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WIND TURBINE GENERATOR SITING HANDBOOK

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Thomas B.A. Senior and Dipak L. Sengupta

Radiation Laboratory

Department of Electrical and Computer Engineering

The University of Michigan

Ann Arbor, Michigan 48109

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ABSTRACT

The rotating blades of a horizontal axis wind turbine can distort the video portion of a television signal and thereby interfere with TV reception in the vicinity of the machine. The nature of this interference is described and methods are presented for calculating the zone within which the interference may be severe. Specific results are given for the MOD-OA, MOD-1 and MOD-2 machines as functions of the TV frequency.

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LARGE WIND TURBINE SITING HANDBOOK

1. INTRODUCTION

The purpose of this Handbook is to show how to predict the region where a large horizontal axis wind turbine (WT) can significantly affect the reception of television (TV) signals. Such information can assist in the selection of a site for a WT facility and in the analysis of the interference under a variety of circumstances.

The Handbook is a revision of one previously published [1] and differs from it in several particulars. As a result of data that has become available since that time it is apparent that a change in height at which the WT reflects TV signals can have just as much effect as a change in the blade area responsible for the reflection. Since the tower height used throughout [1] was 30 m, the curves given there are applicable only to a MOD-OA (or similar) machine. In addition, on-site and laboratory measurements of WT-produced interference have shown that the modulation threshold used to specify the interference zone increases with decreasing time delay of the secondary (scattered) signal relative to the primary. This not only reduces the interference zone radius in the forward scattering region but also permits some simplification in the method used to calculate the entire zone. Three numbers now suffice and these are tabulated as functions of the frequency and distance to the TV transmitter for MOD-OA, MOD-1 and MOD-2 machines. For these same machines with blades other than metallic, information is provided to enable the corresponding numbers to be obtained.

References [2-4] contain a detailed description of the theoretical and experimental investigations that have been performed, and the reader may wish to consult these. To avoid needless repetition we include here only those portions of [1] which are necessary to understand the nature of the TV interference and the method used for its prediction. This interference is intimately connected with the characteristics of radio wave propagation over the earth and in the presence of the WT. 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 [2] that the rotating blades of a horizontal axis WT can interfere with TV reception by producing video distortion. At a given distance from a WT 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 well 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 WT 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, causing the pricture to roll over ('flip') or even 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. As the angle ϕ (see Figure 1) between WT-transmitter and WT-receiver directions increases, the separation of the ghost decreases, and a somewhat greater interference is now required to produce the same amount of video distortion. In the forward scattering region when the WT is almost in line between the transmitter and the receiver, there is virtually no difference in the times of arrival of the primary and secondary signals. The ghost is then superimposed on the undistorted picture and the video interference appears as an intensity (brightness) fluctuation of the picture in synchronism with the blade rotation. In all cases, 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 WT.

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 measurements [2], field tests [2,3], and controlled measurements using a small scale model [4], it has been established for all TV channels as 0.15 for $\phi \simeq 0$ increasing to 0.35 for $\phi \simeq 180°$ as shown in Figure 2. The threshold is independent of the signal strength at the receiver and, for a given WT, determines the maximum distance from the WT at which the intereference can still be objectionable.

On the assumption that the WT 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 roughly a cardioid centered at the WT 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 may provide the maximum distance from the WT 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. The shapes of the zones are only weakly dependent on the TV channel number, but their size increases markedly with increasing number.

4. THEORETICAL CONSIDERATIONS

The calculation of the interference zones of a WT is based on the theoretical expressions for the fields derived in [2] and differs somewhat from the procedure used in [1].

We consider a TV transmitter (T) at a height h_1 (in m) above the earth radiating a horizontally polarized signal with effective power P (in kW). The signal impinges on a WT whose tower height is h_3 (in m) located a distance d (in km) from the transmitter, and is also picked up by a receiving antenna (R) at a height h_2 (in m) above the earth and distance r (in km) from the WT. The receiving antenna is assumed omni-directional and in the absence of the WT the direct field at R would constitute the only signal. The rotating blade(s) of the WT scatter some of the energy incident upon them and are the source of a secondary signal which is also picked up by the receiving antenna. The ratio of the secondary and primary signals at R is the amplitude modulation index and, hence, a measure of the interference produced by the WT.

The above concepts can be expressed in mathematical form as follows. The amplitude modulation index of the total field at R is

$$m = E^B(R)/E^T(R) \qquad (1)$$

where $E^T(R)$ is the amplitude of the primary field at R and $E^B(R)$ is the amplitude of the secondary field which reaches the receiver after reflection off a rotating blade (B) of the WT. The latter field is itself the product of the direct field of amplitude $E^T(B)$ illuminating the WT and the field $E^{BT}(R)$ 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

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

In practice, the height h_3 at which the blade scattering occurs is usually different from the height h_2 of the receiving antenna, and the ratio $E^T(B)/E^T(R)$ will then differ from unity for this reason as well as because of the distance r of the receiving antenna from the WT. It is convenient to separate these two effects by writing

$$E^T(B) = E^T(B') \frac{E^T(B)}{E^T(B')} \qquad (4)$$

where B' is an 'equivalent' blade located at the WT, but at height h_2 equal to that of the receiving antenna. On inserting this into (4), we have

$$m = N \frac{E^T(B)}{E^T(B')} \frac{E^T(B')}{E^T(R)} E^{BT}(R) \quad . \qquad (5)$$

The parameter N is determined by the scattering characteristics of the blades. Laboratory and full scale tests and analyses indicate [2,3] that the blade scattering is predominantly in the specular (mirror reflection) and forward (blocking) directions, and is usually directed towards the receiving antenna when the blade is horizontal. We can therefore take the height h_3 of the phase (scattering) center of the blade to be the same as that of the WT tower. It is also found that for machines such as the MOD-OA and MOD-1 having two fully controllable blades, each blade contributes individually, whereas with the MOD-2 just a portion of the single blade is responsible for the largest scattered signal observed. With both types of machine, the rotation of the blades generates a periodic impulsive form of modulation. For blades of large electrical size, 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 [3].

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

$$N = N_0 n(\phi) \tag{6}$$

where

$$N_0 = \frac{A_e f}{4.5 \times 10^4 \sqrt{P}} , \tag{7}$$

$$n(\phi) = \begin{cases} \cos \frac{\phi}{2} & \text{for } 0 \leq |\phi| \lesssim \pi - \lambda/L_e \\ \text{sinc}\left(\frac{L_e}{\lambda} \sin \phi\right) & \text{for } \pi - \lambda/L_e < |\phi| \leq \pi \end{cases} , \tag{8}$$

f is the frequency (in MHz), L_e is the effective length (in m) of that portion of the blade responsible for the scattering, and

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

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

If the plane of the blade rotation is always chosen so as to direct the maximum reflected or forward scattered field to the receiver, ϕ also specifies the angle which the line RB makes with TB and, hence, the angular position of the receiver. N then achieves its maximum value N_0 when $\phi = 0$ and π, corresponding respectively to backscattering off the blades (R in line between T and B) and forward scattering (R on the extension of TB).

We now consider the factors other than N on the right-hand side of (5). The ratio $E^T(B)/E^T(B')$ is obviously independent of ϕ and r, and measures the change in primary field strength due to the differing heights of the blade (i.e., WT tower) and the receiving antenna. It is therefore a height gain factor which is rather easily computed for any f, d, h_1, h_2 and h_3. The next factor $E^T(B')/E^T(R)$ is weakly dependent on r. It is unity when r = 0, i.e., when the receiver is at the WT tower, and remains unity if the receiver is moved away from the WT along the circumference of a circle centered on the transmitter, i.e., for $\phi \simeq 90°$. For a fixed r the ratio is an increasing function of ϕ, being less than unity for $0 \leq \phi < 90°$ and greater than unity for $\phi > 90°$, but if r is small the ϕ dependence is relatively slight. Finally, there is the factor $E^{BT}(R)$. This is a rapidly decreasing function of r independent of ϕ, and is the main source of the r dependence of the right-hand side of (5).

As r increases, the right-hand side of (5) decreases, and a procedure for determining the interference zone is now apparent. For any given ϕ, r is increased until the threshold modulation index m_o (see Figure 2) is attained. The resulting r then specifies the radius of the interference zone in that direction. If the value of r so obtained is fairly small, e.g. $\lesssim$ 1 km, most of the ϕ dependence is provided by the factor N, and the slight dependence that $E^T(B')/E^T(R)$ provides is, in part, cancelled by the variation of the threshold modulation index m_o. In this case the zone has the shape indicated by $n(\phi)$, i.e., is a cardioid plus a forward spike, and a knowledge of r in just two directions, one in the forward part of the zone (i.e., ϕ = 180°) and one in the backward part, e.g., ϕ = 0 or 90°, is sufficient to establish the entire zone. Unfortunately, this is not true if r is larger.

5. COMPUTATIONAL PROCEDURES

A computer program is available for calculating ground wave propagation over a smooth homogeneous spherical earth. At any frequency f (in MHz) the program computes the field of a horizontally polarized transmitting antenna height h_1 (in m) above the earth as a function of the distance d (in km) to a horizontally polarized receiving antenna of height h_2 (in m). The field strength obtained is typically as shown in Figure 3 for h_1 = 300 m, h_2 = 10 m and f = 500 MHz. The distance $\bar{d}$ to the radio horizon is

$$\bar{d} = 3.57 \, (h_1^{1/2} + h_2^{1/2}) \qquad (9)$$

and the horizon is marked in Figure 3. 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 WT 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. As evident from equation (3) of [5] with P = 1, the values are such that

$$E \simeq 0.3/d \text{ mV/m} \qquad (10)$$

independent of h_1, h_2 and f, though the locations of the peaks do, of course, depend on all three parameters. From (10) it follows that throughout the interference region

$$20 \log E = -(10.46 + 20 \log d) \quad , \qquad (11)$$

and the corresponding straight line is indicated in Figure 3.

The field strength program is the basis of our method for computing the interference zones about a WT. It is assumed that the equivalent (blade) scattering area A_e and the tower height h_3 are known for the WT in question, and all calculations are carried out for a transmitting antenna of height h_1 = 300 m and a receiving antenna of height h_2 = 10 m, typical of the values encountered in practice. Since the effective radiated power P plays no role in our analysis, we henceforth set P = 1.

The following computations are performed:

(i) field strength as a function of distance r (in km) for a transmitter of height h_3 and a receiver of height $h_2 = 10$ m at 7 frequencies spanning $50 \leq f \leq 900$ MHz, from which plots of $20 \log E^{BT}(R)$ vs r are constructed;

(ii) field strength of a transmitter of height $h_1 = 300$ m at a receiver of height h_3 a distance d = 20(20)100 km away at the same 7 frequencies;

(iii) field strength of a transmitter of height $h_1 = 300$ m at a receiver of height $h_2 = 10$ m a distance $d \pm r$ away for the same values of d and the same frequencies as above, with incremented values of r up to (say) 15 km.

In all cases the actual field strengths in the interference region are replaced by those deduced from (11).

The second set of data in conjunction with the third for r = 0 gives $E^T(B)/E^T(B')$ at 7 frequencies and 5 WT-to-transmitter distances d. The ratio is just the height gain factor associated with the different receiver and WT tower heights. For the values of h_3 of concern to us it is found that if $d \geq 100$ km the ratio is virtually independent of d and can, in fact, be obtained from an analytical expression for the height gain factor appropriate to the deep shadow region [6]. When normalized to the values for r = 0, the third set of data then yields plots of $20 \log E^T(R)/E^T(B')$ vs r, representing the dB attenuation as a function of the distance r of the receiver from the WT. For $d > 100$ km the attenuation is also independent of d to a first approximation and can be determined analytically [6,7].

A graphical method for calculating the interference zone about a WT is as follows. From (5)

$$20 \log E^{BT}(R) = 20 \log \frac{E^T(R)}{E^T(B')} + y \qquad (12)$$

where

$$y = y_1 + y_2 \qquad (13)$$

with

$$y_1 = 20 \log \frac{m_o(0)}{N_o} \frac{E^T(B')}{E^T(B)} \tag{14}$$

$$y_2 = 20 \log \frac{m_o(\phi)}{m_o(0)n(\phi)} \quad . \tag{15}$$

Knowing A_e for the WT blade, N_o can be computed (see 7 with P = 1) at each of the chosen frequencies. From (ii) and (iii) above with $m_o(0) = 0.15$ (see Figure 2), a table is then compiled showing y_1 for all combinations of the 5 ranges and seven frequencies. Also, from Figure 2 and the equation (8) for $n(\phi)$, y_2 can be computed for any ϕ, $0 \leq \phi \leq 180°$. The results are independent of d and (for all practical purposes) f and the particular WT, and are plotted in Figure 4.

To compute the interference zone of the WT for some specific TV transmission, the gist of the method is as follows. Knowing the actual frequency (see Table 1 on pp.17 and 18 to convert TV Channel number into frequency) and the WT-transmitter distance, we use the data for the closest frequency f (in MHz) and distance d (in km). By appropriately overlaying graphs of 20 log $E^{BT}(R)$ and 20 log $E^T(R)/E^T(B')$ versus r, intercepts of corresponding curves are found, and these give the zone radius $r(\phi)$ for any desired azimuthal location ϕ of the receiver with respect to the WT-transmitter direction. The procedure is illustrated in the next section and if greater accuracy is needed, results can be obtained for frequencies and distances on both sides of the actual ones, and linear interpolation employed.

6. SPECIFIC COMPUTATIONS

Our main concern is with the MOD-0A, MOD-1 and MOD-2 machines whose tower heights h_3 will be taken as 30, 45 and 60 m respectively. An important parameter affecting the interference is the equivalent scattering area A_e of a blade. This is related to the projected geometrical area A_p via the scattering efficiency η such that $A_e = \eta A_p$, and the projected areas of the MOD-0A and MOD-1 blades are 18 and 62.5 m^2 respectively. From laboratory model and full scale scattering tests [3] the scattering efficiencies of these metal blades were found to be 0.67 and 0.63 respectively, implying A_e = 12 and 40 m^2 for the two machines. For a MOD-0A blade of fiberglass construction with a minimal configuration (stage #2 of [3]) of lightning arrestor strips, the corresponding scattering efficiency is 0.27, so that A_e = 5 m^2 approximately. These values of η and A_e are also applicable to the corresponding wooden blade.

In the case of the MOD-2 machine, measurements of the scattering from a small scale model blade show that the largest scattering is provided by a central section of the blade of approximate length 63 m, and the equivalent scattering area implied by this is A_e = 140 m^2. The relevant parameters for the three machines with metal blades are then as follows:

	h_3(m)	A_e(m^2)	L_e(m)
MOD-0A	30	12	15
MOD-1	45	40	25
MOD-2	60	140	63

Tables 2(a) - (c) on page 19 list y_1 (see equation 14) for these machines for f = 100, 200, 300(200)900 MHz and d = 20(20)100 km.

The following graphs are needed to compute the interference zones, and are presented in the Figures cited:

20 log $E^{BT}(R)$ vs r for the seven frequencies and the three tower heights listed above: Figures 5(a) - (c).

20 log $E^T(R)/E^T(B')$ vs r for the seven frequencies and the five WT-transmitter distances d = 20(20)100 km: Figures 6(a) - (e). For a receiver closer to the transmitter than the WT, i.e., $0 \leq \phi < 90°$, the appropriate curves are shown as solid lines, whereas for $90° < \phi \leq 180°$ the lines are broken.

To illustrate the procedure, consider the computation of the interference zone for a MOD-1 WT on TV Channel 56 whose transmitter is

75 km away. From Table 1 the closest frequency for which curves are provided is 700 MHz, and the closest value of d is 80 km, implying Figure 6(d). From Table 2(b) the appropriate dB level y_1 is then -28.1.

1. $\phi = 0$. Since $y_2 = 0$, $y = y_1 = -28.1$. Overlay Figures 5(b) and 6(d) positioning the -28.1 level of Figure 5(b) at the 0 level of Figure 6(d). Read off the value of r at which the 700 MHz curves cross, using the solid lines in Figure 6(d). The result is r(0) = 4.6 km.
2. $\phi = 180°$. Figure 4 gives $y_2 = 7.4$. Hence, $y = y_1 + y_2 = -28.1 + 7.4 = -20.7$. Overlay Figures 5(b) and 6(d), positioning the -20.7 level of Figure 5(b) at the 0 level of Figure 6(d). Read off the value of r at which the 700 MHz curves cross, using the dashed lines in Figure 6(d). The result is r(180) = 5.5 km.
3. $\phi = 90°$. Figure 4 gives $y_2 = 5.5$. Hence, $y = y_1 + y_2 = -28.1 + 5.5 = -22.6$. Using Figure 5(b) alone, read off the value of r at which the 700 MHz curve crosses the -22.6 level. The result is r(90) = 4.0 km.

Under most circumstances the approximate shape of the interference zone is known, and the entire zone is then determined by the values of r(0), r(180) and, perhaps, r(90). However, if greater accuracy is required, $r(\phi)$ can be computed for any desired ϕ using the above-mentioned graphs. The approach is based on the fact that for $\phi \neq 0$ the distance of the receiver from the transmitter is approximately $d - r\cos\phi$ and not d-r. The manner in which this affects the computation of $r(\phi)$ for $\phi \neq 0$, 90 or 180° is illustrated by the following example.

4. $\phi = 60°$. Figure 4 gives $y_2 = 2.6$. Hence, $y = y_1 + y_2 = -28.1 + 2.6 = -25.5$. Also, $\cos\phi = 0.5$. Overlay Figures 5(b) and 6(d) such that the -25.5 level of Figure 5(b) is at the 0 level of Figure 6(d) with the r = 1 of Figure 5(b) at the $r = |\cos\phi| = 0.5$ position of Figure 6(d). Read off from Figure 5(b) the value of r at which the 700 MHz curves cross, using the solid lines (dashed if $\phi > 90°$) in Figure 6(d). The result is r(60) = 4.5 km.

Three typical interference zones are shown in Figures 7(a) - (c), all computed for the MOD-1 machine with a transmitter at a distance $d \geq 100$ km. The first two are adequately approximated by

$$\text{(A)} \qquad r(\phi) = \begin{cases} r(0) \cos \phi/2 & \text{for } 0 \leq \phi \lesssim 180(1 - \frac{\lambda}{\pi L_e}) \\ r(180) \operatorname{sinc} (\frac{L_e}{\lambda} \sin \phi) & \text{for } 180(1 - \frac{\lambda}{\pi L_e}) < \phi \leq 180° \end{cases} \tag{16}$$

and the zone then consists of a cardioid and a forward spike as suggested by the behavior of $n(\phi)$. For the third zone, however, a better approximation is

$$\text{(B)} \qquad r(\phi) = \begin{cases} r(90) & \text{for } 0 \leq \phi \leq 90° \\ r(90) \sin \phi & \text{for } 90 < \phi \lesssim 180(1 - \frac{\lambda}{\pi L_e}) \\ r(180) \operatorname{sinc} (\frac{L_e}{\lambda} \sin \phi) & \text{for } 180(1 - \frac{\lambda}{\pi L_e}) < \phi \leq 180° \end{cases} . \tag{17}$$

Both shapes are completely specified by a knowledge of r(0), r(90) and r(180), and the ratio r(90)/r(0) can serve as the basis for the choice of shape. The ratio is 0.71 for type A and 1 for type B, and in those rare cases where it substantially exceeds unity, neither approximation is good. A precise determination of the interference zone is then desirable.

The computed interference zone radii r(0), r(90) and r(180) for the MOD-0A, MOD-1 and MOD-2 machines with metal blades are shown in Table 3(a) - (c) for f = 50, 100, 200, 300(200)900 MHz with d = 20(20)100 km. Except possibly at the highest frequencies for the larger d the zones are of type A, but in the case of the MOD-2 machine there are a few instances, e.g., f = 900 MHz with $d \geq 60$ km where even the type B shape does not provide an accurate approximation.

7 CONCLUSIONS

Using results obtained from a computer program for ground wave propagation, an efficient graphical procedure has been developed for predicting the zones of TV interference about a large WT. The rough shapes of these zones are similar for all horizontal axis machines but their size increases with increasing WT height, blade area and TV channel number or frequency. The interference is therefore worst on the higher UHF channels and increases in severity with the size of the machine.

For the MOD-0A, MOD-1 and MOD-2 machines with metal blades, the interference zone radii in three directions are tabulated at seven frequencies spanning the VHF and UHF TV bands for five WT-transmitter distances, and under most circumstances these three parameters are sufficient to define the entire zone. At other frequencies and/or distances adequate accuracy can be obtained by linear interpolation of the tabulated values, but if, for any reason, it is felt desirable to compute the interference zone precisely, the graphs which are needed to do this are included herewith. The method is such that an accuracy of better than 0.2 km is achievable, particularly if a light table is used in conjunction with transparencies made from the graphs.

The data which are presented are for the standardized heights h_1 = 300 m for the transmitting antenna, h_2 = 10 m for the receiving antenna, and h_3 = 30, 45 and 60 m, corresponding to the tower heights of the MOD-0A, MOD-1 and MOD-2 machines, respectively. For heights which differ substantially from these it is necessary to generate a new set of graphs before proceeding with the interference calculations, and we comment that the difference between h_2 and h_3 has a significant effect on the level of interference observed. If, on the other hand, the blade size and/or materials alone differ from the ones discussed here, the graphs are still applicable, and it is only necessary to change the equivalent blade scattering area A_e in the expression (14) for y_1. For blades of similar shape to those on the MOD-0A and MOD-1 machines the scattering efficiency is approximately 0.65 and 0.25 for metallic and non-metallic blades, respectively, and these values can be used to deduce the equivalent area from the projected area.

As evident from the data in Table 3, a large WT can interfere with TV reception at distances of several kilometers, particularly at the higher UHF frequencies. However, this is on the assumption of an omnidirectional receiving antenna, and a directional antenna could substantially reduce the distance at which a given level of interference is observed. In computing the interference zone the effect of using a directional antenna can be taken into account as follows. Let $f(\phi')$ be the voltage polar diagram of the antenna where ϕ' is the angle (in degrees) measured from the center of the main beam with $f(0) = 1$. In the expression (λ) for y_2, divide the function $m(\phi)$ by $f(\phi')$ where ϕ' is now the angle between the directions to the transmitter and the windmill (approximately $180 - \phi$ for $d >> r$). The results of this operation are illustrated in [4] where the interference due to the MOD-OA machine on Block Island is examined. Except within the forward part of the interference zone where the antenna is forced to look directly through the WT, a voltage gain of (say) 4 can reduce the zone dimensions by a similar amount provided the antenna is correctly deployed. Obviously, if the antenna were pointed at the WT rather than the transmitter the interference would be increased.

There are two final points that should be made. All calculations have been carried out on the assumption of a smooth homogeneous earth, and the local topography could increase or decrease the level of interference. Terrain effects are particularly important in mountainous regions, and it is therefore recommended that in the final consideration of a specific site the influence of the local terrain be taken into account in arriving at a judgement. 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 small fraction of the total time.

8. REFERENCES

[1] T.B.A. Senior and D. L. Sengupta, "Wind Turbine Generator Siting and TV Reception Handbook," Technical Report on Contract No. EY-76-S-02-2846.A001, DOE, Washington, D.C., 20545, January 1978 (COO/2846-1).

[2] 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.

[3] D. L. Sengupta and T.B.A. Senior, "Electromagnetic Interference by Wind Turbine Generators," Final Report on Contract No. EY-76-S-02-2846.A002, DOE, Washington, D.C., 20545, March 1978 (TID-28828).

[4] D. L. Sengupta and T.B.A. Senior, "Wind Turbine Generated Interference to Electromagnetic Systems," Final Report on Contract EY-76-S-07-2846.A003, DOE, Washington, D.C., 20545, August 1979.

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

[6] P. A. Azriliant and N. G. Belkina, "Numerical Results of the Theory of Diffraction of Radio Waves around the Earth's Surface," Soviet Radio Press, Moscow, 1957.

[7] N. A. Logan, "Numerical Investigations of Electromagnetic Scattering and Diffraction by Convex Objects," Lockheed Missiles and Space Company Report AFCRL-66-153, 1965.

TABLE 1: 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

Table 2: dB Level y_1 (see equation 14)

(a) MOD-0A (A_e = 12 m^2)

f(MHz)	d(km)				
	20	40	60	80	≥100
50	11.7	11.5	11.5	11.3	11.5
100	6.4	5.5	5.4	5.4	5.3
200	4.0	-0.3	-1.0	-1.0	-0.9
300	3.4	-3.6	-4.5	-4.8	-4.6
500	1.3	-6.2	-8.8	-9.6	-9.5
700	-1.5	-5.9	-11.7	-12.9	-12.8
900	-3.7	-6.1	-13.7	-15.5	-15.3

(b) MOD-1 (A_e = 40 m^2)

f(MHz)	d(km)				
	20	40	60	80	≥100
50	-2.0	-2.4	-2.5	-2.7	-2.6
100	-6.2	-8.3	-8.7	-8.7	-8.8
200	-6.5	-13.8	-15.2	-15.3	-15.3
300	-7.1	-16.7	-18.6	-19.2	-19.2
500	-9.2	-16.2	-22.8	-24.4	-24.4
700	-11.9	-16.4	-25.2	-28.1	-28.1
900	-14.1	-16.6	-26.5	-31.0	-30.9

(c) MOD-2 (A_e = 140 m^2)

f(MHz)	d(km)				
	20	40	60	80	≥100
50	-14.9	-15.8	-16.0	-16.2	-16.1
100	-17.3	-21.5	-22.1	-22.3	-22.4
200	-17.4	-26.5	-28.7	-29.1	-29.1
300	-18.0	-28.2	-32.0	-33.2	-33.2
500	-20.0	-27.5	-35.7	-38.7	-38.9
700	-22.8	-27.2	-37.1	-42.6	-42.8
900	-25.0	-27.4	-36.7	-45.7	-45.9

Table 3: Computed Interference Zone Radii

(a) MOD-0A

f(MHz)	d(km)														
	20			40			60			80			$\geq$100		
50	0.08	0.04	0.03	0.08	0.04	0.03	0.08	0.04	0.03	0.08	0.04	0.03	0.08	0.04	0.03
100	0.14	0.08	0.06	0.16	0.08	0.07	0.16	0.09	0.07	0.16	0.09	0.07	0.16	0.09	0.07
200	0.18	0.10	0.08	0.29	0.17	0.13	0.36	0.17	0.13	0.33	0.17	0.14	0.33	0.17	0.14
300	0.20	0.11	0.09	0.43	0.24	0.20	0.50	0.26	0.21	0.50	0.26	0.23	0.49	0.26	0.23
500	0.25	0.14	0.11	0.58	0.32	0.26	0.79	0.43	0.36	0.84	0.47	0.39	0.83	0.47	0.39
700	0.34	0.19	0.15	0.56	0.31	0.25	1.1	0.61	0.52	1.1	0.70	0.59	1.1	0.69	0.59
900	0.35	0.24	0.20	0.59	0.32	0.26	1.3	0.75	0.66	1.5	0.93	0.82	1.4	0.92	0.82

In each box the three entries are, from left to right, r(0), r(90), r(180).

(b) MOD-1

f(MHz)	d(km)														
	20			40			60			80			$\geq$100		
50	0.36	0.20	0.16	0.36	0.21	0.17	0.37	0.21	0.17	0.37	0.21	0.18	0.37	0.21	0.18
100	0.60	0.32	0.26	0.70	0.41	0.34	0.72	0.44	0.35	0.71	0.44	0.36	0.71	0.44	0.36
200	0.61	0.34	0.28	1.3	0.78	0.66	1.6	0.91	0.76	1.5	0.91	0.76	1.5	0.91	0.76
300	0.66	0.36	0.29	1.8	1.1	0.93	2.2	1.4	1.2	2.3	1.4	1.3	2.3	1.4	1.3
500	0.84	0.45	0.38	1.8	1.1	0.93	3.2	2.2	2.1	3.4	2.6	2.7	3.4	2.6	2.7
700	1.1	0.63	0.55	1.8	1.1	0.93	4.0	2.9	2.7	4.6	4.0	5.5	5.4	5.2	7.7
900	1.5	0.80	0.68	1.9	1.1	0.93	4.2	3.3	4.2	4.4	4.0	5.8	5.2	5.4	11

In each box the three entries are, from left to right, r(0), r(90), r(180).

(c) MOD-2

f(MHz)	d(km)														
	20			40			60			80			$\geq$100		
50	0.96	0.70	0.64	1.0	0.74	0.66	1.0	0.75	0.68	1.0	0.76	0.68	1.0	0.76	0.68
100	1.5	1.1	1.0	1.9	1.4	1.2	2.0	1.5	1.4	2.0	1.5	1.4	2.0	1.5	1.4
200	1.8	1.2	1.1	3.3	2.6	2.6	3.8	3.1	3.1	3.8	3.2	3.2	3.8	3.2	3.2
300	2.0	1.3	1.2	4.2	3.5	3.6	5.2	4.6	5.0	5.4	4.9	5.6	5.4	4.9	5.8
500	2.6	1.6	1.4	4.7	3.7	4.0	7.4	7.2	10	7.8	8.6	16	7.8	8.5	18
700	3.4	2.2	1.8	5.0	3.6	4.1	8.5	8.9	18	9.7	12	*	9.7	12	*
900	4.2	2.8	2.5	5.2	3.7	4.3	8.7	9.6	*	11	15	*	11	16	*

In each box the three entries are, from left to right, r(0), r(90), r(180).

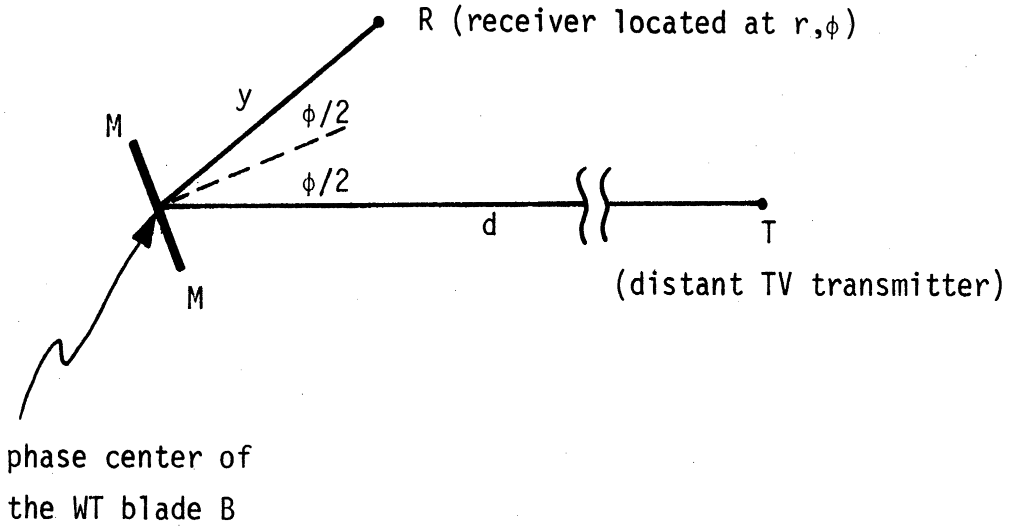

Figure 1. Geometry of the WT blade scattering.

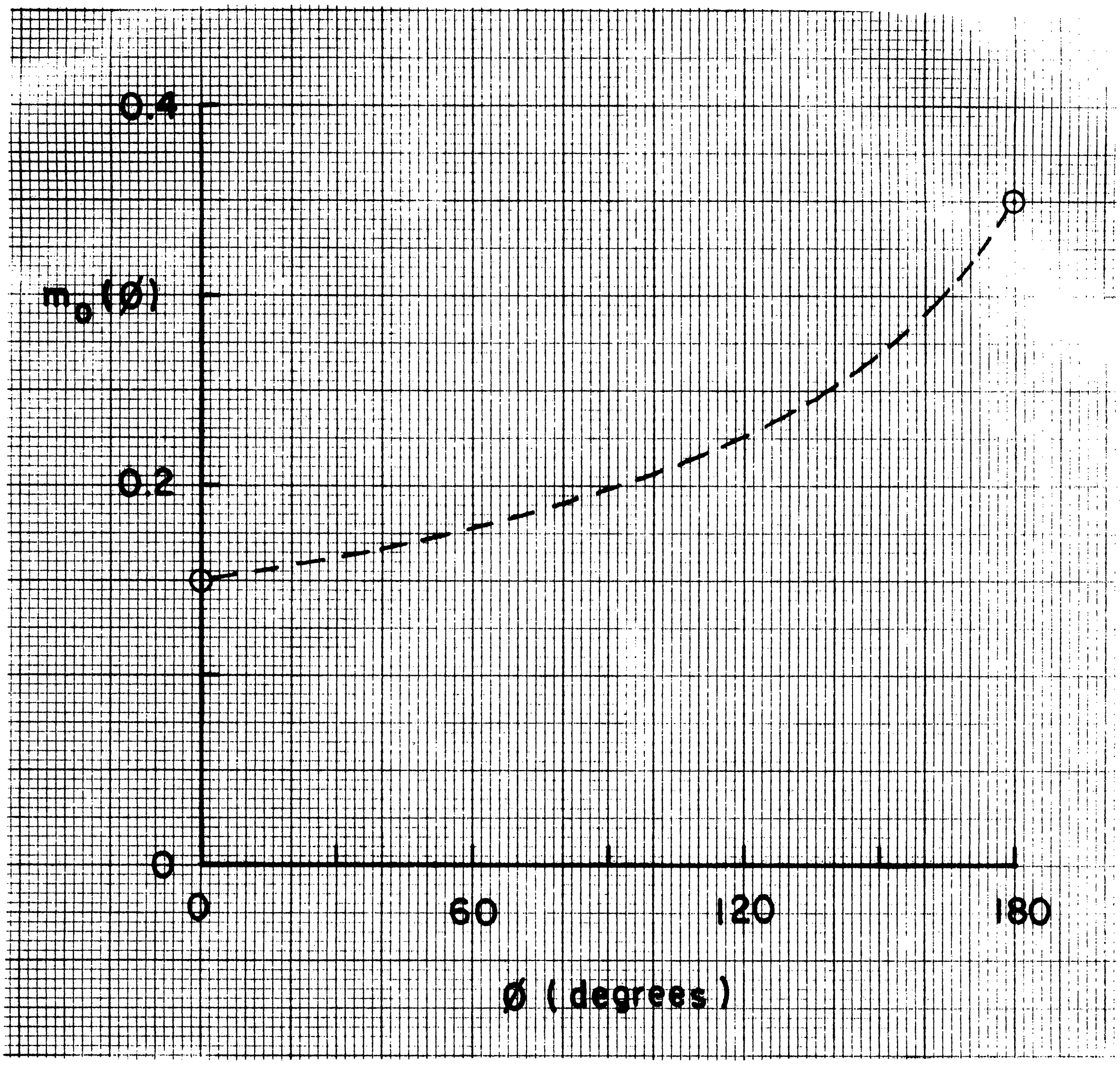

Figure 2. Chosen threshold modulation index $m_o(\phi)$ as a function of the angular position of the receiver with respect to the WT-transmitter direction.

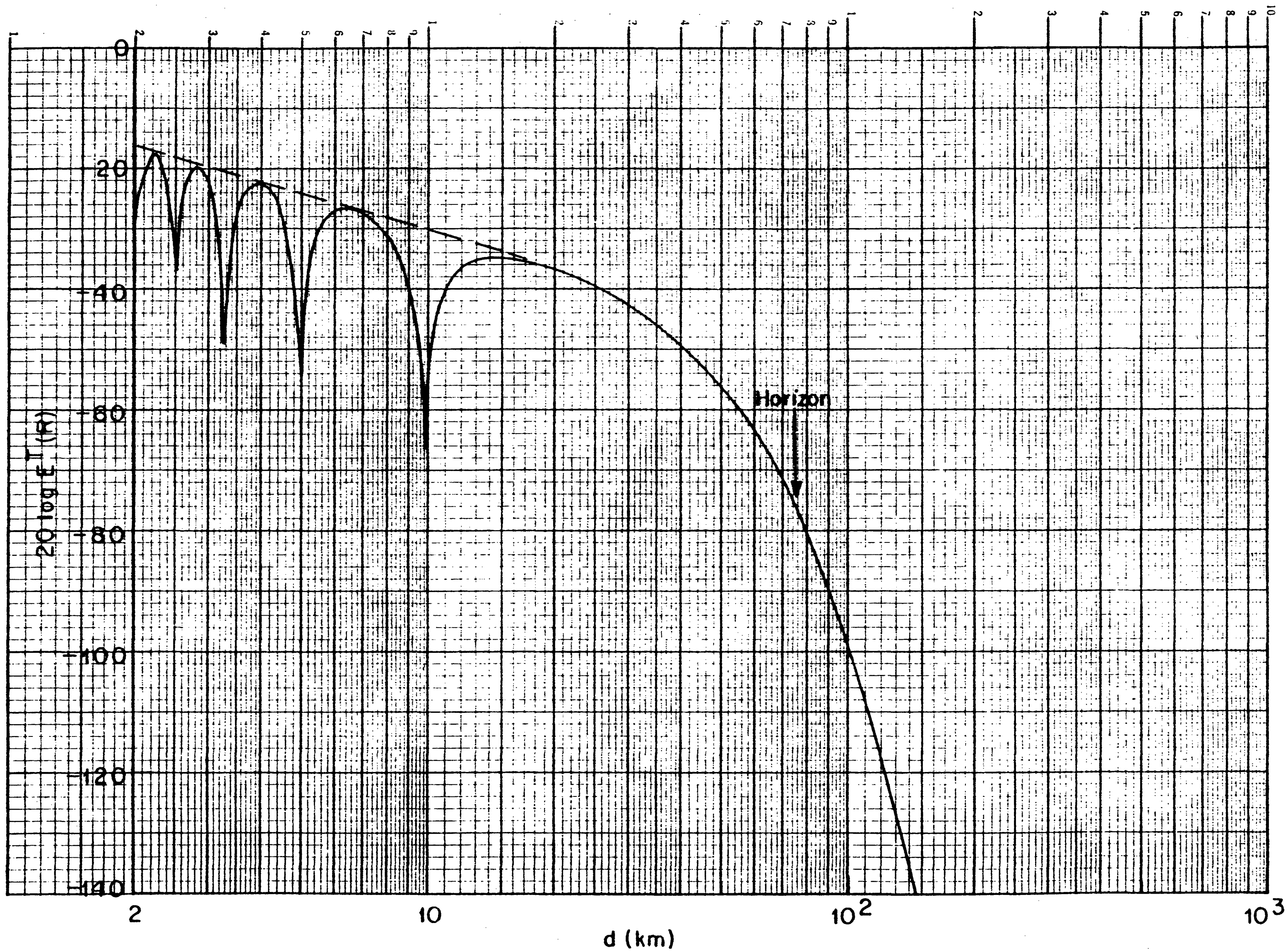

Figure 3. Field strength in dB above mv/m as a function of distance d from a horizontally polarized transmitter radiating 1 kw effective power: h_1 = 300 m, h_2 = 10 m, f = 500 MHz.

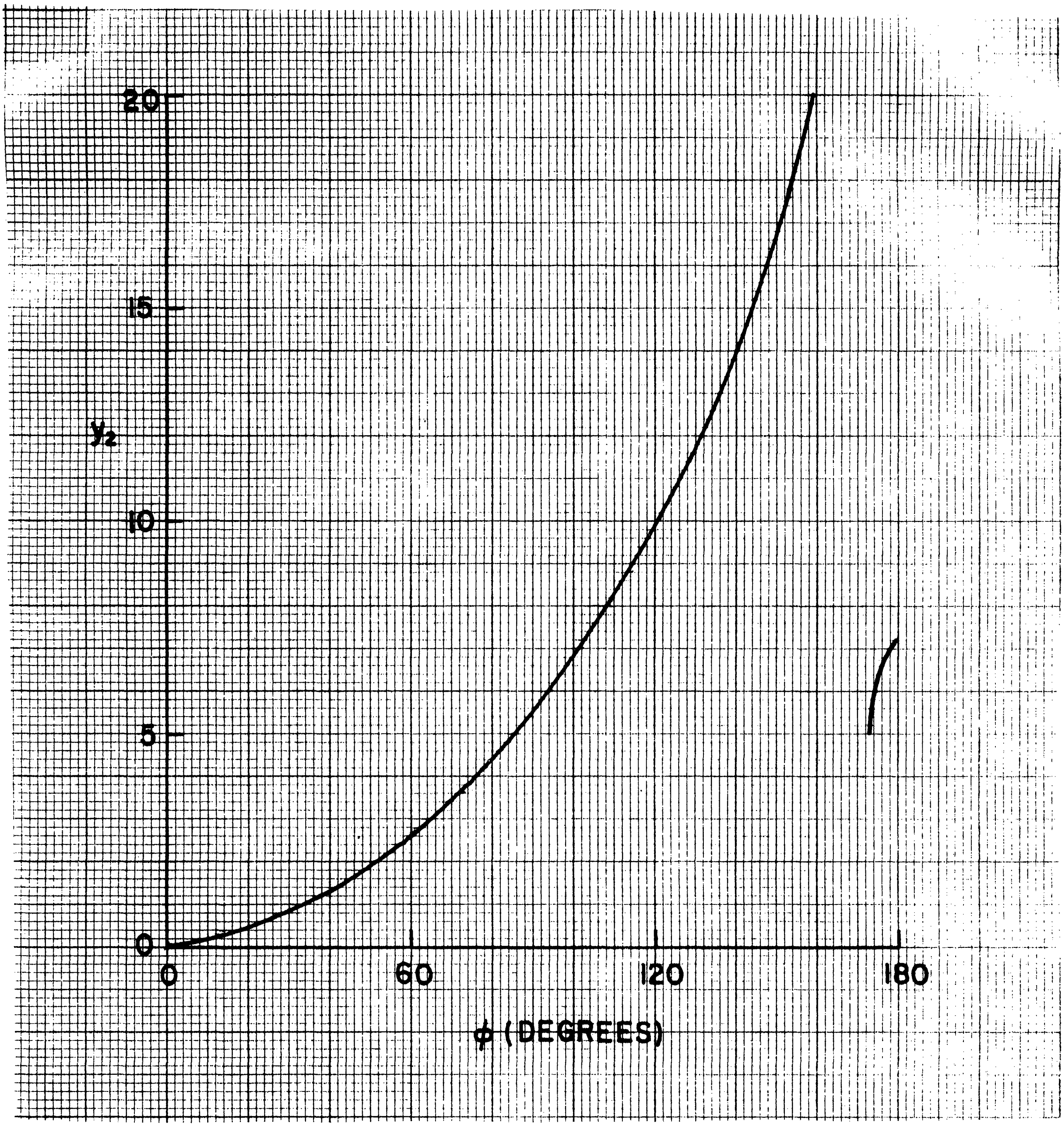

Figure 4. dB level y_2 versus ϕ (see equation 15).

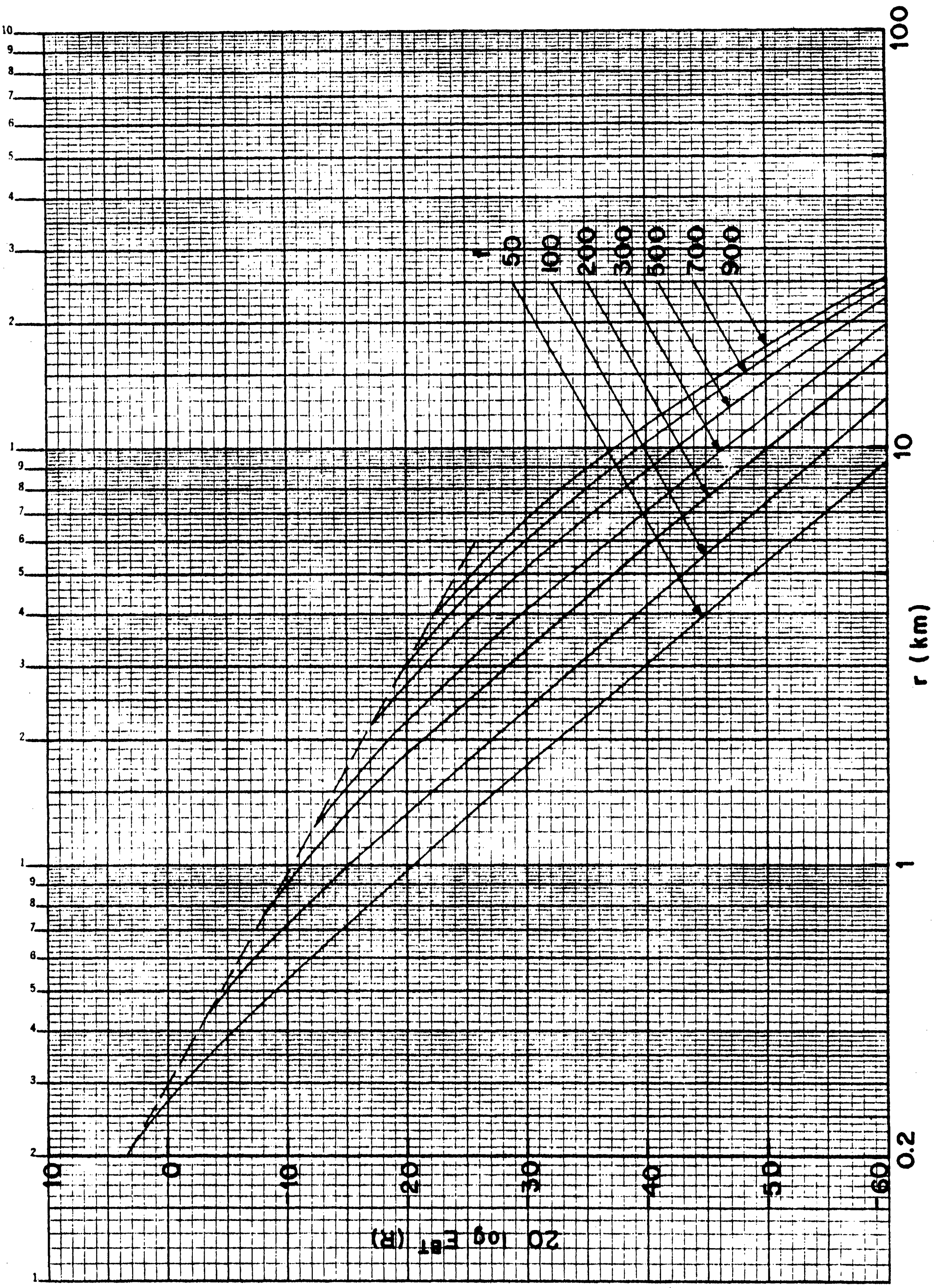

Figure 5(a). Field strength $[E^{BT}(R)]$ in dB above mv/m as a function of distance r from a transmitter located at the WT blade phase center and radiating 1 Kw effective power: h_2 = 10 m, h_3 = 30 m (MOD-OA)

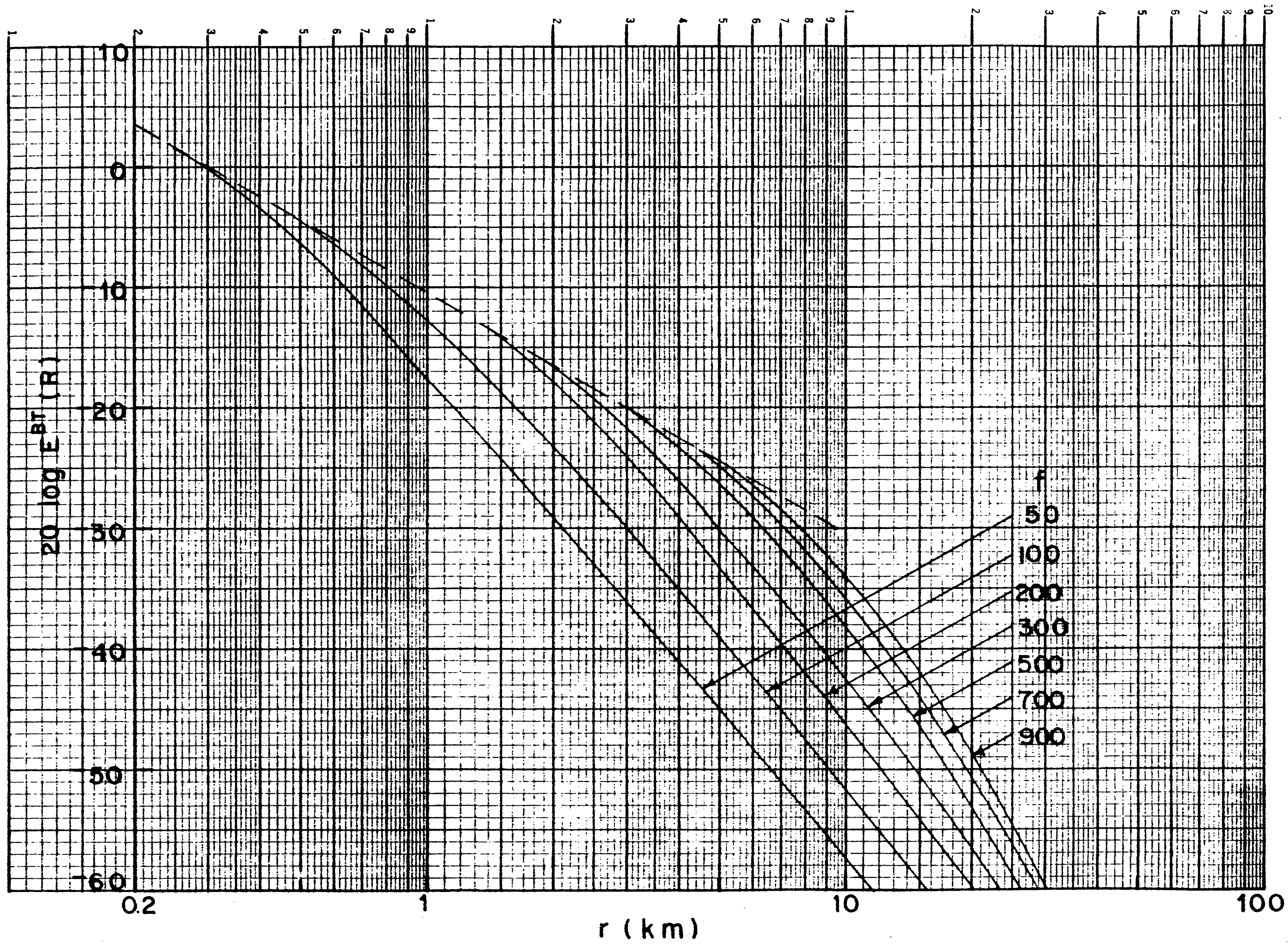

Figure 5(b). Field strength $[E^{BT}(R)]$ in dB above mv/m as a function of distance r from a transmitter located at the WT blade phase center and radiating 1 Kw effective power: h_2 = 10 m, h_3 = 45 m (MOD-1)

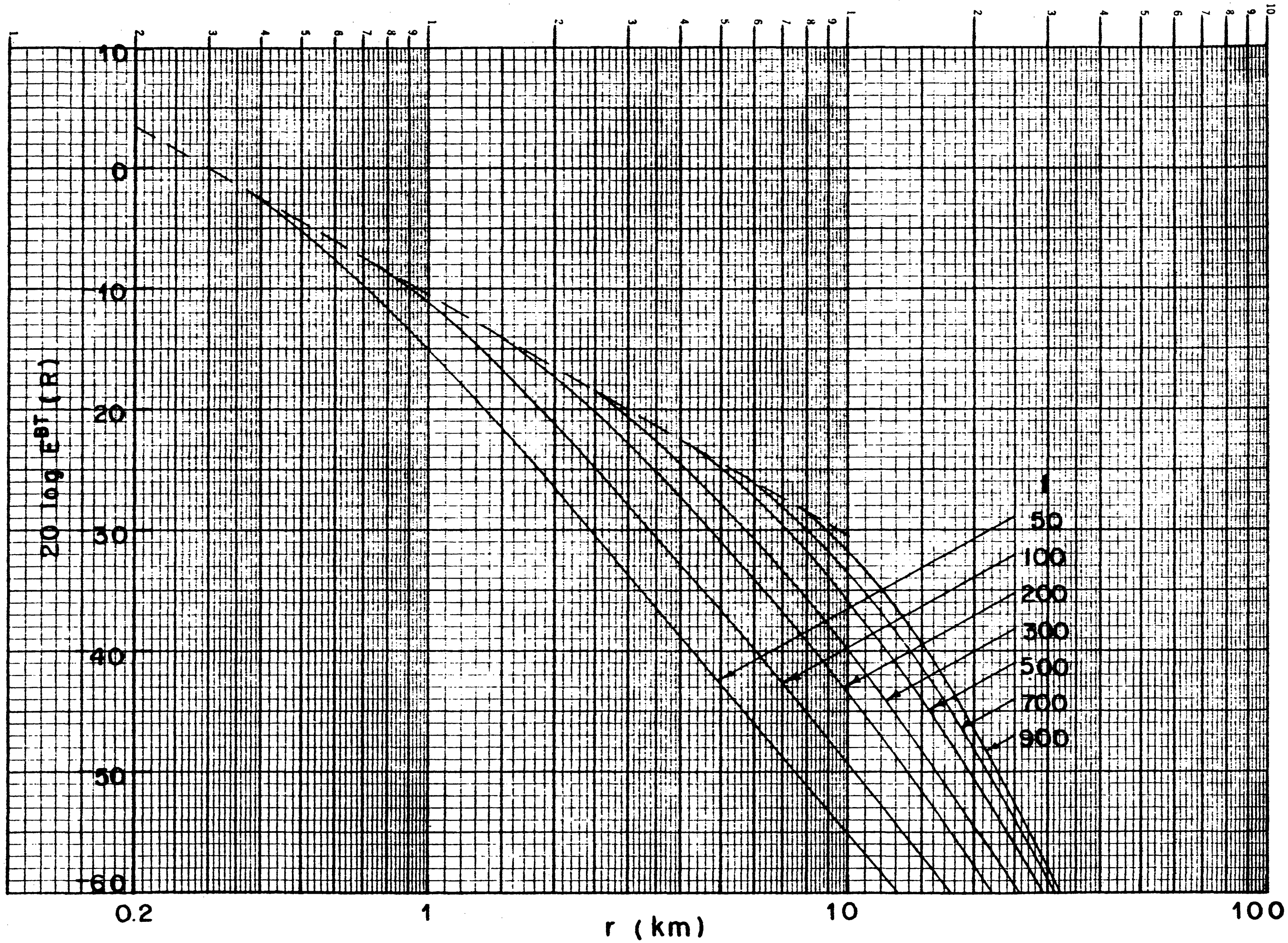

Figure 5(c). Field strength $[E^{BT}(R)]$ in dB above mv/m as a function of distance r from a transmitter located at the WT blade phase center and radiating 1 Kw effective power: h_2 = 10 m, h_3 = 60 m (MOD-2)

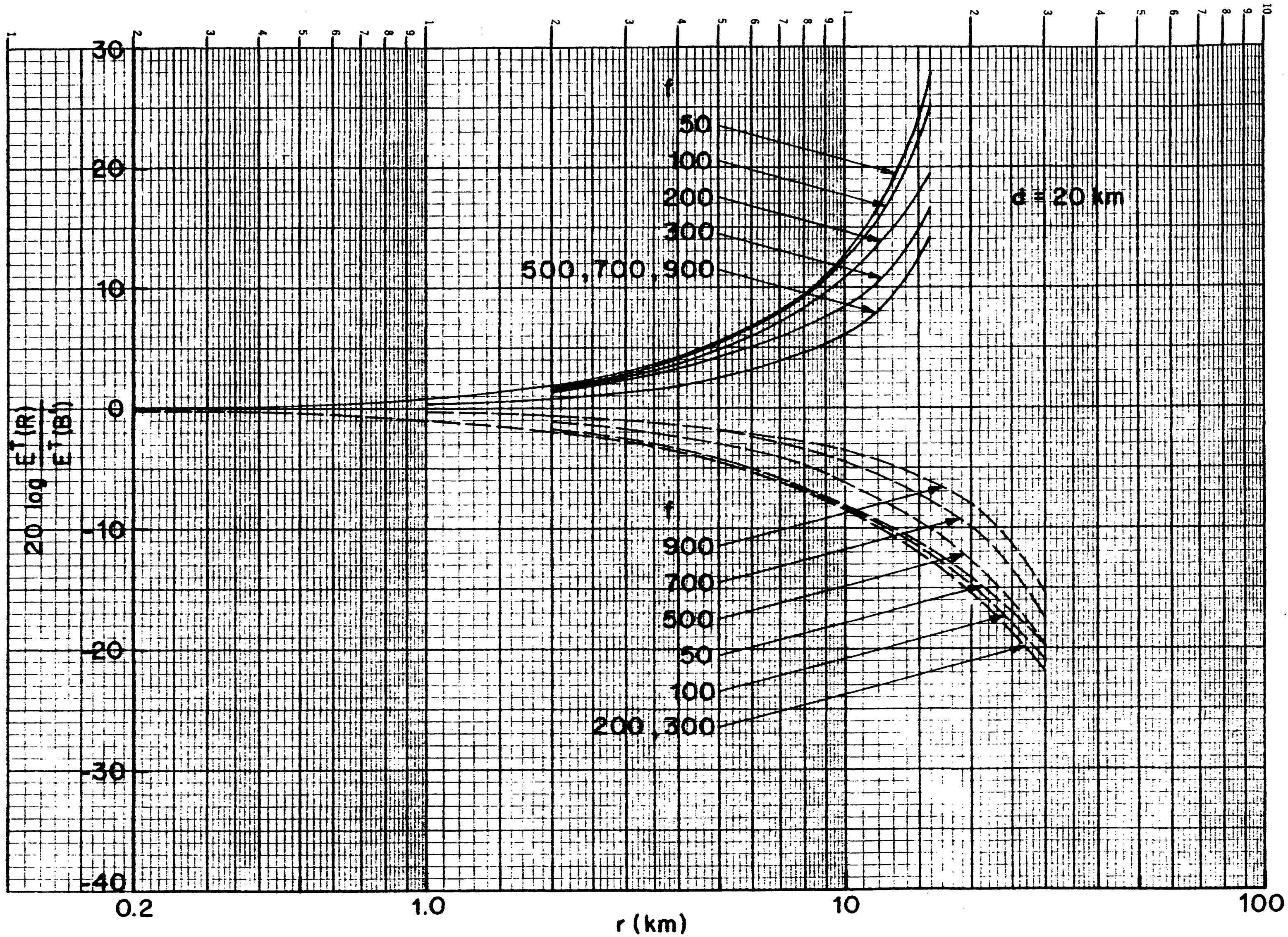

Figure 6(a). Ratio of the direct field strengths at the receiver (R) and WT blade phase center (B) $[E^T(R)/E^T(B)]$ in dB as a function of the distance r from the WT: ----- $\phi = 0$; ______ $\phi = \pi$. d = 20 km

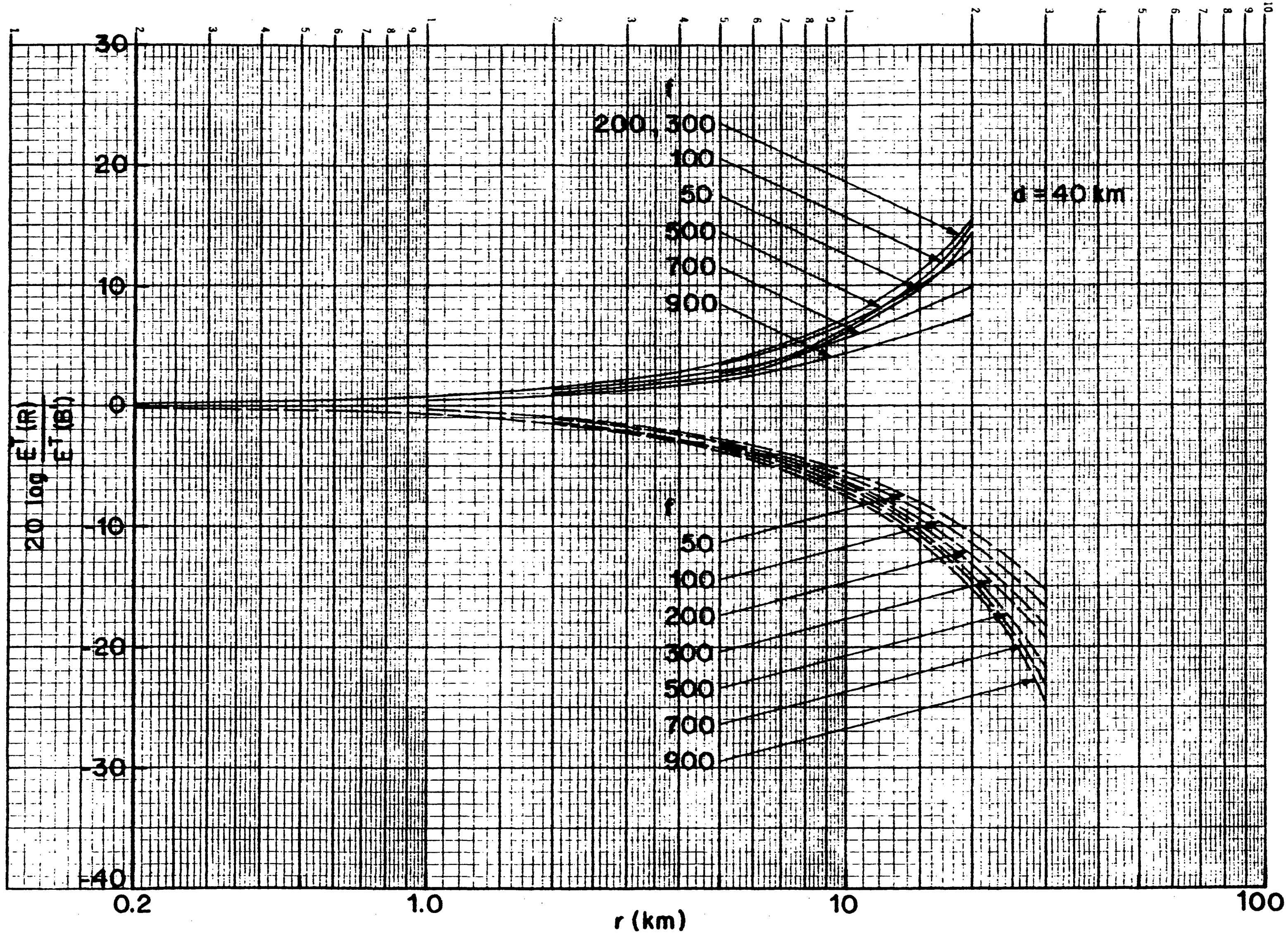

Figure 6(b). Ratio of the direct field strengths at the receiver (R) and WT blade phase center (B) $[E^T(R)/E^T(B)]$ in dB as a function of the distance r from the WT: ----- $\phi = 0$; ——— $\phi = \pi$. d = 40 km.

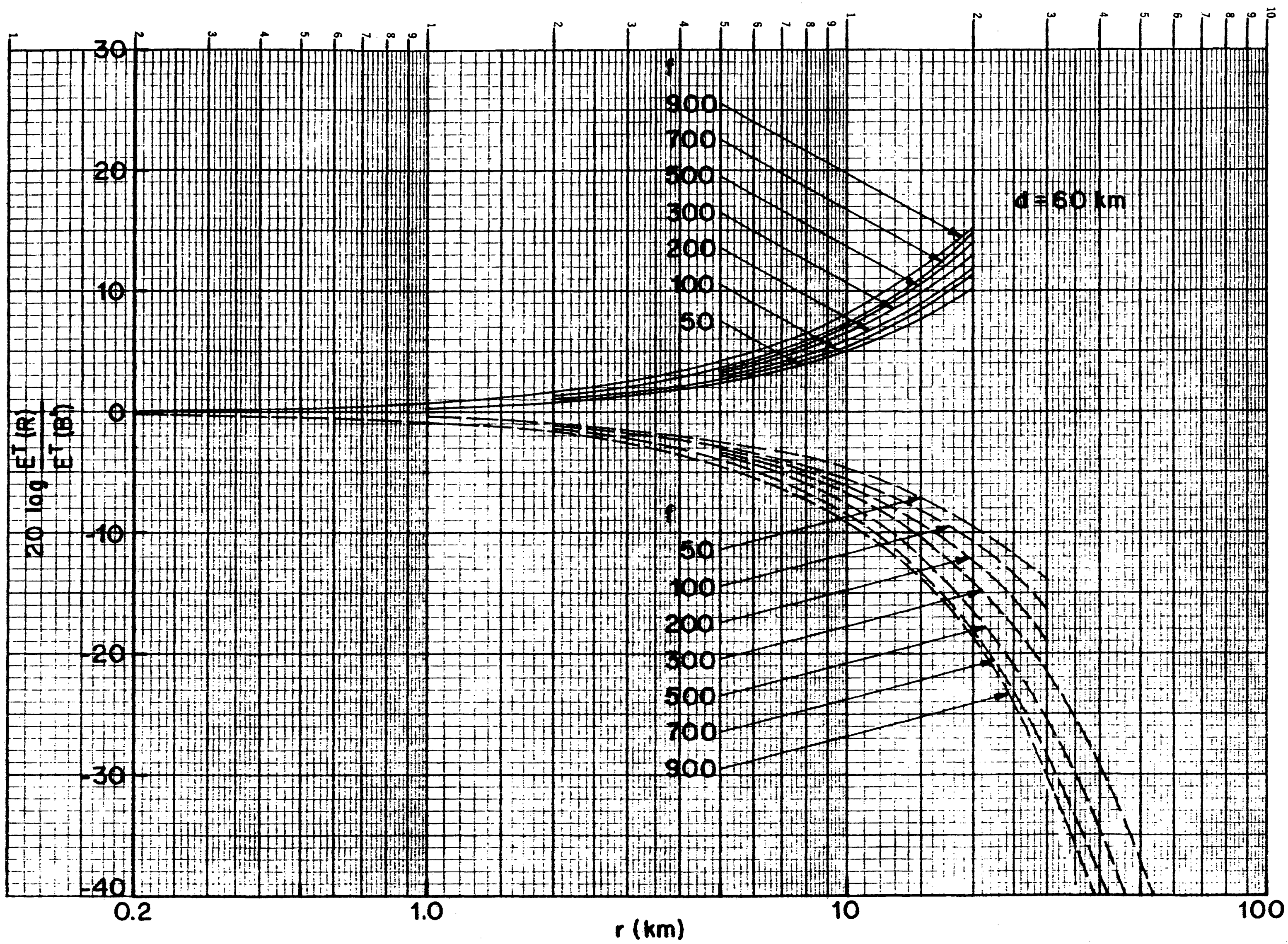

Figure 6(c). Ratio of the direct field strengths at the receiver (R) and WT blade phase center (B) $[E^T(R)/E^T(B)]$ in dB as a function of the distance r from the WT: ----- $\phi = 0$; ______ $\phi = \pi$. d = 60 km.

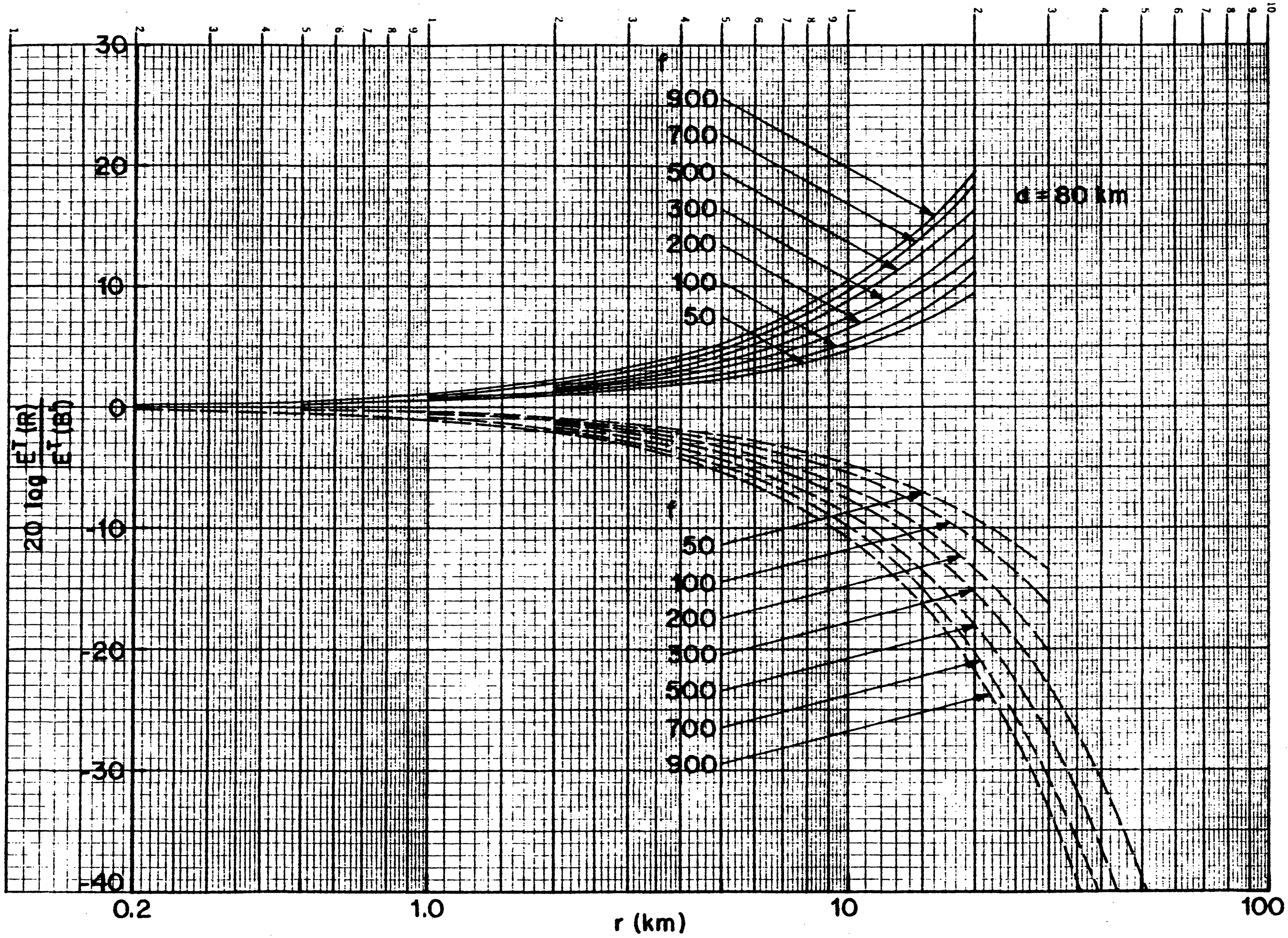

Figure 6(d). Ratio of the direct field strengths at the receiver (R) and WT blade phase center (B) $[E^T(R)/E^T(B)]$ in dB as a function of the distance r from the WT: ----- $\phi = 0$; ——— $\phi = \pi$. d = 80 km.

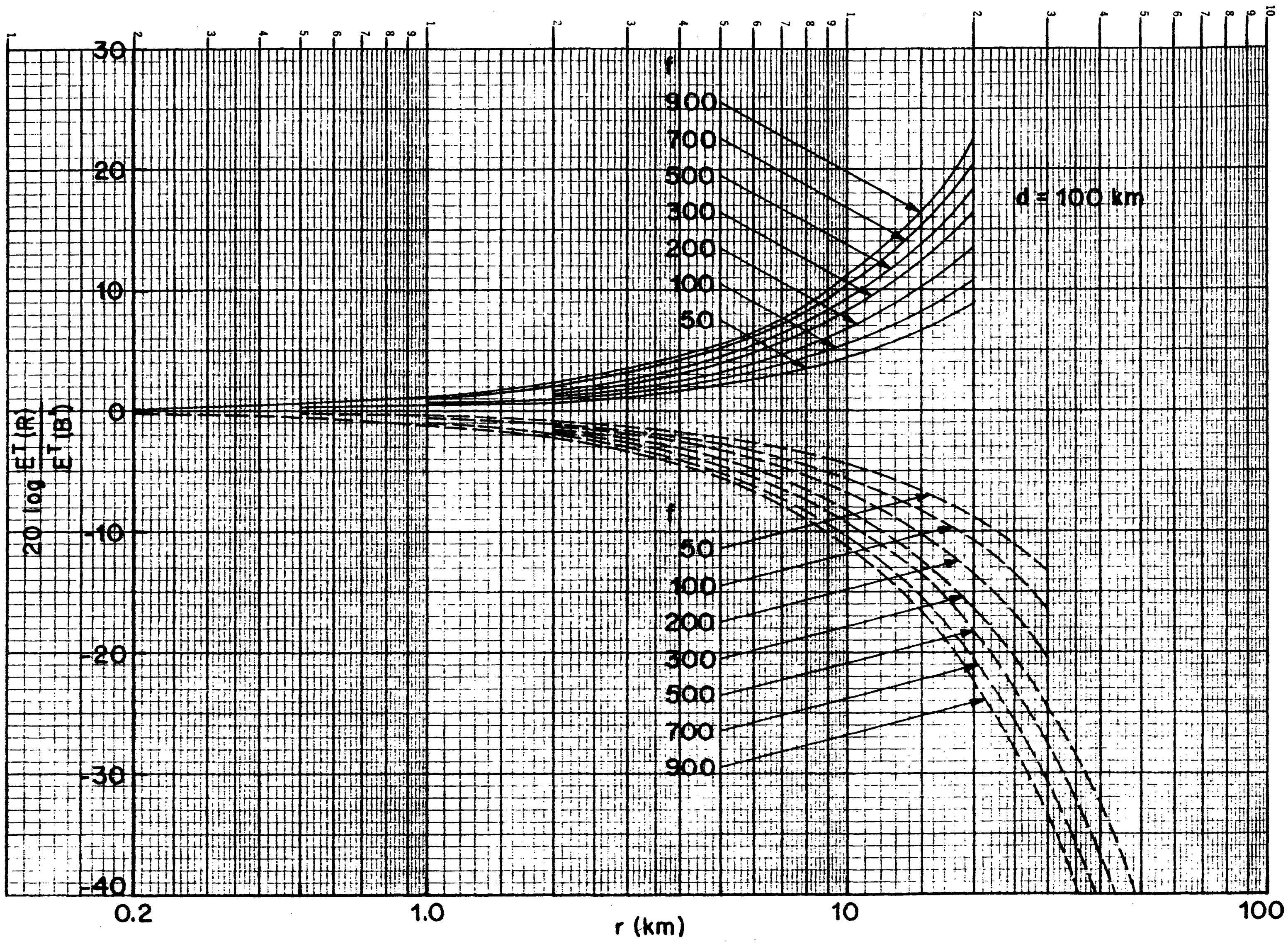

Figure 6(e). Ratio of the direct field strengths at the receiver (R) and WT blade phase center B $[E^T(R)/E^T(B)]$ in dB as a function of the distance r from the WT: ----- $\phi = 0$; ——— $\phi = \pi$. $d \geq 100$ km

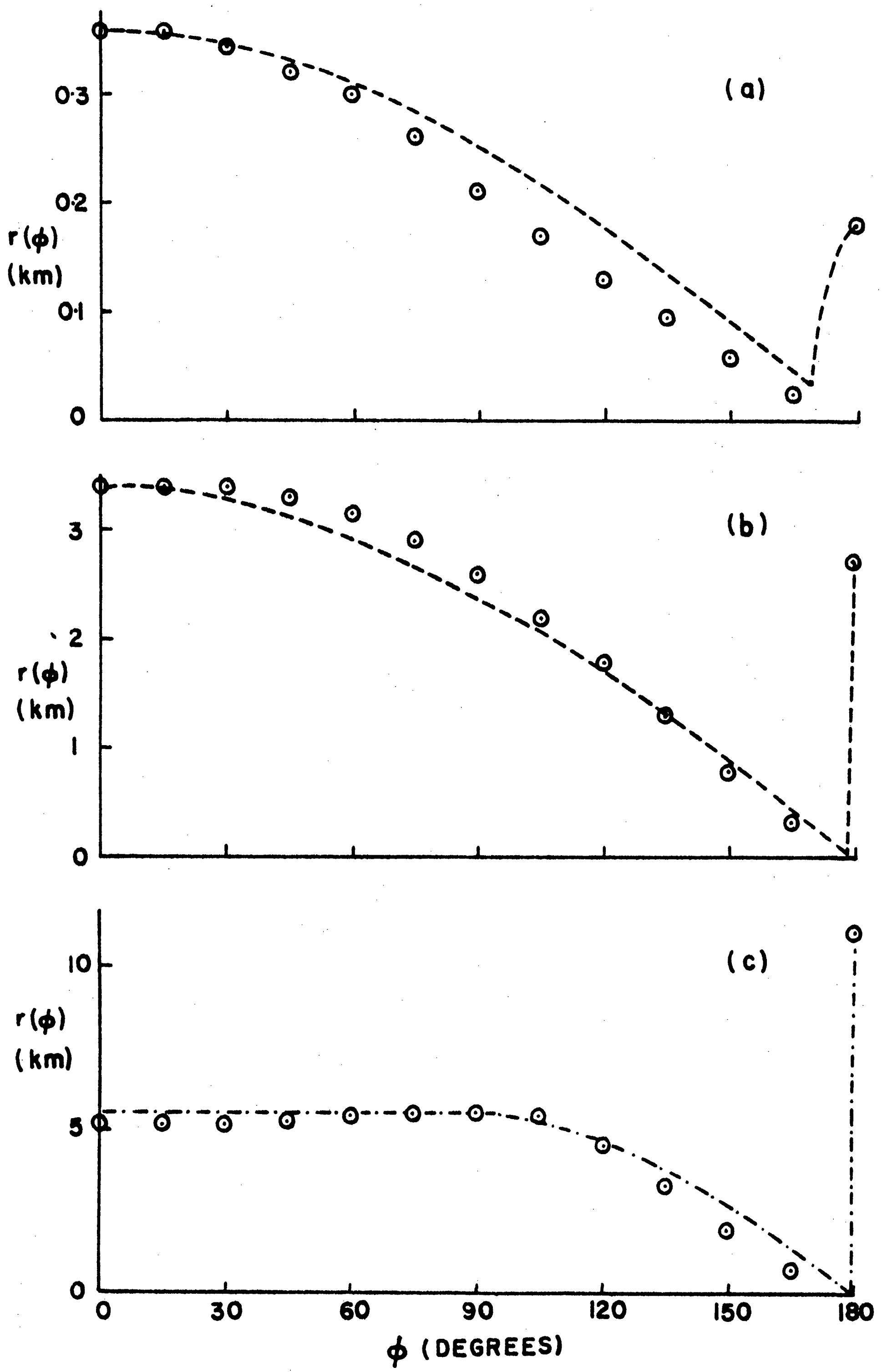

Figure 7. Computed interference zones (⊙ ⊙ ⊙) for the MOD-1 with $d \geq 100$ km and (a) f = 50 MHz, (b) f = 500 MHz, (c) f = 900 MHz; --- type A zone, —·—· type B zone.