



Recommendation ITU-R P.684-7
(09/2016)

**Prediction of field strength at
frequencies below about 150 kHz**

P Series
Radiowave propagation



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Note: This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.

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RECOMMENDATION ITU-R P.684-7

Prediction of field strength at frequencies below about 150 kHz

(Question ITU-R 225/3)

(1990-1994-2001-2003-2005-2009-2012-2016)

Scope

This Recommendation provides waveguide and wave-hop methods for the prediction of field strength at frequencies below about 150 kHz.

Keywords

Ionospheric propagation, ELF, VLF, LF, ray-path, sky-wave

The ITU Radiocommunication Assembly,

considering

- a) that there is a need to give guidance to engineers for the planning of radio services in the frequency band below about 150 kHz;
- b) that the following methods have been developed:
 - a wave-hop treatment for frequencies above about 60 kHz, based on a statistical analysis of field strength measurements in the band 16 kHz to about 1 000 kHz;
 - a waveguide mode method for frequencies below about 60 kHz, based on a theoretical model of the Earth and the ionosphere, employing ionospheric model parameters determined from propagation data;
 - a method for the frequency band 150-1 700 kHz, described in Recommendation ITU-R P.1147,

recommends

- 1 that the following methods be used, taking particular note of the cautions on accuracy in their application to certain regions as discussed in Annex 2.

1 Introduction

Two methods are available for theoretically calculating the field strength of ELF, VLF and LF signals.

It may be noted that the information in this Recommendation includes values of $f \cos i$ exceeding 150 Hz. The use of this information for frequencies exceeding 150 kHz is not recommended. Recommendation ITU-R P.1147 gives information for frequencies above 150 kHz.

1.1 The wave-hop method is that in which electromagnetic energy paths between a given transmitter and receiver are represented geometrically as is done in the case of HF.

This method should be used at LF and, for distances less than 1 000 km, at VLF. The method treats radio transmission as taking place along certain paths defined by one or more ionospheric reflections, depending on whether the propagation in question involves one or more hops, as well as a ground wave. The total field is then the vectorial resultant of the fields due to each path. In view of the long wavelengths concerned, the diffraction of the waves by the Earth's surface must be taken into account, which is not the case for HF. The wave-hop method may be justified by the fact that, with oblique

incidence, the dimensions of the section of altitude in which propagation takes place are equal to or greater than several wavelengths.

With this method it is necessary to know the values of the reflection coefficients of the incident wave on the ionosphere. These vary greatly with frequency, length and geographic and geomagnetic coordinates of transmission path, time of day, season, and epoch of the solar cycle. It is also necessary to know the electrical characteristics (conductivity and permittivity) of the ground at the transmitting and receiving sites, since the finite conductivity of the Earth affects the vertical radiation patterns of the terminal antennas.

1.2 The waveguide mode method should be used at VLF for distances greater than 1 000 km. In this method, the propagation is analysed as the sum of the waves corresponding to each of the different types of propagation in the Earth-ionosphere waveguide, analogous to a mode as defined for waveguides in the microwave region. The selection of the method to be used for field calculation depends on practical consideration of numerical calculations.

1.3 In the case of VLF at distances of less than 1 000 km and for LF in general, the series of modes are slightly convergent and the calculations then require adding together vectorially a large number of components. The wave-hop theory, on the other hand, requires only a limited number of paths, including the ground wave, and it is particularly convenient for the long-distance propagation of LF, taking into account, if possible, the diffraction.

For VLF at distances of more than 1 000 km, the wave-hop theory requires the vectorial addition of the field due to a large number of paths whereas, since the series of modes converge rapidly, sufficient accuracy can be obtained by adding together only a small number of modes. But in many cases for calculation with sufficient accuracy it is possible to use the wave-hop model at large distances for frequencies down to 10 kHz, and it is possible to limit the number of paths to be taken into account to three or in rare cases to four. Propagation at ELF also may be described in terms of a single waveguide mode.

2 Wave-hop propagation theory

2.1 General description

According to this theory, the sky-wave field (strength and phase) at a point is treated as the resultant of the fields created by different waves propagated directly from the transmitter in one or more hops. The total field at this point is then the resultant of the field due to the wave diffracted by the ground and of the field due to the sky wave.

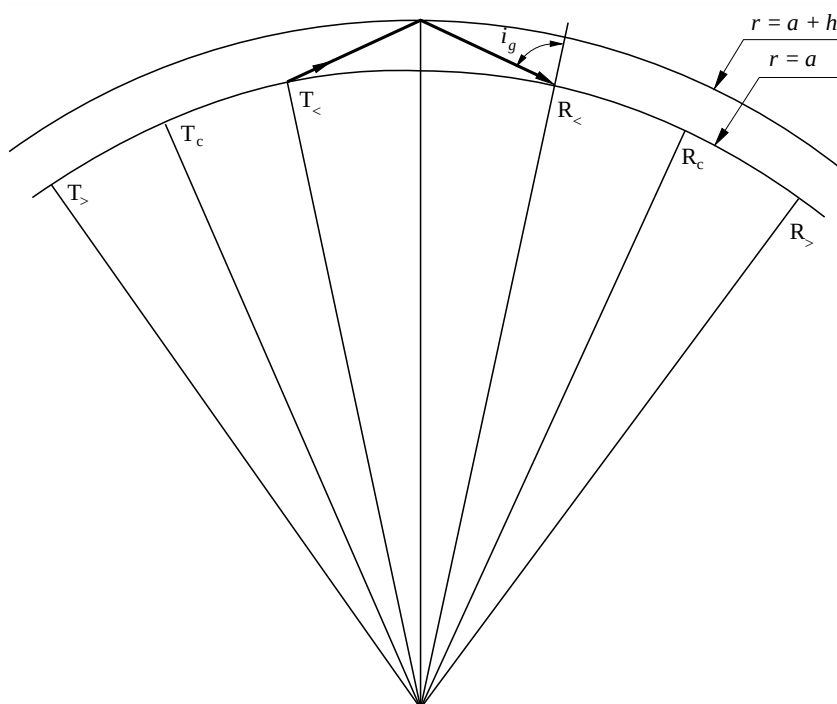
The sky-wave field is calculated by applying the theory of rays in the regions where the methods of geometric optics are applicable and by integrating the effects of diffraction or by applying the full wave theory in regions where optics are no longer valid.

The geometry of a path comprising a single hop is shown in Fig. 1.

The surface of the Earth is defined by $r = a$ and a smooth reflecting ionospheric layer located at $r = a + h$. It is convenient to distinguish three cases. In the first, the receiving antenna located at $R_<$ is illuminated by the once-reflected sky wave from the transmitting antenna located at $T_<$ where i_g is less than $\pi/2$. In the second, the two antennas at T_c and R_c are located at the critical points where $i_g = \pi/2$. In the third case the antennas are located at $T_>$ and $R_>$ beyond the critical points such that the first sky-wave hop propagates into the diffraction or shadow zone.

FIGURE 1

Ray path geometry for the wave-hop radio propagation theory (first hop sky wave)



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2.2 Calculating the ray-path field strength

The electromotive force corresponding to the electric field radiated from a short vertical dipole is given by:

$$V_u = 300 \sqrt{p_t} \quad \text{V} \quad (1)$$

where p_t is radiated power (kW).

The field strength of the downcoming sky wave, before reflection at the ground in the vicinity of the receiving antenna, is given by:

$$E_t = \frac{V_u}{L} \cos \psi \parallel R_{\parallel} D F_t \quad \text{mV/m} \quad (2)$$

where:

L : sky-wave path length (km)

$\parallel R_{\parallel}$: the ionospheric reflection coefficient which gives the ratio of the electric field components parallel to the plane of incidence

D : ionospheric focusing factor

F_t : transmitting antenna factor

ψ : the angle of departure and arrival of the sky wave at the ground, relative to the horizontal.

If reception is by a small in-plane loop antenna located on the surface of the Earth, the effective field strength of the sky wave is:

$$E_s = \frac{2V_u}{L} \cos \psi \parallel R_{\parallel} D F_t F_r \quad \text{mV/m} \quad (3)$$

For reception by a short vertical antenna equation (3) becomes:

$$E_s = \frac{2V_u}{L} (\cos \psi)^2 \parallel R_{\parallel} D F_t F_r \quad \text{mV/m} \quad (4)$$

where F_r is the appropriate receiving antenna factor.

For propagation over great distances, the wave-hop method can be extended to include sky waves reflected more than once from the ionosphere. For example for a two-hop sky wave, the field strength received by a receiving loop antenna can be represented simply as:

$$E_s = \frac{2V_u}{L} \cos \psi \parallel R_{1\parallel} \parallel R_{2\parallel} D^2 D_G \parallel R_{g\parallel} F_t F_r \quad \text{mV/m} \quad (5)$$

where:

D_G : divergence factor caused by the spherical Earth, approximately equal to D^{-1}

$\parallel R_{g\parallel}$: effective reflection coefficient of the finitely conducting Earth

L : total propagation path of the two-hop ray-path

$\parallel R_{1\parallel}$ and $\parallel R_{2\parallel}$: ionospheric reflection coefficients for the first and second reflection.

In general, the ionospheric reflection coefficients will not be equal, because the polarizations of the incident waves are not the same. However, in the simple method for calculating field strengths given here, for propagation at very oblique angles of incidence, $\parallel R_{1\parallel} = \parallel R_{2\parallel}$ as a first order approximation.

2.2.1 Angles of elevation and ionospheric incidence

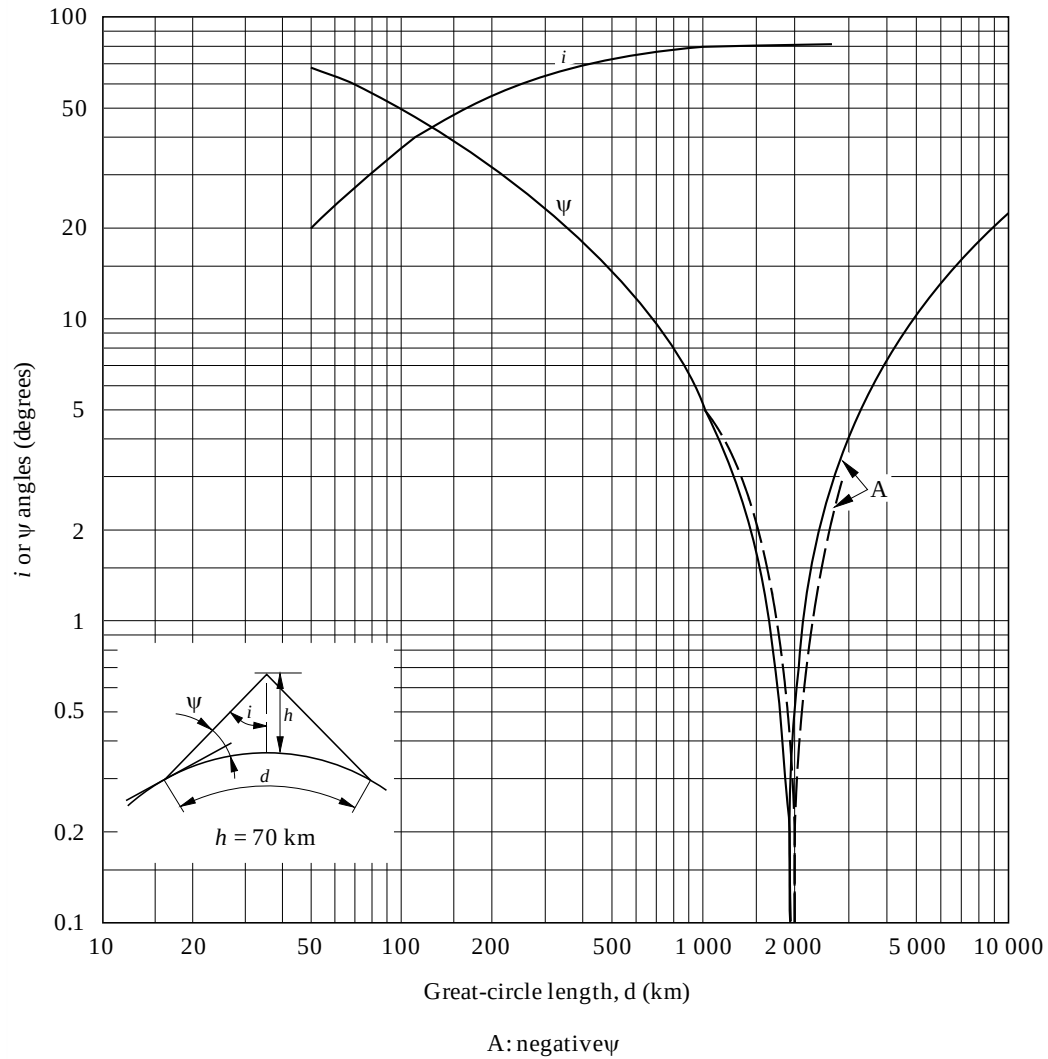
The ray path geometry for determining the angles of departure and arrival of the sky wave at the ground, ψ , and ionospheric angles of incidence, i , is shown on Figs. 2 and 3. These angles are given in Fig. 2 for an effective reflection height of 70 km which corresponds to typical daytime conditions and in Fig. 3 for an effective reflection of 90 km which corresponds to typical night-time conditions. The effects of atmospheric refraction on the departure and arrival angles are included and shown by the dashed curve although they are probably not valid for frequencies below about 50 kHz.

2.2.2 Path length and differential time delay

To calculate L the sky-wave path length and estimates of the diurnal phase changes, Fig. 4 is used. This shows the differential time delay between the surface wave and the one, two or three hop sky wave for ionospheric reflection heights of 70 and 90 km, corresponding to daytime and night-time conditions. A propagation velocity of 3×10^5 km/s is assumed.

FIGURE 2

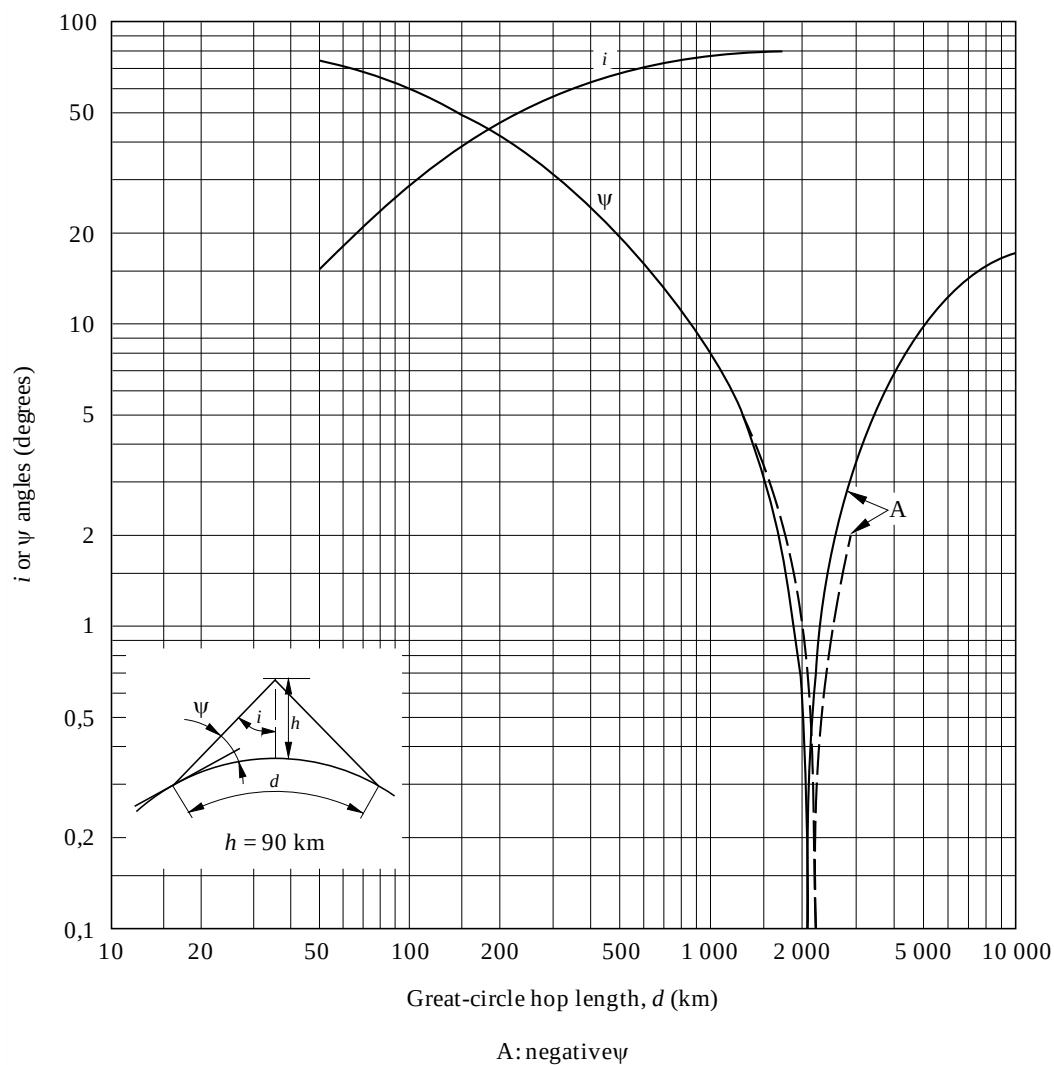
Departure and arrival angles, ψ , and ionospheric angles of incidence, i , for typical daytime conditions ($h = 70$ km). The dashed curve includes the effects of atmospheric refraction



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FIGURE 3

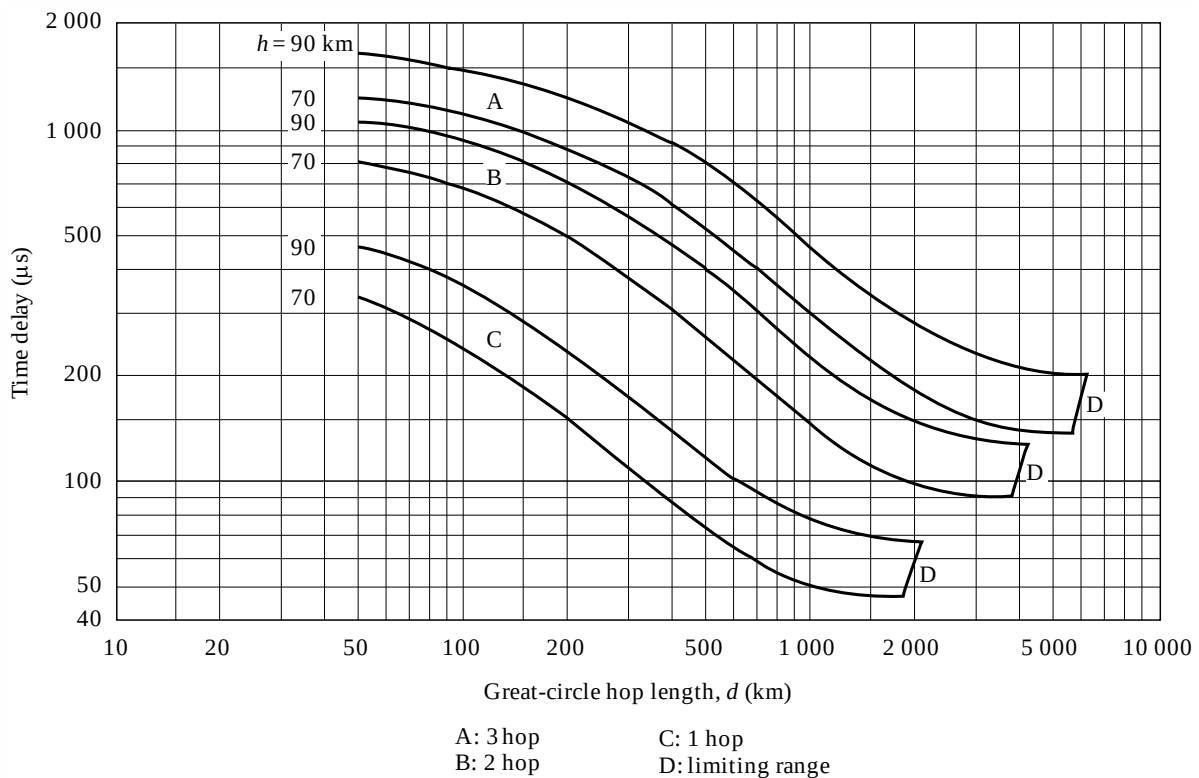
Departure and arrival angles, ψ , and ionospheric angles of incidence, i , for typical nighttime conditions ($h = 90$ km). The dashed curve includes the effects of atmospheric refraction



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FIGURE 4

Differential time delay between surface wave and one, two and three hop sky waves



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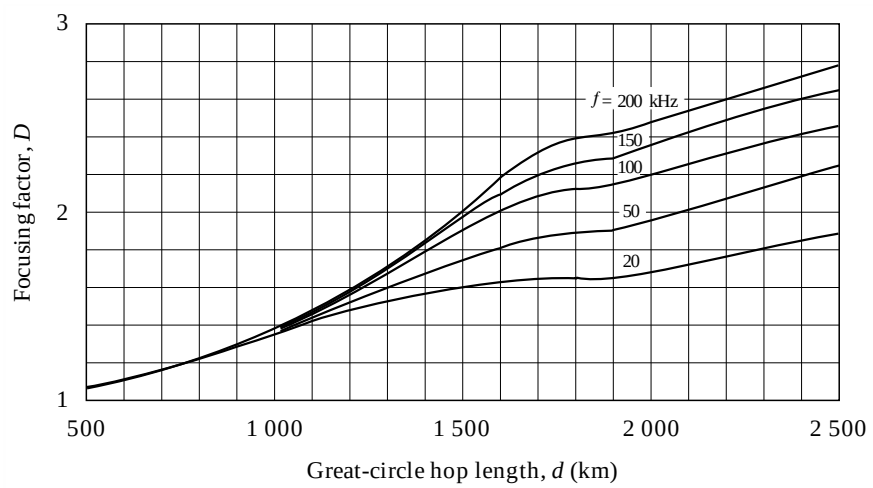
2.2.3 Focusing factor

The ionospheric focusing factor, D , for a spherical Earth and ionosphere is shown in Fig. 5 for daytime conditions and in Fig. 6 for night-time conditions.

2.2.4 Antenna factors

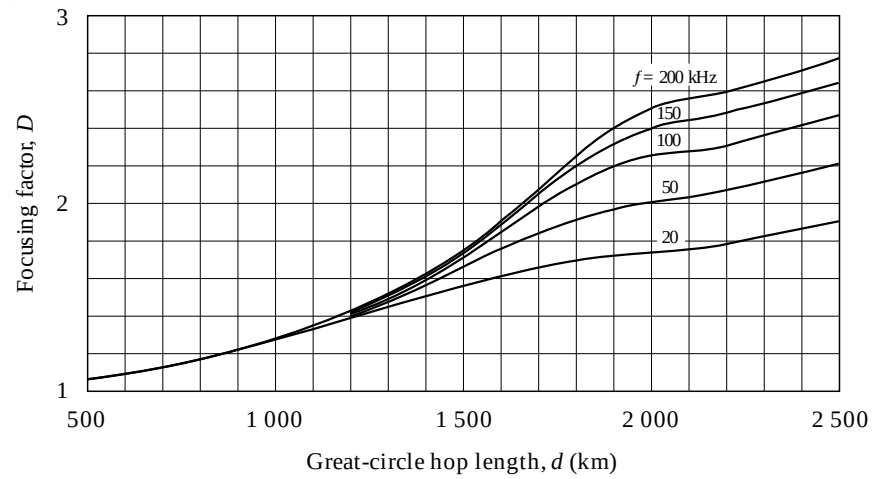
The antenna factors, F_t and F_r , which account for the effect of the finitely conducting curved Earth on the vertical radiation pattern of the transmitting and receiving antennas are shown in Figs. 7 to 9. Factors are calculated for land, sea and ice conditions which are defined by their electrical characteristics (conductivity and permittivity), as shown in Table 1.

FIGURE 5
Ionospheric focusing factor – daytime



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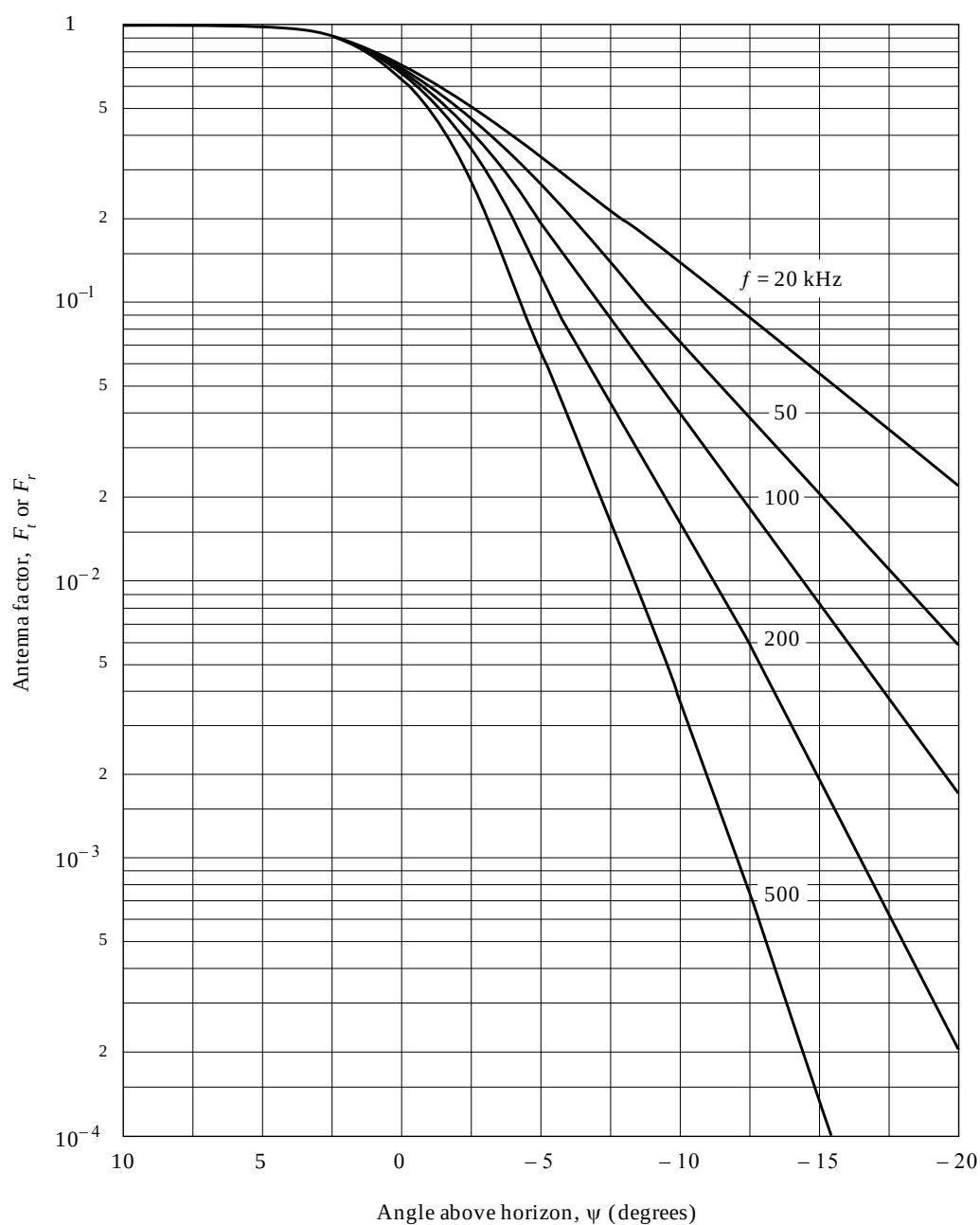
FIGURE 6
Ionospheric focusing factor – night-time



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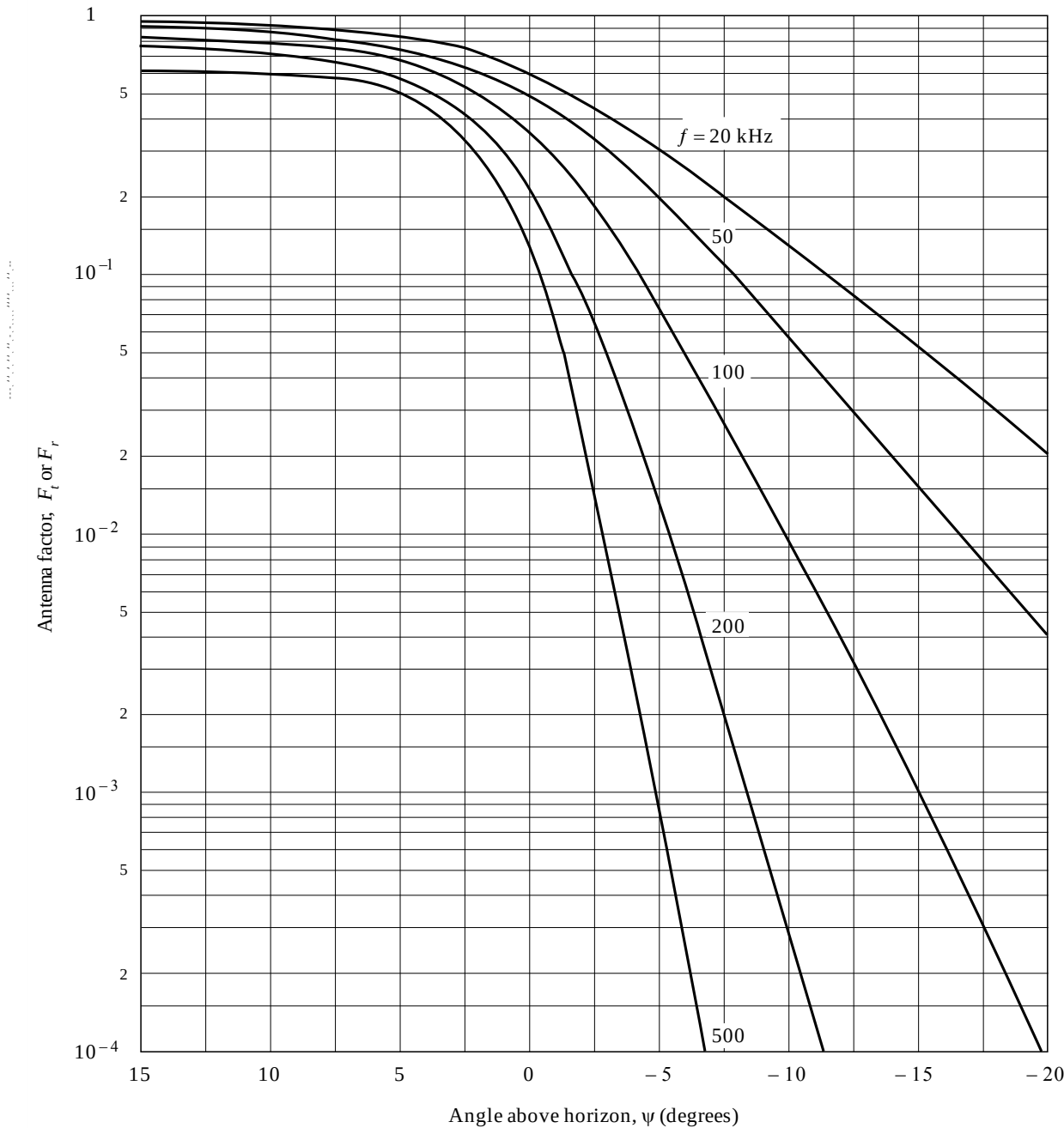
FIGURE 7
Antenna factor – Sea water



$$\begin{aligned}\epsilon &= 80 \epsilon_0 \\ \sigma &= 5 \text{ S/m} \\ \alpha &= 4/3 \times 6360 \text{ km}\end{aligned}$$

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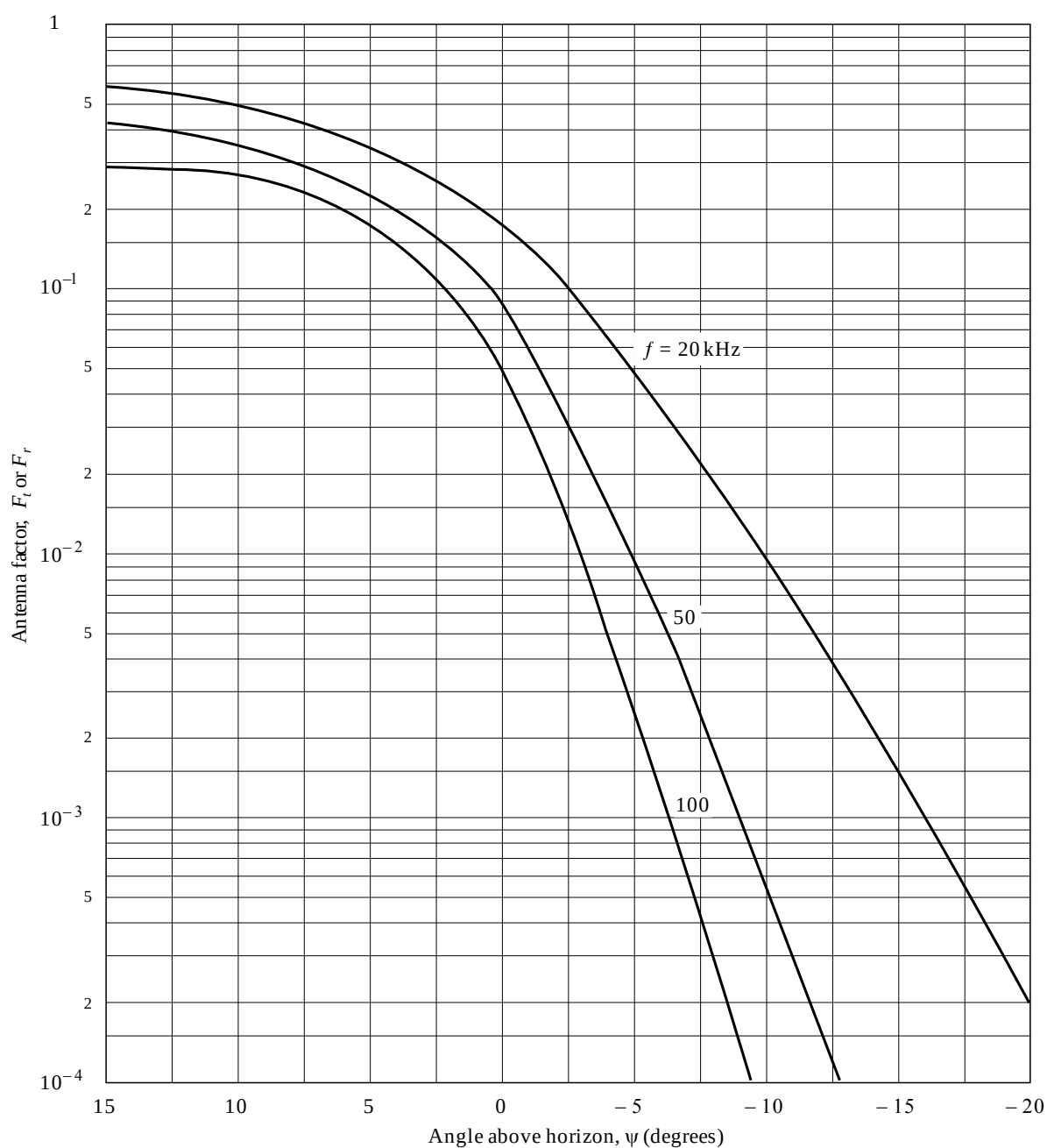
FIGURE 8
Antenna factor – Land



$\epsilon = 15 \epsilon_0$
 $\sigma = 2 \times 10^{-3} \text{ S/m}$
 $\alpha = 4/3 \times 6360 \text{ km}$

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FIGURE 9
Antenna factor – Ice at -4°C



$$\begin{aligned}\epsilon &= 3 \epsilon_0 \\ \sigma &= 0,025 \times 10^{-3} \text{ S/m} \\ \alpha &= 4/3 \times 6\,360 \text{ km}\end{aligned}$$

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TABLE 1

	Conductivity, σ (S/m)	Permittivity, ϵ
Sea water	5	$80 \epsilon_0$
Land	2×10^{-3}	$15 \epsilon_0$
Polar ice	2.5×10^{-5}	$3 \epsilon_0$

ϵ_0 : permittivity of free space

The curves were calculated assuming an effective Earth's radius, 8 480 km, which is 4/3 of its actual value to take account of atmospheric refraction effects. The factors F are the ratio of the actual field strength to the field strength that would have been measured if the Earth were perfectly conducting. Negative values of ψ refer to propagation beyond the geometric optical limiting range for a one hop sky wave (see Figs. 1 to 3).

2.2.5 Ionospheric reflection coefficients $\|R\|$

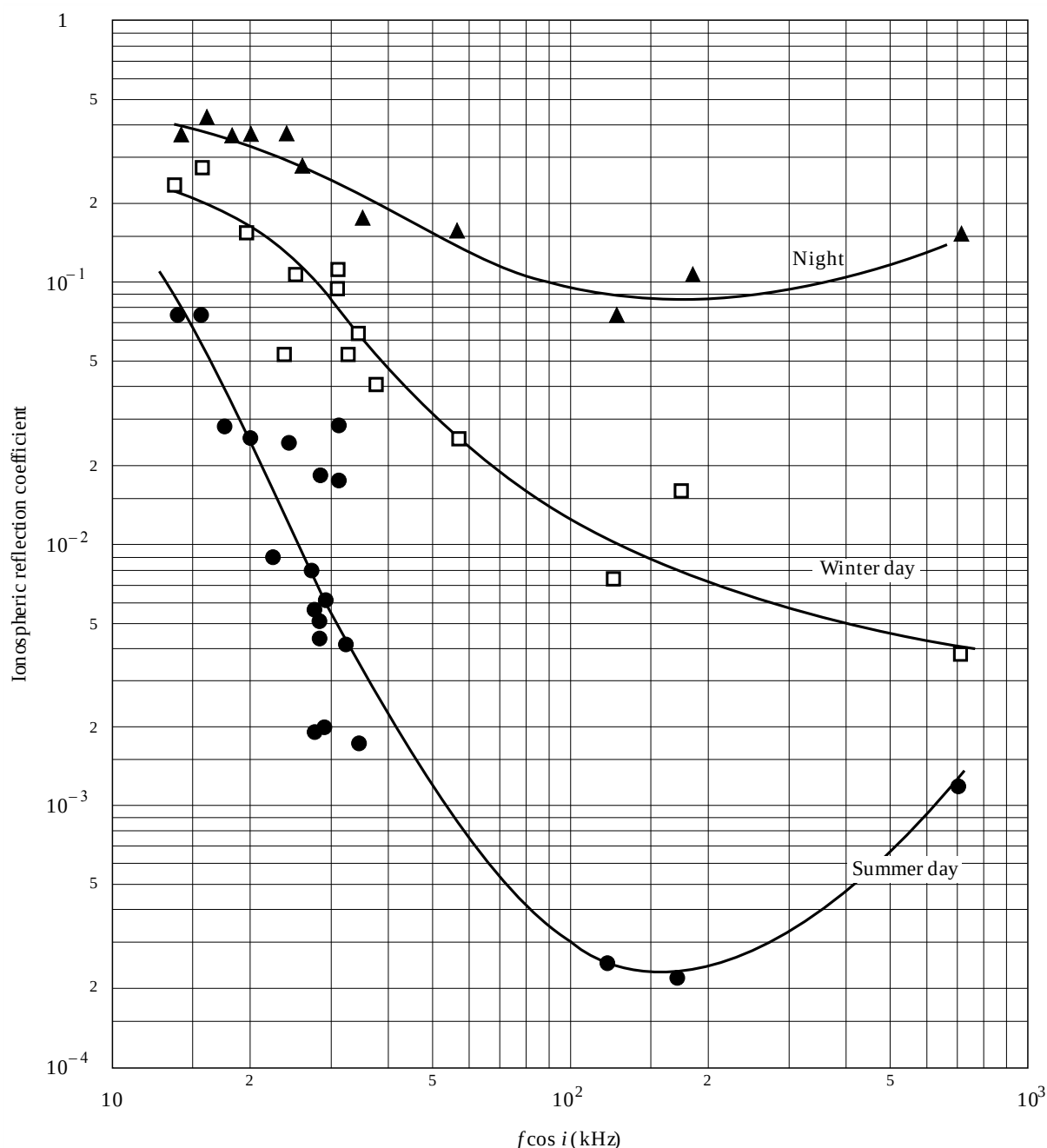
Values of the ionospheric reflection coefficient $\|R\|$ are shown in Fig. 10 for solar cycle minimum. To take account of frequency and distance changes, the values of $\|R\|$ are given as a function of $f \cos i$, where f is the transmitted frequency and i is the ionospheric angle of incidence. Curves are shown for night during all seasons, and for day conditions during winter and summer. Measured values at vertical and oblique incidence are indicated based upon the results given in numerous reports.

In all cases the ionospheric reflection coefficient data given in the various references mentioned have been modified, if necessary, to account for ionospheric focusing, antenna factors, etc., so that the results of the measurements are consistent with the analysis technique given here.

The concept of an effective frequency $f \cos i$ for which reflection coefficients are constant cannot, however, always be relied on. The curves in Fig. 10 are derived from data obtained at steep incidence ($d < 200$ km) and at more oblique incidence ($d > 500$ km) and the $f \cos i$ concept is likely to be approximately correct for such distances. At intermediate distances, however, the concept of an equivalent frequency is likely to lead to substantial errors in reflection coefficient, because in such circumstances the reflection coefficient and polarization of the wave change rapidly with distance.

While many data have been incorporated into the curves in Fig. 10, which show that the ionospheric reflection coefficient varies with time of day (midnight and noon) and season, much more work is needed to establish clearly how it varies over the epoch of the solar cycle. There is clearly a solar cycle variation (see Fig. 11) in that reflection coefficients are larger in sunspot maximum years at the very low frequencies, whereas at medium frequencies they are smaller. The physical interpretation of this fact is as follows. During sunspot maximum years, the base of the ionosphere is lower and the electron density gradient is steeper than during sunspot minimum years. Thus, VLF waves which are reflected from this lower layer are more strongly reflected in sunspot maximum years, whereas MF waves, that are reflected above this lower layer, are more strongly absorbed. Clearly, the transition between greater and smaller reflection coefficients would be expected to be a function of frequency, time of day, season and epoch of the solar cycle; and a discontinuity in the reflection coefficient-frequency curve, at some particular frequency and time might be expected. A sharp change in the values for effective frequencies of 35 to 45 kHz is apparent in the data for sunspot maximum years in summer, but this is not revealed in the presentation of the data here.

FIGURE 10
Ionospheric reflection coefficients – solar minimum conditions



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It should be noted that the frequency range of the MF broadcast band for oblique propagation lies in the range of effective frequencies where the solar cycle change in ionospheric reflectivity is opposite. That is, 1 600 kHz propagated over a path of 1 500 km corresponds to a $f \cos i$ of 278 kHz; whereas at 500 kHz the effective frequency is 86 kHz. An example of a calculation by the ray-path method is given in Annex 1.