along with the corresponding $y_2$ and $y_3$, and the resulting (backward) portion of the interference zone is shown in Figure 7. Note the relative close agreement with the approximation found in step 7.

Table 1. Backward portion of interference zone for MOD-1 WTG (precise calculation): TV Channel 52, d = 120 Km.

| $\phi$ (degrees) | $y_2$ (dB) | $y_3$ (dB) | $r(\phi)$ (Km) | |
|---|---|---|---|---|
| | | | dashed | solid |
| 0 | 0.0 | -12.4 | 3.1 | |
| 30 | - 0.4 | -12.0 | 3.1 | |
| 60 | - 1.3 | -11.1 | 3.1 | |
| 90 | - 3.1 | - 9.3 | 3.0 | |
| 120 | - 6.1 | - 6.3 | | 2.5 |
| 135 | - 8.4 | - 4.0 | | 1.9 |
| 150 | -11.8 | - 0.6 | | 1.3 |
| 160 | -15.2 | + 2.8 | | 0.86 |
| 170 | -21.2 | + 8.8 | | 0.43 |

The calculations for the MOD-0 machine are similar. It is found that $r_1 = 1.1$, $r_2 = 1.5$ and $r_0 = 1.3$ Km. The half width of the forward lobe is $\sin^{-1} 0.0238 = 1.36$ degrees, and some of the values associated with a precise determination of the backward portion of the interference zone are listed in Table 2.

Table 2. Backward portion of the interference zone for MOD-0 WTG (precise calculation): TV Channel 52, d = 120 Km.

| $\phi$ (degrees) | $y_2$ (dB) | $y_3$ (dB) | $r(\phi)$ (Km) |
|---|---|---|---|
| 0 | 0 | - 1.9 | 1.1 |
| 30 | - 0.4 | - 1.5 | 1.0 |
| 60 | - 1.3 | - 0.6 | 1.0 |
| 90 | - 3.1 | 1.2 | 0.86 |
| 120 | - 6.1 | 4.2 | 0.76 |
| 150 | -11.8 | 9.9 | 0.36 |

## 9. CONCLUSIONS

Using results obtained from a computer program, an efficient graphical method has been developed for predicting the interference zones around a WTG. The shape of these zones is similar for all horizontal axis WTG and for all TV channels, but their size increases with increasing blade scatter and with increasing TV channel number or frequency. For any given WTG it may therefore be sufficient to calculate the interference zone only for the highest TV channel of interest. If a single number is required to specify the distance at which the interference could still be severe, it is more appropriate to use the backward distance $r_1$ rather than the radius $r_0$ of the equivalent circular zone, and the resulting estimate is reasonable except in directions close to that of forward scattering.

The graphical method described is such that an accuracy of better than 0.2 Km is achievable, particularly if a light table is used in conjunction with the transparencies accompanying this Handbook. In those cases where the results have been compared with data from the extended computer program [1], the agreement has been within 0.1 Km.

As evident from the sample calculations, at the higher frequencies a large WTG can interfere with TV reception at distances of several kilometers. However, this is based on the use of an omnidirectional receiving antenna, and a directional antenna could reduce the distance at which a given level of interference is observed provided the antenna is able to discriminate against the unwanted signal coming from the WTG blades.

The data given in this Handbook are for three WTG blades (MOD-0, MOD-0A and MOD-1) and for the standardized heights $h_1 = 300$ m, $h_2 = 10$ m and $h_3 = 30$ m of the TV transmitting antenna, the receiving antenna and the WTG tower, respectively. These are typical of the heights in practice, but for heights which differ substantially it would be necessary to generate a new set of graphs using the general computer program [1] before proceeding with the interference zone calculations. However, if only the blades are different, the data are still applicable if the equivalent scattering area of the blades can be found. For blades of similar shape to the MOD-0 and MOD-1, the scattering efficiency is approximately 0.65 and 0.25 for metallic and non-metallic blades respectively, and these figures can now be used to obtain the equivalent scattering area from the projected area.

A fundamental parameter which affects the size of the interference zone is the threshold modulation index $m_o$. Based on the results of our laboratory and field tests [2], $m_o = 0.15$ was selected as the threshold (largest value of the) modulation index for which the video interference is still acceptable. A video tape showing the effects of larger and smaller modulation indices has been furnished to DOE and should it be decided that a threshold different from 0.15 is more appropriate, it is only necessary to note that the size of the interference zone is inversely proportional to $m_o$.

There are two final remarks that should be made. All calculations have been carried out on the assumption of a smooth homogeneous earth, and local topography could increase or decrease the level of interference. It is therefore recommended that in the final consideration of a specific site the effects of local terrain be taken into account in arriving at a judgment. Even within the interference zone the interference observed in practice will only be severe when the blades are so positioned (in pitch as well as azimuth) to direct the maximum scattered signal to the receiving antenna. Depending on the prevailing winds, some parts of the interference zone could suffer interference for only a very small fraction of the total time.

## 10. REFERENCES

[1] T.B.A. Senior, D.L. Sengupta and J.E. Ferris, "TV and FM Interference by Windmills", Final Report on Contract No. E-(11-1)-2846, ERDA, Washington, D.C., 20001, February 1977.

[2] T.B.A. Senior and D.L. Sengupta, "Broadcast Interference by Windmills", Final Report on Contract EY-76-S-02-2846, DOE, Washington, D.C., 20545, February 1978.

[3] L.A. Berry, "Fortran Program for Calculating Ground Wave Propagation over Spherical Earth", National Bureau of Standards, Boulder, Colorado.

# APPENDIX A: TELEVISION FREQUENCIES

| Channel No. | Center Frequency (MHz) | |
|---|---|---|
| | video | audio |
| 2 | 55.25 | 59.75 |
| 3 | 61.25 | 65.75 |
| 4 | 67.25 | 71.75 |
| 5 | 77.25 | 81.75 |
| 6 | 83.25 | 87.75 |
| 7 | 175.25 | 179.75 |
| 8 | 181.25 | 185.75 |
| 9 | 187.25 | 191.75 |
| 10 | 193.25 | 197.75 |
| 11 | 199.25 | 203.75 |
| 12 | 205.25 | 209.75 |
| 13 | 211.25 | 215.75 |
| 14 | 471.25 | 475.75 |
| 15 | 477.25 | 481.75 |
| 16 | 483.25 | 487.75 |
| 17 | 488.25 | 493.75 |
| 18 | 495.25 | 499.75 |
| 19 | 501.25 | 505.75 |
| 20 | 507.25 | 511.75 |
| 21 | 513.25 | 517.75 |
| 22 | 519.25 | 523.75 |
| 23 | 525.25 | 529.75 |
| 24 | 531.25 | 535.75 |
| 25 | 537.25 | 541.75 |
| 26 | 543.25 | 547.75 |
| 27 | 549.25 | 553.75 |
| 28 | 555.25 | 559.75 |
| 29 | 561.25 | 565.75 |

| Channel No. | Center Frequency (MHz) | |
|---|---|---|
| | video | audio |
| 30 | 567.25 | 571.75 |
| 31 | 573.25 | 577.75 |
| 32 | 579.25 | 583.75 |
| 33 | 585.25 | 589.75 |
| 34 | 591.25 | 595.75 |
| 35 | 587.25 | 601.75 |
| 36 | 603.25 | 607.75 |
| 37 | 609.25 | 613.75 |
| 38 | 615.25 | 619.75 |
| 39 | 621.25 | 625.75 |
| 40 | 627.25 | 631.75 |
| 41 | 633.25 | 637.75 |
| 42 | 639.25 | 643.75 |
| 43 | 645.25 | 649.75 |
| 44 | 651.25 | 655.75 |
| 45 | 657.25 | 661.75 |
| 46 | 663.25 | 667.75 |
| 47 | 669.25 | 673.75 |
| 48 | 675.25 | 679.75 |
| 49 | 681.25 | 685.75 |
| 50 | 687.25 | 691.75 |
| 51 | 693.25 | 697.75 |
| 52 | 699.25 | 703.75 |
| 53 | 705.25 | 709.75 |
| 54 | 711.25 | 715.75 |
| 55 | 717.25 | 721.75 |
| 56 | 723.25 | 727.75 |
| 57 | 729.25 | 733.75 |

TELEVISION FREQUENCIES (Continued)

| Channel No. | Center Frequency (MHz) | |
|---|---|---|
| | video | audio |
| 58 | 735.25 | 739.75 |
| 59 | 741.25 | 745.75 |
| 60 | 747.25 | 751.75 |
| 61 | 753.25 | 757.75 |
| 62 | 759.25 | 763.75 |
| 63 | 765.25 | 769.75 |
| 64 | 771.25 | 775.75 |
| 65 | 777.25 | 781.75 |
| 66 | 783.25 | 787.75 |
| 67 | 789.25 | 793.75 |
| 68 | 795.25 | 799.75 |
| 69 | 801.25 | 805.75 |
| 70 | 807.25 | 811.75 |
| 71 | 813.25 | 817.75 |
| 72 | 819.25 | 823.75 |
| 73 | 825.25 | 829.75 |
| 74 | 831.25 | 835.75 |
| 75 | 837.25 | 841.75 |
| 76 | 843.25 | 847.75 |
| 77 | 849.25 | 853.75 |
| 78 | 855.25 | 859.75 |
| 79 | 861.25 | 865.75 |
| 80 | 867.25 | 871.75 |
| 81 | 873.25 | 877.75 |
| 82 | 879.25 | 883.75 |
| 83 | 885.25 | 889.75 |

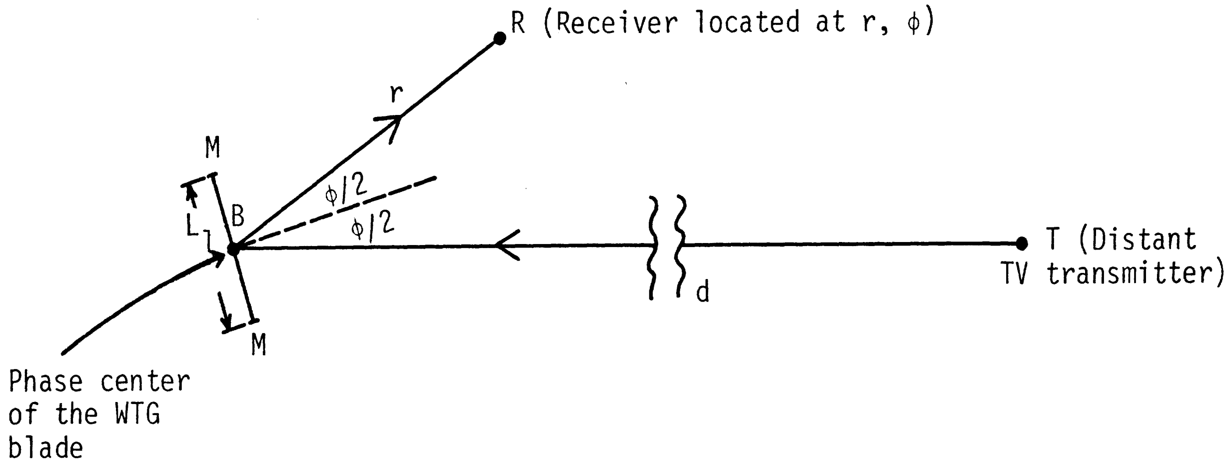



Figure 1. Geometry of the WTG blade scattering.

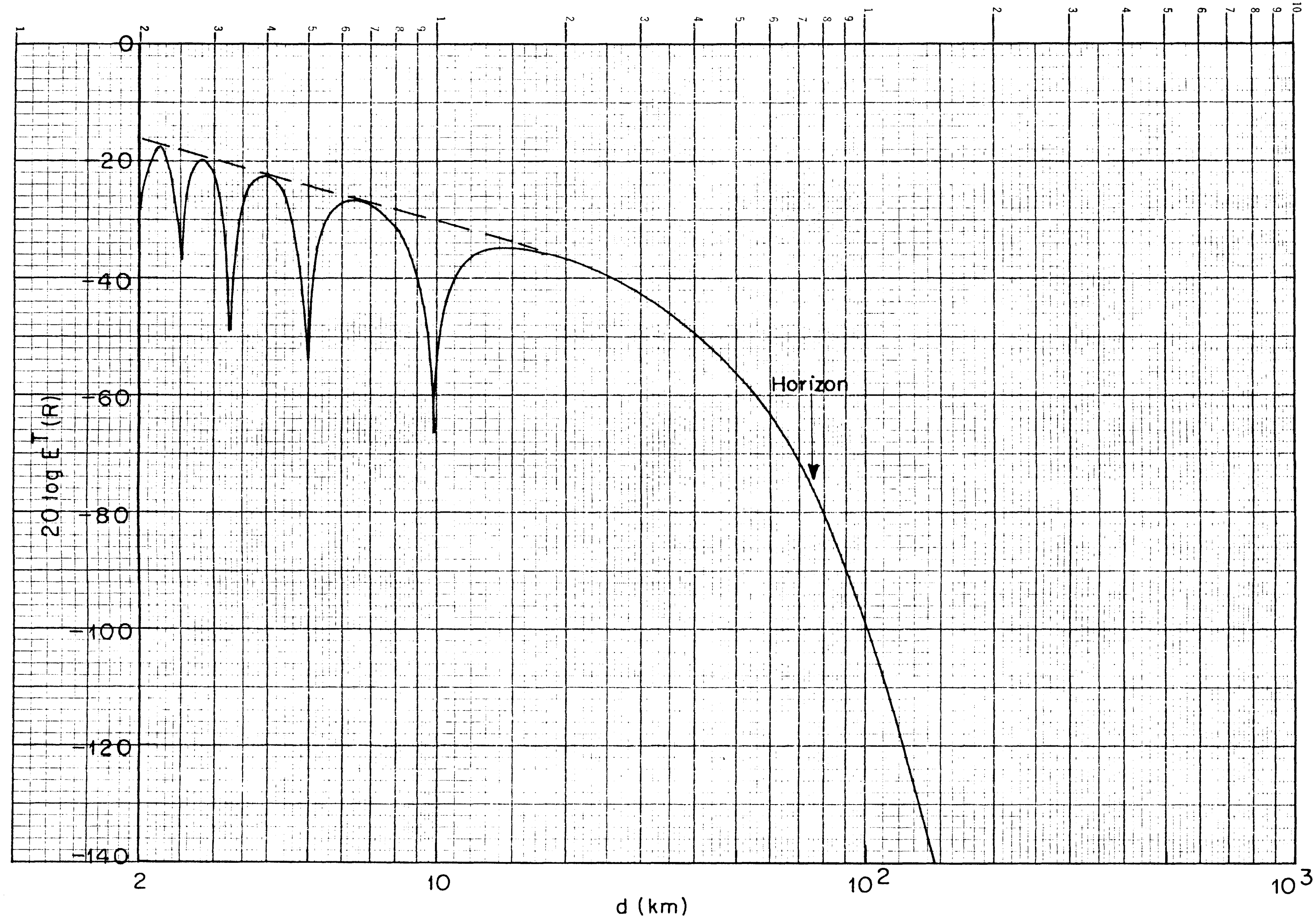



Figure 2. Field strength in dB above mv/m as a function of distance d from a horizontally polarized transmitter radiating 1 Kw effective power: $h_1$ = 300 m, $h_2$ = 10 m, f = 500 MHz.

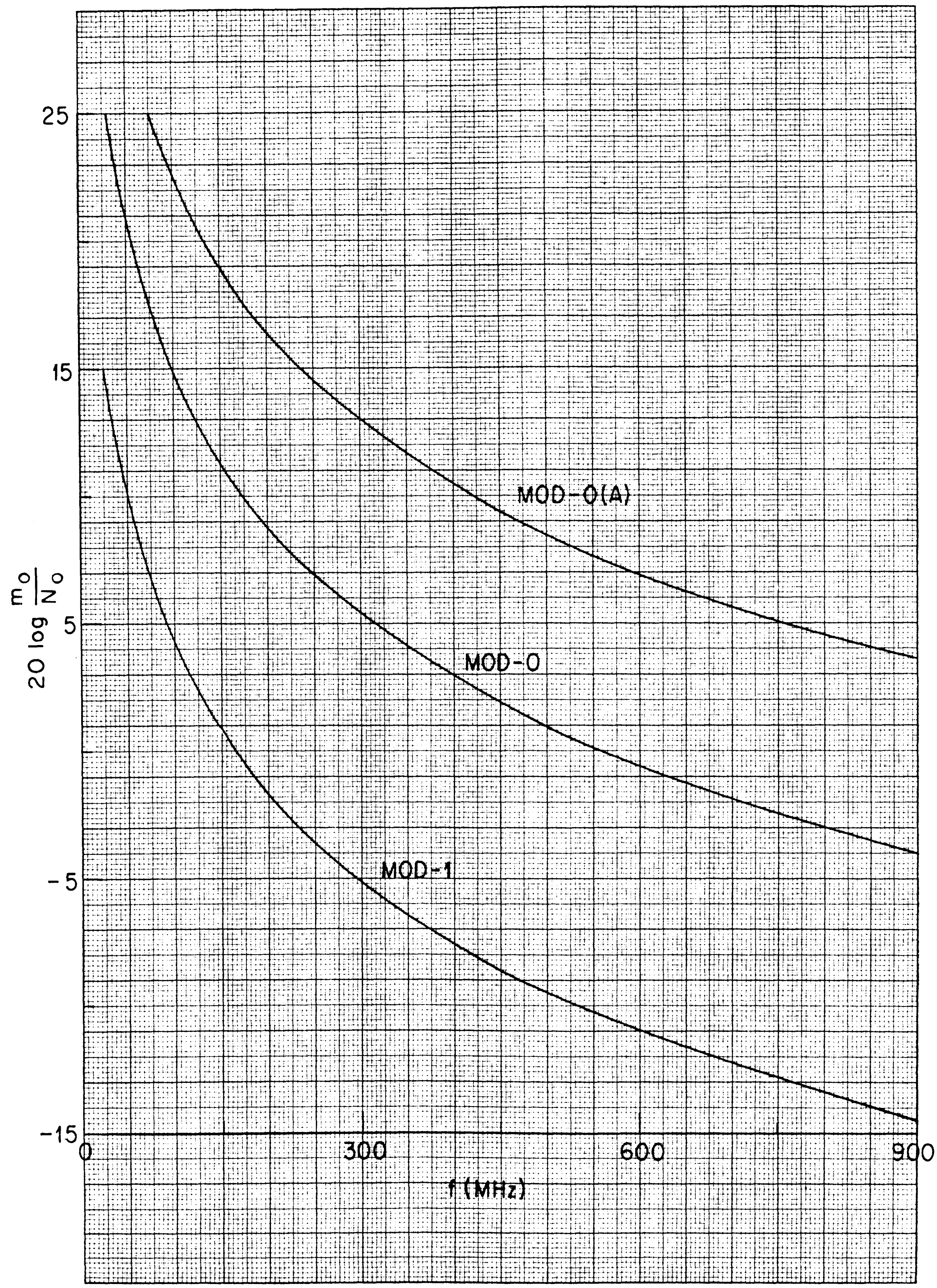



Figure 3. 20 log $m_o/N_o$ as a function of frequency for three different WTG blades. (Equation (15) with $m_o$ = 0.15).

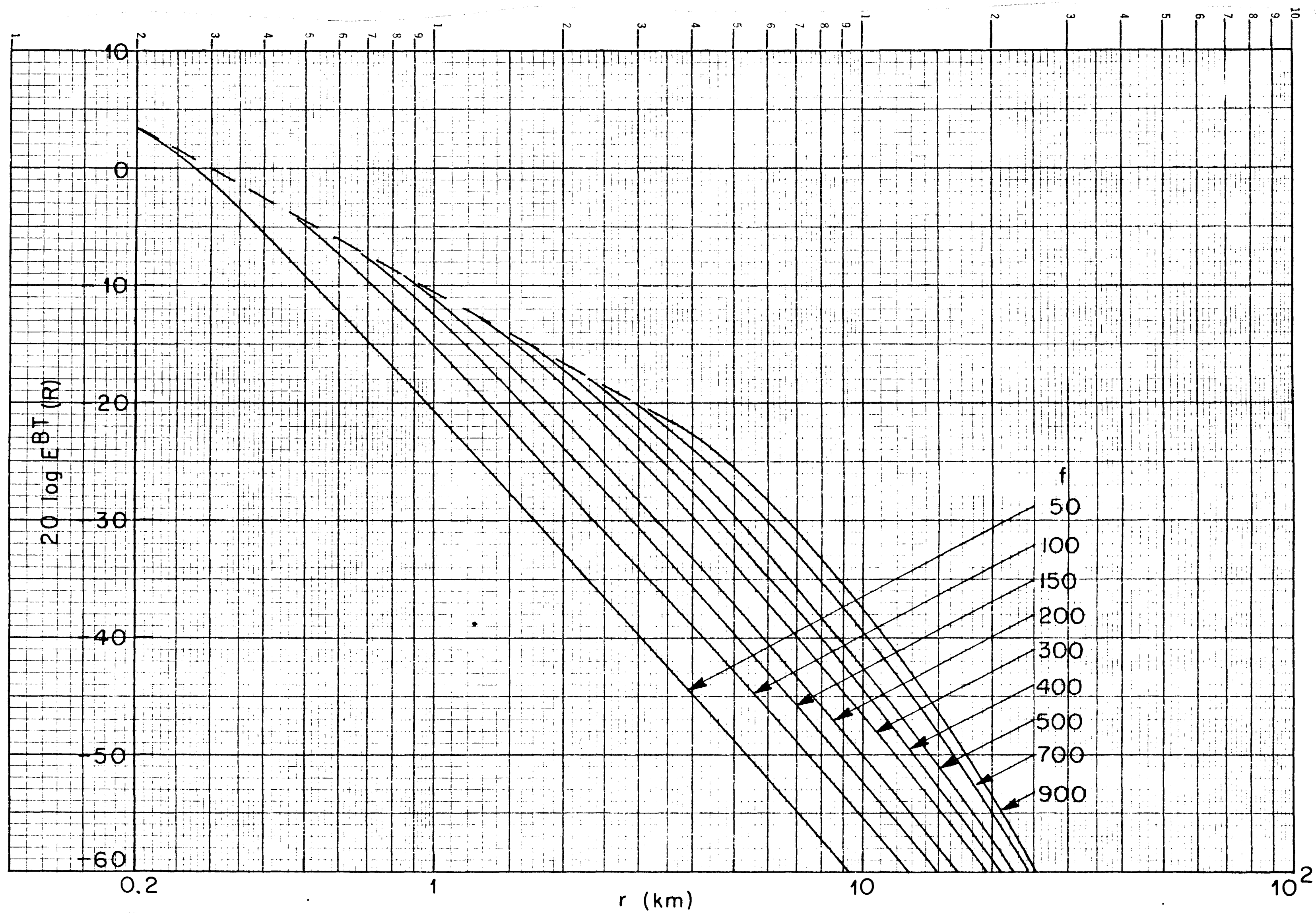



Figure 4. Field strength $\left(E^{BT}(R)\right)$ in dB above mv/m as a function of distance r from a transmitter located at the WTG blade phase center and radiating 1 Kw effective power: $h_1$ = 30 m, $h_2$ = 10 m.

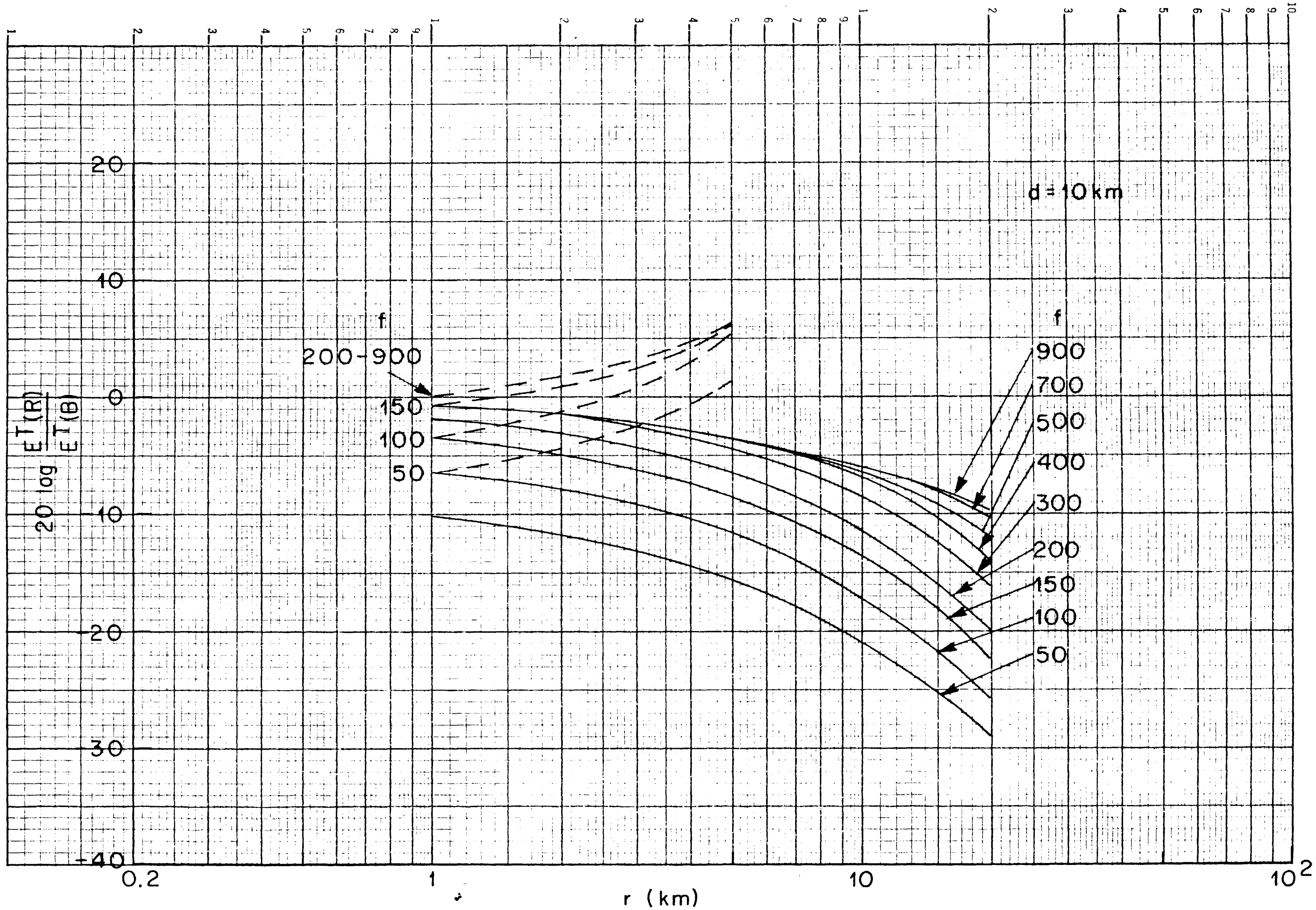



Figure 5(a). Ratio of the direct field strengths at the receiver (R) and WTG blade phase center (B) $[E^T(R)/E^T(B)]$ in dB as a function of the distance r from the WTG: ----- $\phi = 0$, ——— $\phi = \pi$.

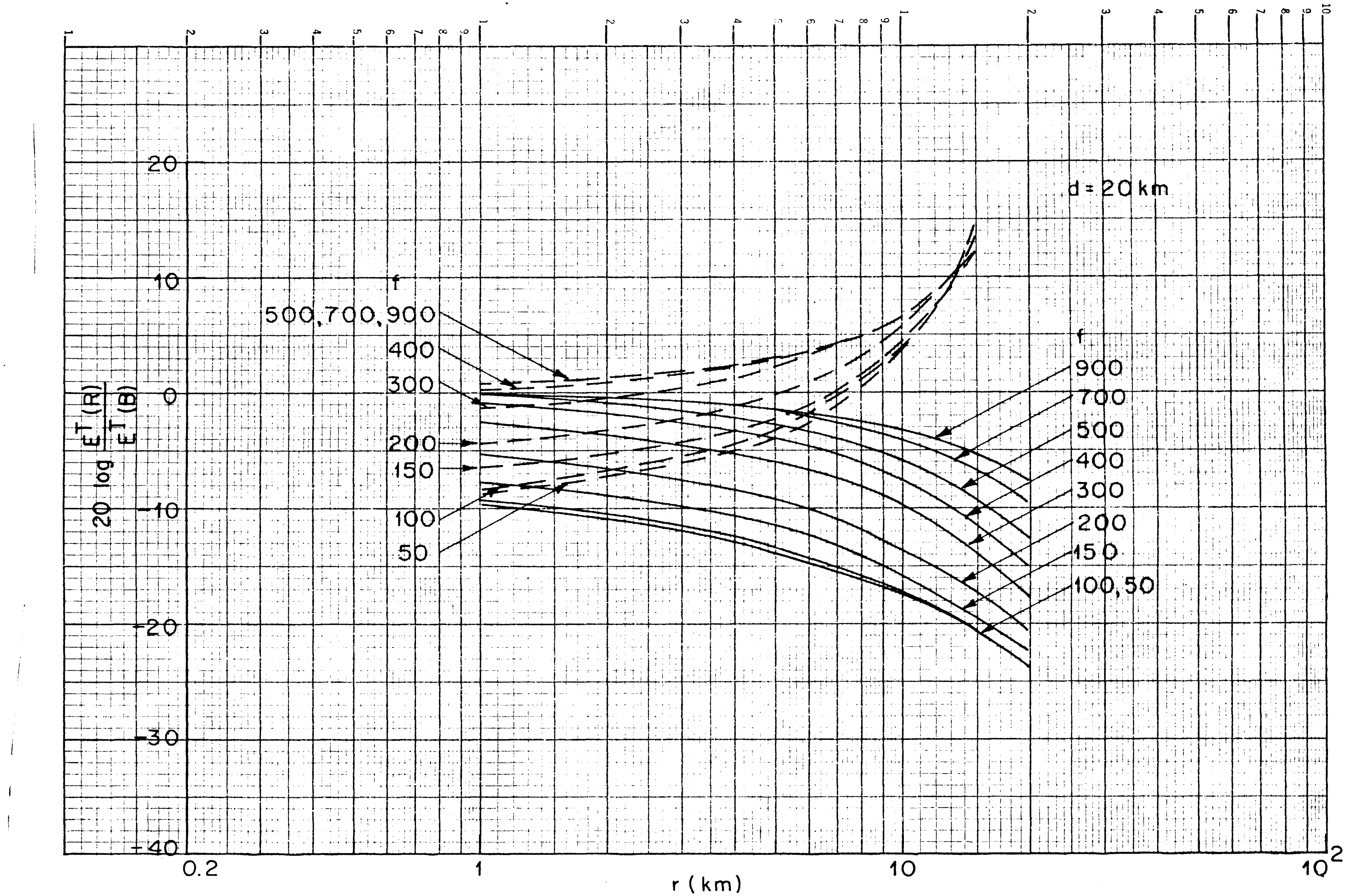



Figure 5(b). Ratio of the direct field strengths at the receiver (R) and WTG blade phase center (B) $[E^T(R)/E^T(B)]$ in dB as a function of the distance r from the WTG: ----- $\phi = 0$, ——— $\phi = \pi$.

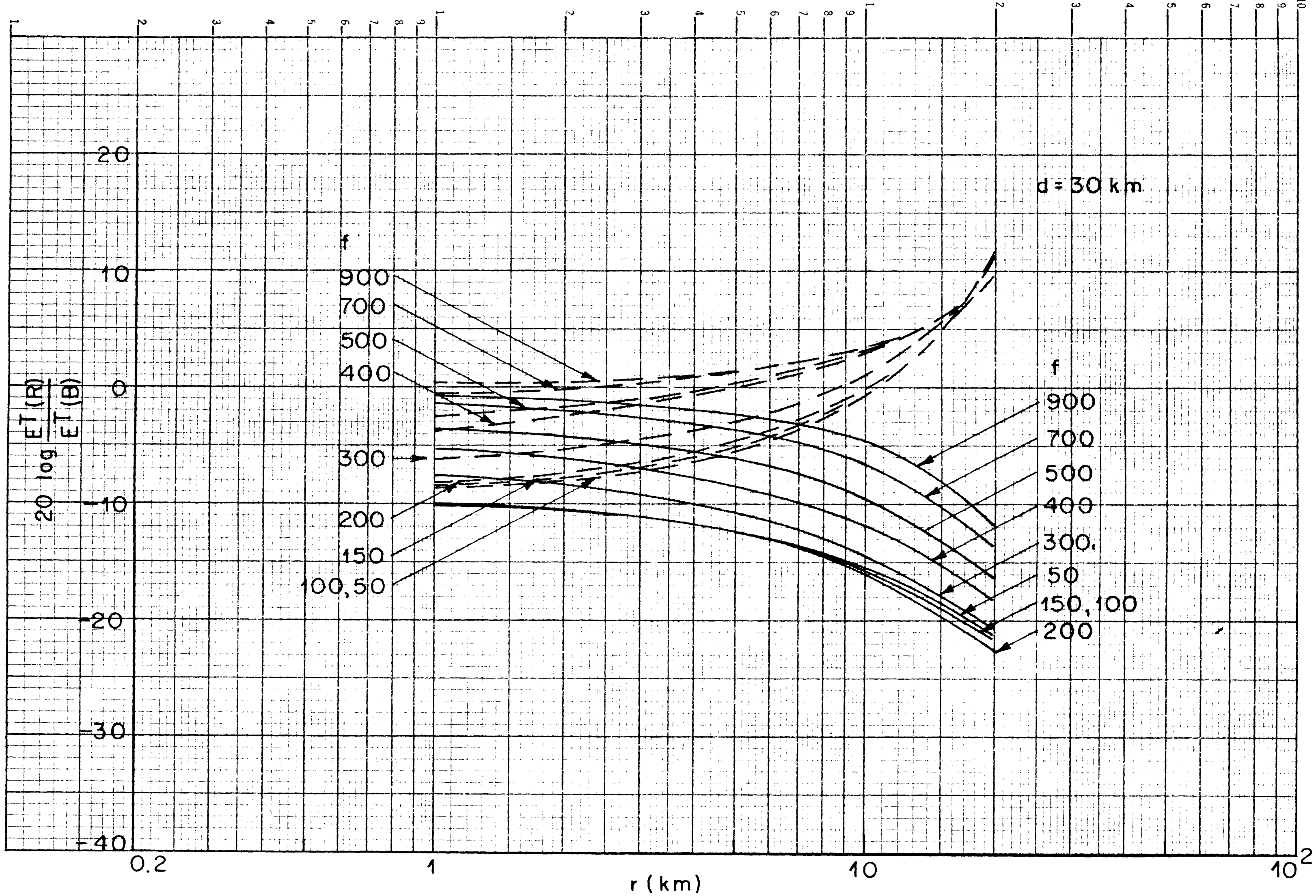



Figure 5(c). Ratio of the direct field strengths at the receiver (R) and WTG blade phase center (B) $[E^T(R)/E^T(B)]$ in dB as a function of the distance r from the WTG: ----- $\phi = 0$, ——— $\phi = \pi$.

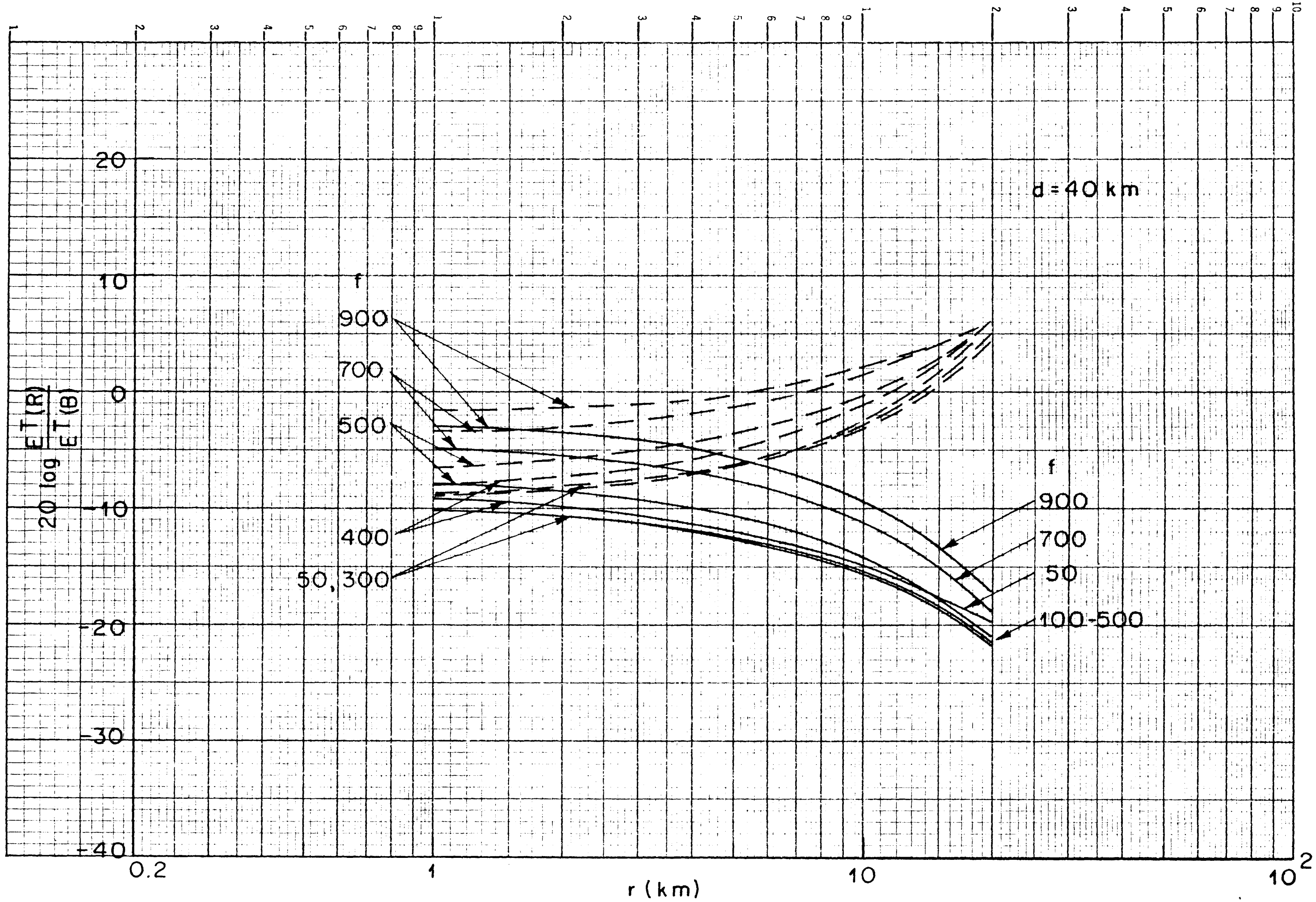



Figure 5(d). Ratio of the direct field strengths at the receiver (R) and WTG blade phase center (B) $[E^T(R)/E^T(B)]$ in dB as a function of the distance r from the WTG: ----- $\phi = 0$, —— $\phi = \pi$.

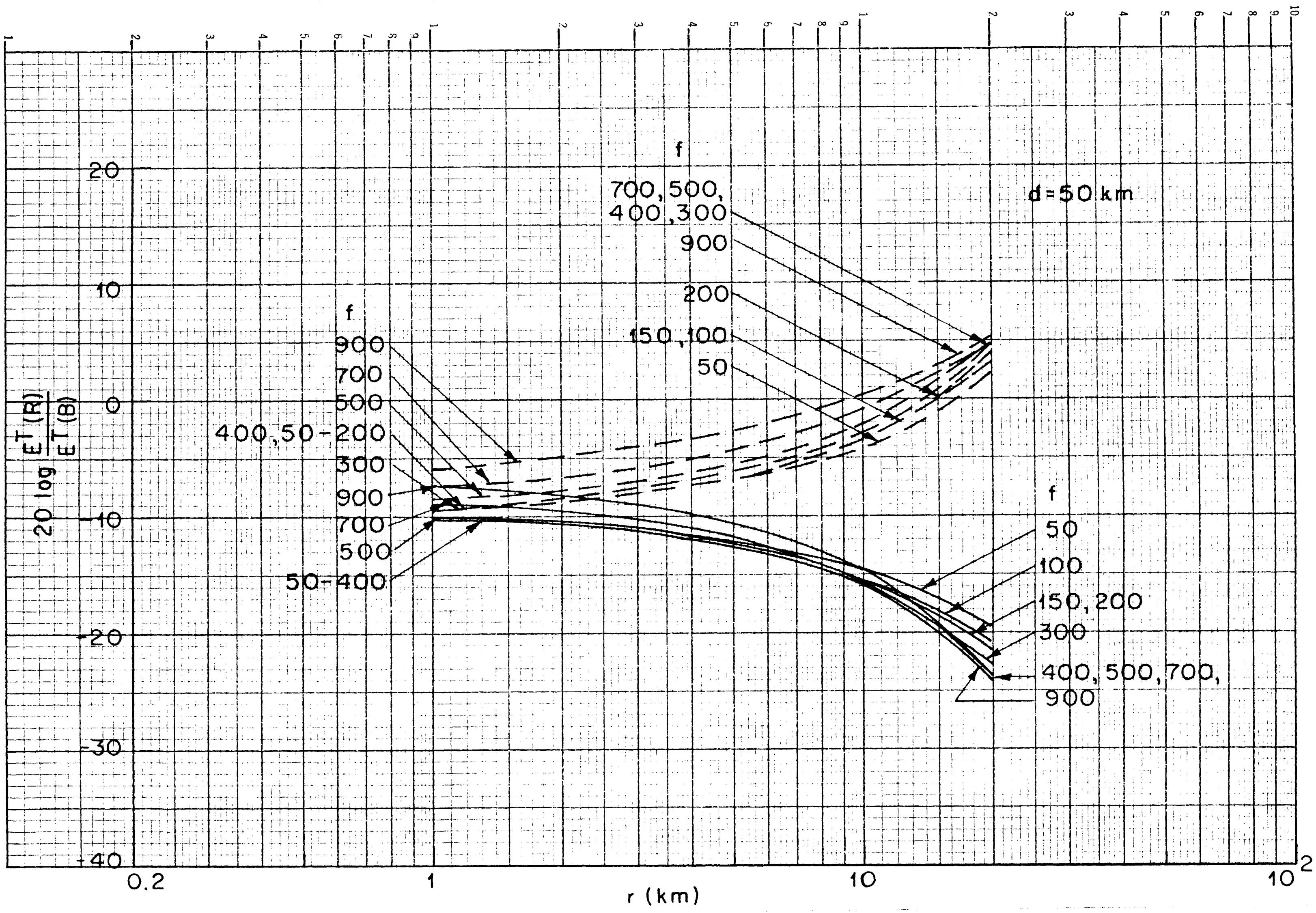



Figure 5(e).. Ratio of the direct field strengths at the receiver (R) and WTG blade phase center (B) $[E^T(R)/E^T(B)]$ in dB as a function of the distance r from the WTG: ----- $\phi = 0$, ——— $\phi = \pi$.

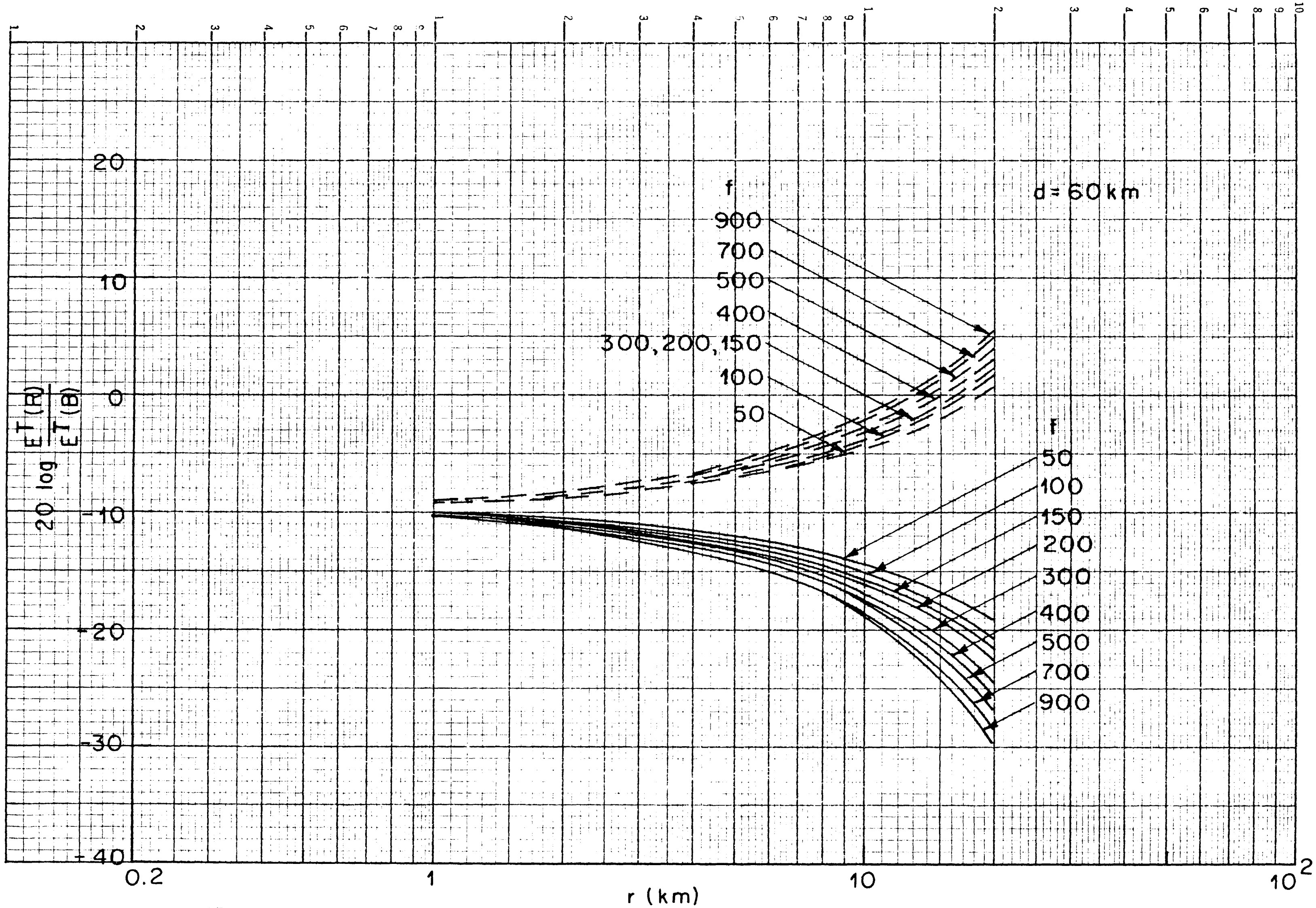



Figure 5(f): Ratio of the direct field strengths at the receiver (R) and WTG blade phase center (B) $[E^T(R)/E^T(B)]$ in dB as a function of the distance r from the WTG: ----- $\phi = 0$, ——— $\phi = \pi$.

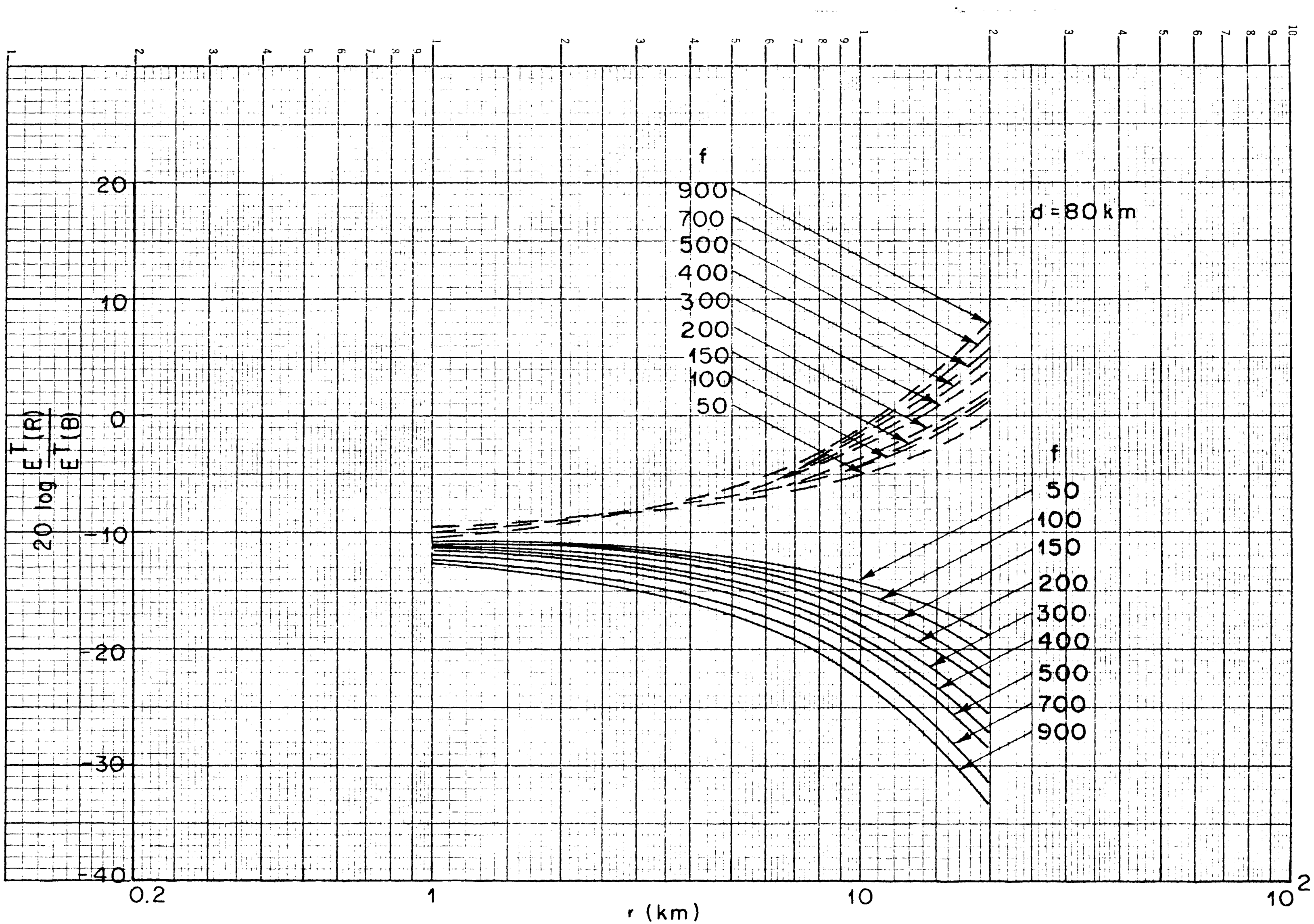



Figure 5(g). Ratio of the direct field strengths at the receiver (R) and WTG blade phase center (B) $[E^T(R)/E^T(B)]$ in dB as a function of the distance r from the WTG: ----- $\phi = 0$, ——— $\phi = \pi$.

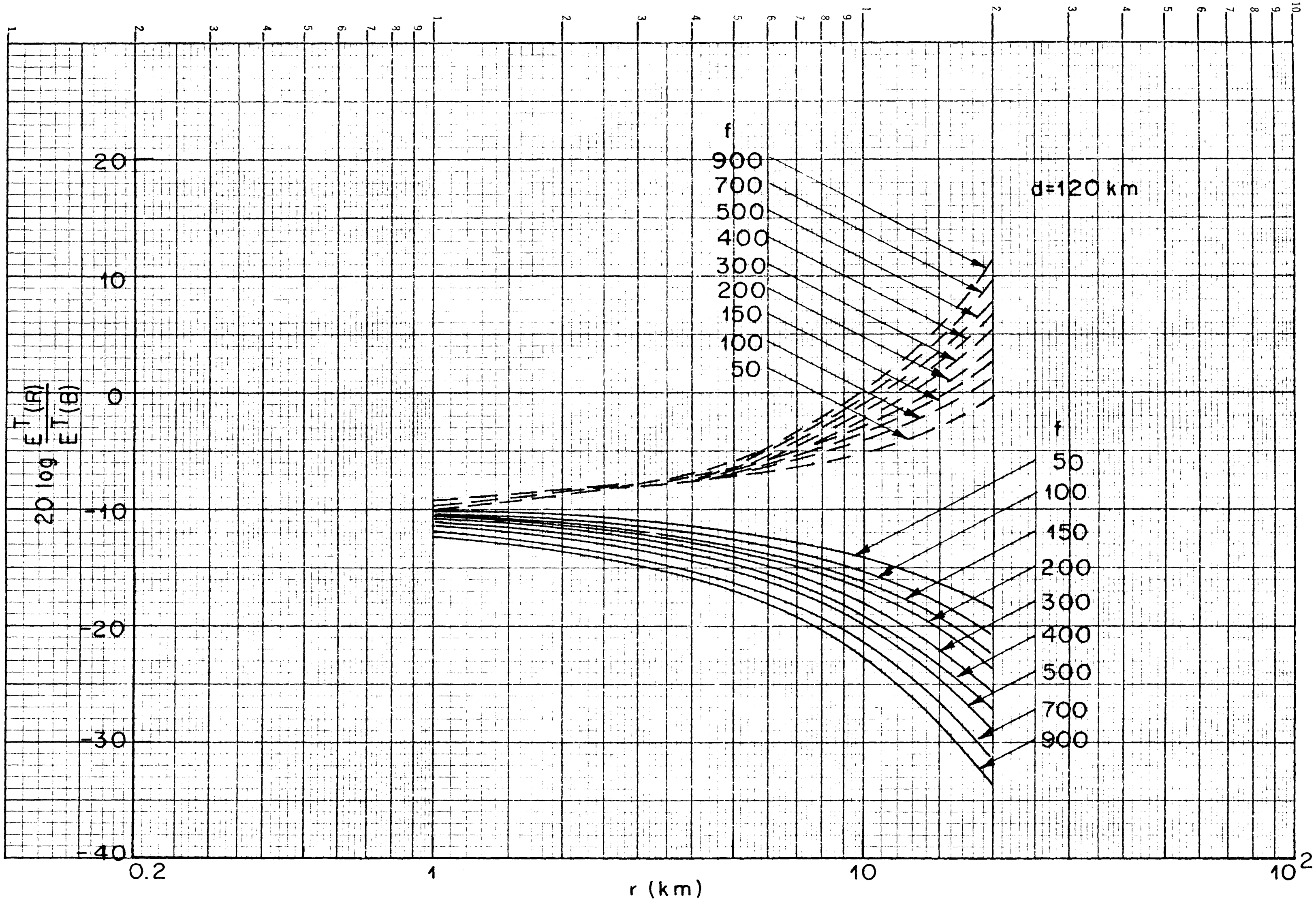



Figure 5(h). Ratio of the direct field strengths at the receiver (R) and WTG blade phase center (B) $[E^T(R)/E^T(B)]$ in dB as a function of the distance r from the WTG: ----- $\phi = 0$, ——— $\phi = \pi$.

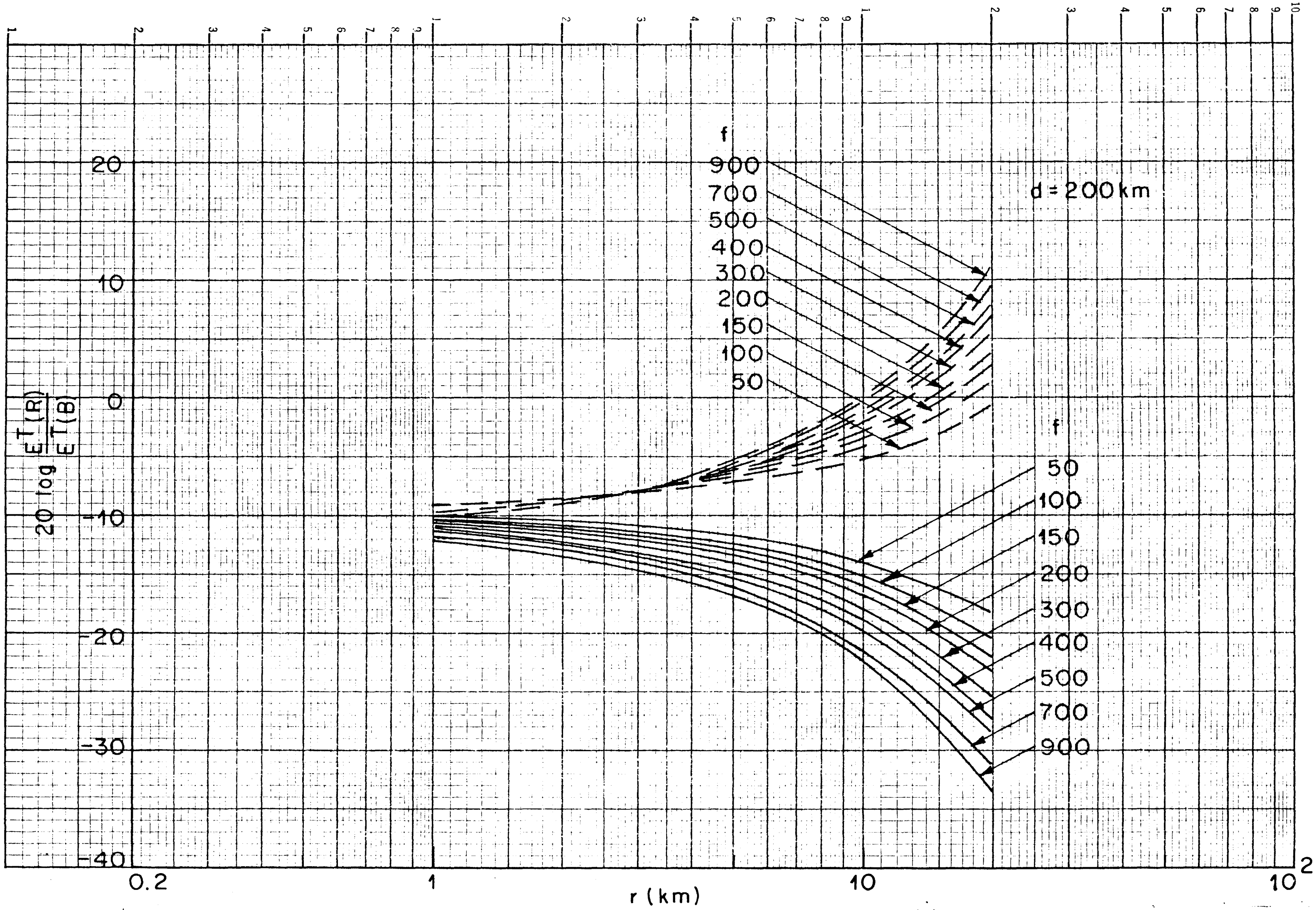



Figure 5(i). Ratio of the direct field strengths at the receiver (R) and WTG blade phase center (B) $[E^T(R)/E^T(B)]$ in dB as a function of the distance r from the WTG: ----- $\phi = 0$, ——— $\phi = \pi$.

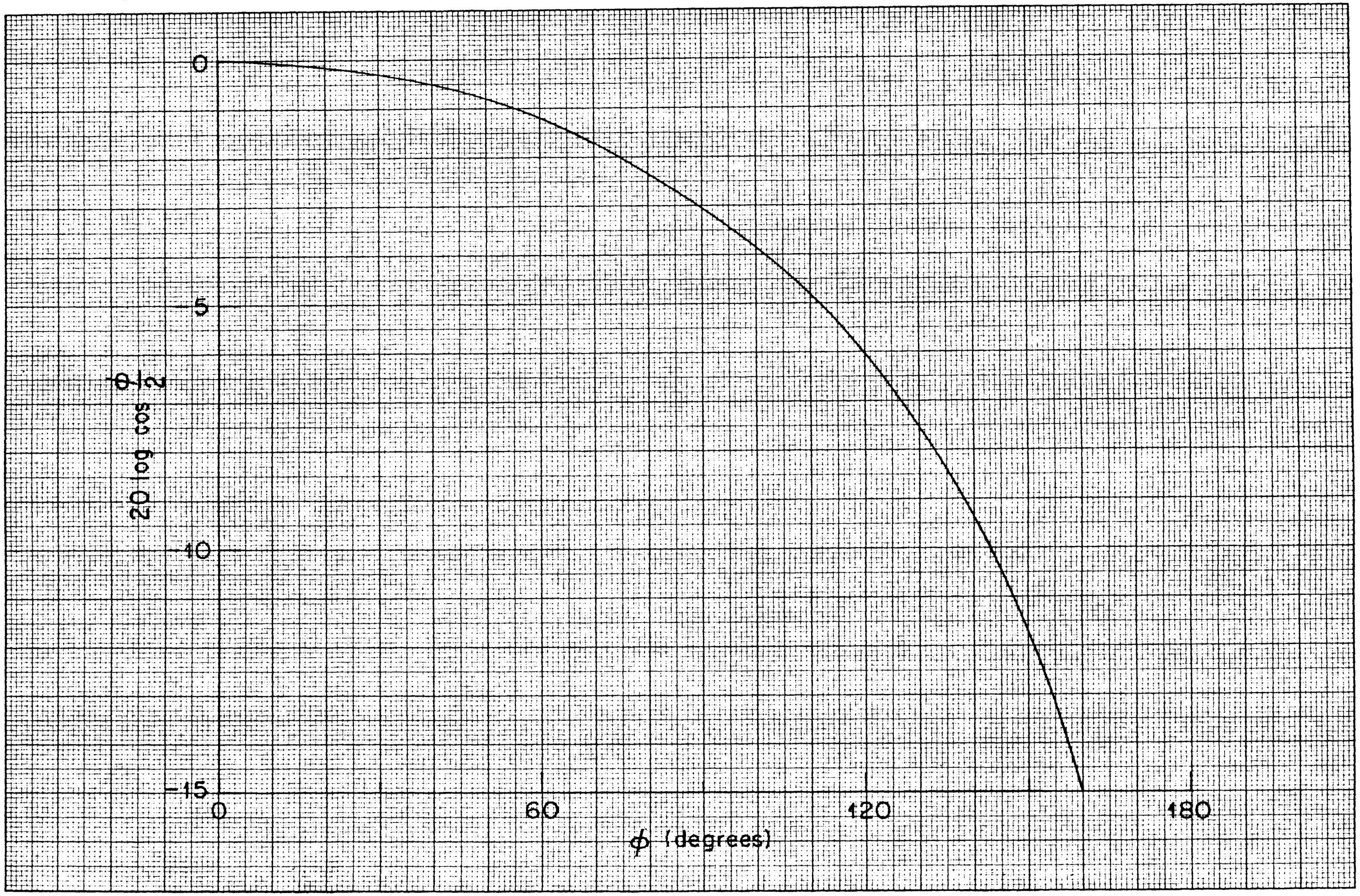



Figure 6. Correction factor 20 log cos $\phi/2$ as a function of $\phi$.

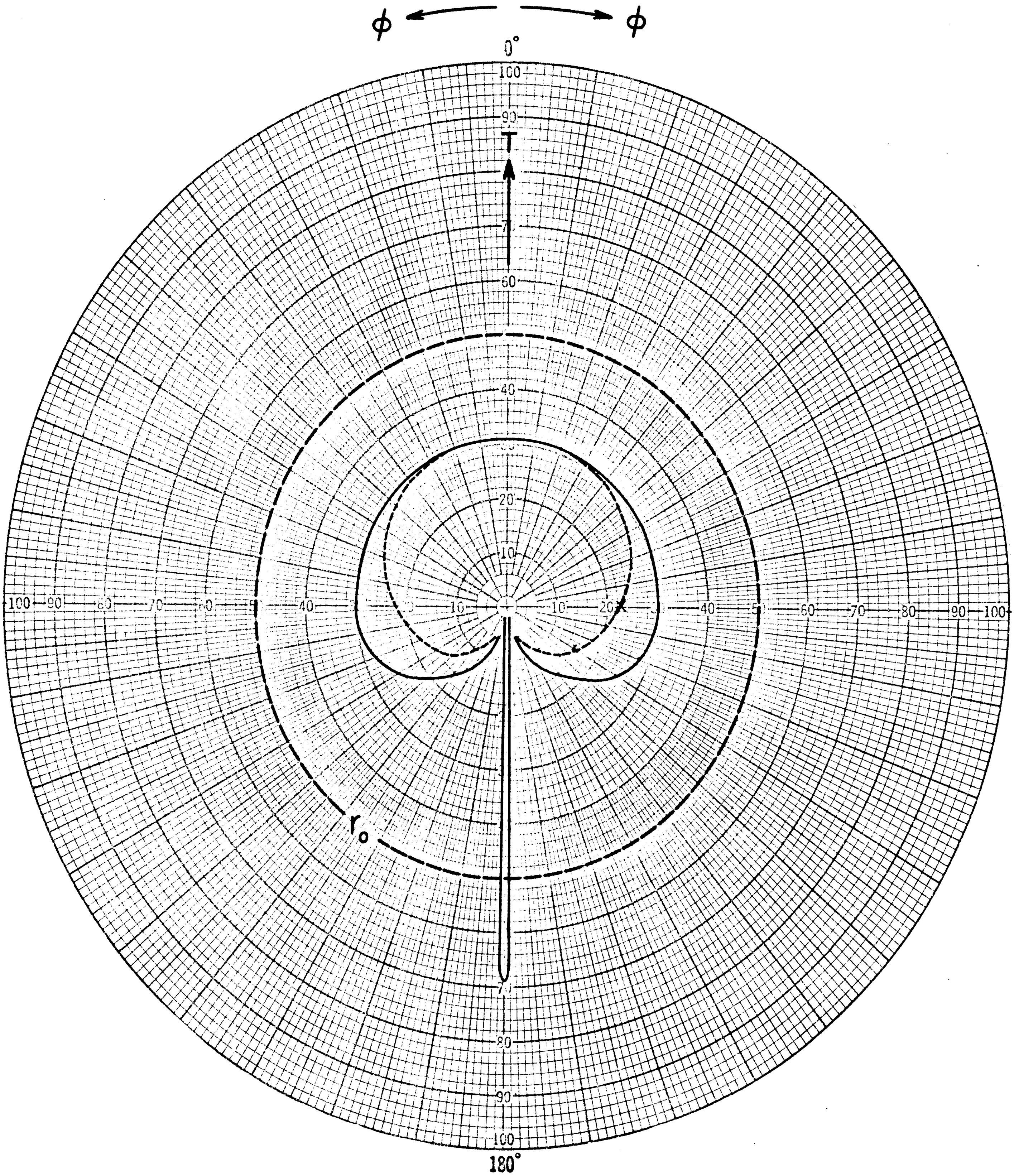
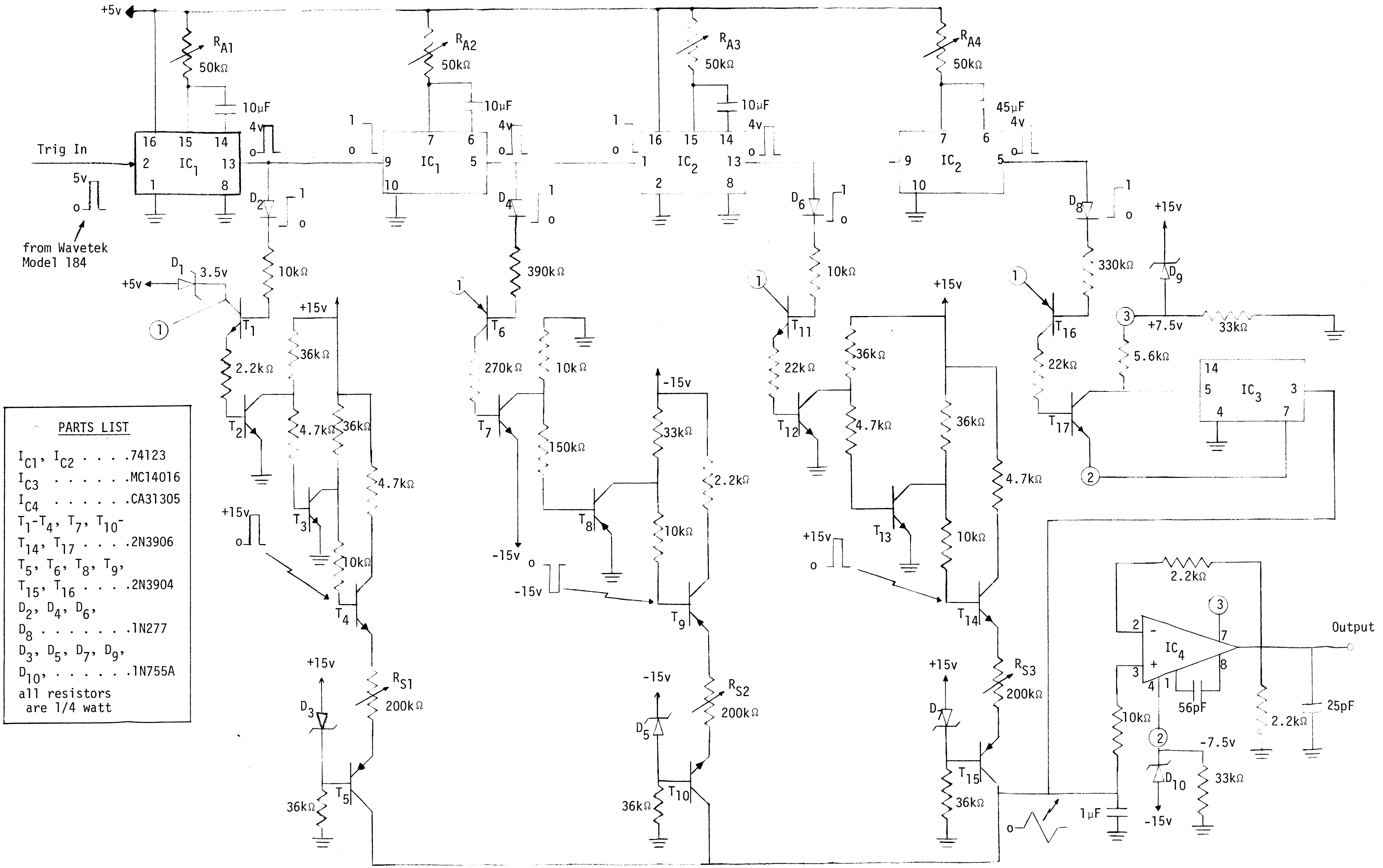



Figure 7. Interference zone of a WTG with MOD-1 blades for TV Channel 52, d = 120 Km. ———— computed by graphical method, – – – – – equivalent circular zone, ------ approximate backward zone calculated using $r(\phi) = r_1 \cos \phi/2$.




PARTS LIST

$I_{C1}$, $I_{C2}$ . . . . .74123
$I_{C3}$ . . . . . . .MC14016
$I_{C4}$ . . . . . . .CA31305
$T_1$-$T_4$, $T_7$, $T_{10}$-
$T_{14}$, $T_{17}$ . . . . .2N3906
$T_5$, $T_6$, $T_8$, $T_9$,
$T_{15}$, $T_{16}$ . . . . .2N3904
$D_2$, $D_4$, $D_6$,
$D_8$ . . . . . . . . .1N277
$D_3$, $D_5$, $D_7$, $D_9$,
$D_{10}$, . . . . . . .1N755A
all resistors
are 1/4 watt