RECOMMENDATION 435-7*

SKY-WAVE FIELD-STRENGTH PREDICTION METHOD FOR THE BROADCASTING SERVICE IN THE FREQUENCY RANGE 150 TO 1 600 kHz**

(Question 31/6)

(1966-1970-1974-1978-1982-1986-1990-1992)

The CCIR,

considering

a) that there is a need to give guidance to engineers in the planning of broadcast services in the LF and MF bands;

b) that it is important, for stations working in the same or adjacent frequency channels, to determine the minimum geographical separation required to avoid interference resulting from long-distance ionospheric propagation;

c) that the method given below is based on the statistical analyses of field-strength measurements for 266 paths distributed throughout the world, supplemented by the results of analyses for geographical areas from which individual path data are not available,

recommends

that the following method be adopted for use, taking particular note of the cautions on accuracy in its application to certain regions as discussed in Annex 1.

1. Introduction

This method predicts values of the night-time sky-wave field strength for a given power radiated from one or more vertical antennas, when measured by a loop antenna at ground level aligned in a vertical plane along the great-circle path to the transmitter. It applies for paths of length 50 to 12 000 km in the LF and MF bands.

Figures 1, 2 and 3 are an essential part of the prediction method. Geomagnetic maps are included for convenience in Figs. 11, 12 and 16. The remaining Figs. 4 to 10, 13 to 15, 17 and Appendix 1, provide additional information to simplify the use of the method.

2. Annual median night-time field strength

The predicted sky-wave field strength is given by:

$$E = V + E_0 - L_t = V + G_S - L_p + A - 20 \log p - 10^{-3} k_R p - L_t \qquad (1)$$

where:

- E: annual median of half-hourly median field strengths (dB(μV/m)) for a given transmitter cymomotive force, V, and at a given time, t, relative to sunset or sunrise as appropriate
- E_0: annual median of half-hourly median field strengths (dB(μV/m)) for a transmitter cymomotive force of 300 V at the reference time defined in § 2.1
- V: transmitter cymomotive force, dB above a reference cymomotive force of 300 V (see § 2.2)

* The Administration of the People's Republic of China reserves its opinion on this Recommendation.

** A computer program associated with the prediction procedure described in this Recommendation is available from the CCIR Secretariat; for details, see Resolution 63.

G_S : sea-gain correction (dB), (see § 2.3)

L_p : excess polarization-coupling loss (dB), (see § 2.4)

$A = 106.6 - 2 \sin \Phi$, where Φ is defined by equation (12)

p : slant-propagation distance (km), (see § 2.5)

k_R : loss factor incorporating effects of ionospheric absorption, focusing and terminal losses, and losses between hops on multi-hop paths (see § 2.6)

L_t : hourly loss factor (dB), (see § 2.7).

To facilitate calculation, Fig. 4 shows the quantity $A - 20 \log p$, for $\Phi = 40°$ as a function of ground distance, d, whereas Figs. 5 to 10 show E_0 as a function of ground distance, d, for various frequencies and for various geomagnetic latitudes when G_S, L_p and R are all zero; where R is the twelve-month smoothed international relative sunspot number.

2.1 *Reference time*

The reference time is taken as six hours after the time at which the Sun sets at a point S on the surface of the Earth. For paths shorter than 2 000 km, S is the mid-point of the path. On longer paths, S is 750 km from the terminal where the sun sets last, measured along the great-circle path.

2.2 *Cymomotive force*

The transmitter cymomotive force V (dB (300 V)) is given as:

$$V = P + G_V + G_H \tag{2}$$

where:

P : radiated power (dB (1 kW))

G_V: transmitting antenna gain factor (dB) due to vertical directivity, given in Fig. 1

G_H: transmitting antenna gain factor (dB) due to horizontal directivity. For directional antennas, G_H is a function of azimuth. For omnidirectional antennas, $G_H = 0$.

2.3 *Sea gain*

The sea gain G_S is the additional signal gain when one or both terminals are situated near the sea, but it does not apply to propagation over fresh water. G_S for a single terminal is given by:

$$G_S = G_0 - c_1 - c_2 \qquad \text{for} \qquad (c_1 + c_2) < G_0 \tag{3}$$

$$G_S = 0 \qquad \text{for} \qquad (c_1 + c_2) \geq G_0 \tag{4}$$

where:

G_0 : sea gain when the terminal is on the coast and the sea is unobstructed by further land (dB)

c_1 : correction to take account of the distance between the terminal and the sea

c_2 : correction to take account of the width of one or more sea channels, or the presence of islands.

If both terminals are near the sea, G_S is the sum of the values for the individual terminals.

G_0 is given in Fig. 2 as a function of d for LF and MF. At MF, $G_0 = 10$ dB when $d > 6\,500$ km; and at LF $G_0 = 4.1$ dB when $d > 5\,000$ km.

The correction c_1 is given by:

$$c_1 = \frac{s_1}{r_1} G_0 \tag{5}$$

where:

s_1 : distance of terminal from sea, measured along great-circle path (km)

$r_1 = 10^3 \, G_0^2 / Q_1 f$ (km)

f: frequency (kHz)

$Q_1 = 0.30$ at LF and 1.4 at MF.

The correction c_2 is given by:

$$c_2 = \alpha \, G_0 \left(1 - \frac{s_2}{r_2} \right) \quad \text{if} \quad s_2 < r_2 \tag{6}$$

$$c_2 = 0 \quad \text{if} \quad s_2 \geq r_2 \tag{7}$$

where:

s_2 : distance of terminal from next section of land, measured along great-circle path (km)

$r_2 = 10^3 \, G_0^2 / Q_2 f$ (km)

$Q_2 = 0.25$ at LF and 1.2 at MF

α: proportion of land in the section of path between r_2 and s_2 ($0 < \alpha \leq 1$).

If a computer is used but a terrain data bank is not available to calculate α, then α should be made equal to 0.5, which implies that land and sea are present in equal proportions in the section of path between r_2 and s_2.

To facilitate calculation, Fig. 14a shows r_1, the greatest distance from the sea for which sea gain has to be calculated, and Fig. 14b shows r_2, the greatest distance to the next section of land for which the correction c_2 is required, for various frequencies.

2.4 Polarization coupling loss

L_p is the excess polarization coupling loss (dB). At LF, $L_p = 0$. At MF, L_p for a single terminal is given by one of the following two formulae:

$$\begin{array}{lll} \text{if} \quad I \leq 45°: & L_p = 180 \, (36 + \theta^2 + I^2)^{-1/2} - 2 & \text{dB} \\ \text{if} \quad I > 45°: & L_p = 0 & \end{array} \tag{8}$$

where I is the magnetic dip, N or S, in degrees at the terminal and θ is the path azimuth measured in degrees from the magnetic E-W direction, such that $| \theta | \leq 90°$. L_p should be evaluated separately for the two terminals, because of the different θ and I that may apply, and the two L_p values added. The most accurate available values of magnetic dip and declination (e.g. see Figs. 11 and 12) should be used in determining θ and I.

Figure 13 shows values of L_p calculated from equation (8).

2.5 *Slant propagation distance p*

For paths longer than 1 000 km, p (km) is approximately equal to the ground distance, d (km) between transmitter and receiver. For shorter paths:

$$p = (d^2 + 40\,000)^{½} \tag{9}$$

Equation (9) may be used for paths of any length with negligible error. It should be used in all cases where the distances considered are both above and below 1 000 km, to avoid discontinuities in field strength as a function of distance.

2.6 *Loss factor*

The loss factor k_R is given by

$$k_R = k + 10^{-2}\ bR \tag{10}$$

where R is the twelve-month smoothed international relative sunspot number. At LF, the solar activity factor $b = 0$. At MF, $b = 4$ for North American paths, 1 for Europe and Australia and 0 elsewhere. For paths where the terminals are in different regions use the average value of b.

The basic loss factor k is given by:

$$k = 3.2 + 0.19\ f^{0.4} \tan^2(\Phi + 3) \tag{11}$$

where f : frequency (kHz); and Φ is the (centred dipole) geomagnetic latitude. If $\Phi > 60°$, equation (11) is evaluated for $\Phi = 60°$. If $\Phi < -60°$, equation (11) is evaluated for $\Phi = -60°$. Figure 15 shows values of k calculated from equation (11) according to these rules.

For paths shorter than 3 000 km:

$$\Phi = 0.5\,(\Phi_T + \Phi_R) \tag{12}$$

where Φ_T and Φ_R are the geomagnetic latitudes at the transmitter and receiver respectively, determined by assuming an Earth-centred dipole field model with northern pole at 78.5° N, 69° W geographic coordinates. The equation for Φ_T and Φ_R is given in Fig. 16 and Φ_T and Φ_R are taken as positive in the northern hemisphere and negative in the southern hemisphere. Paths longer than 3 000 km are divided into two equal sections which are considered separately. The value of Φ for each half-path is derived by taking the average of the geomagnetic latitudes at one terminal and at the mid-point of the whole path, the geomagnetic latitude at the mid-point of the whole path being assumed to be the average of Φ_T and Φ_R. As a consequence:

$$\Phi = (3\Phi_T + \Phi_R)\,/\,4 \quad \text{for the first half of the path and} \tag{13}$$

$$\Phi = (\Phi_T + 3\Phi_R)\,/\,4 \quad \text{for the second half} \tag{14}$$

The values of k calculated from equation (11) for the two half-paths are then averaged and used in equation (10).

2.7 *Hourly loss factor*

The hourly loss factor, L_t (dB) is given in Fig. 3. The time t is the time in hours relative to the sunrise or sunset time as appropriate. These are taken at the ground at the mid-path position for $d < 2\,000$ km and at 750 km from the terminal where the Sun sets or rises first for longer paths. The large values of hourly loss factor near midday are not defined (Fig. 3). For times in this period use a limit value of 30 dB. The hourly loss factor should not be calculated for high latitude paths and seasons when sunrise and sunset do not occur.

Equations generally equivalent to these curves to within 0.5 dB, are given in § 1 of Appendix 1. Figure 3 represents the average annual diurnal variation.

Figure 17 shows sunset and sunrise times for a range of geographic latitudes and months. Equations equivalent to these sunset and sunrise curves are given in § 2 of Appendix 1.

3. Day-to-day and short-period variations of night-time field strength

The field strength exceeded for 10% of the total time on a series of nights at a given season, during short periods centred on a specific time, is:

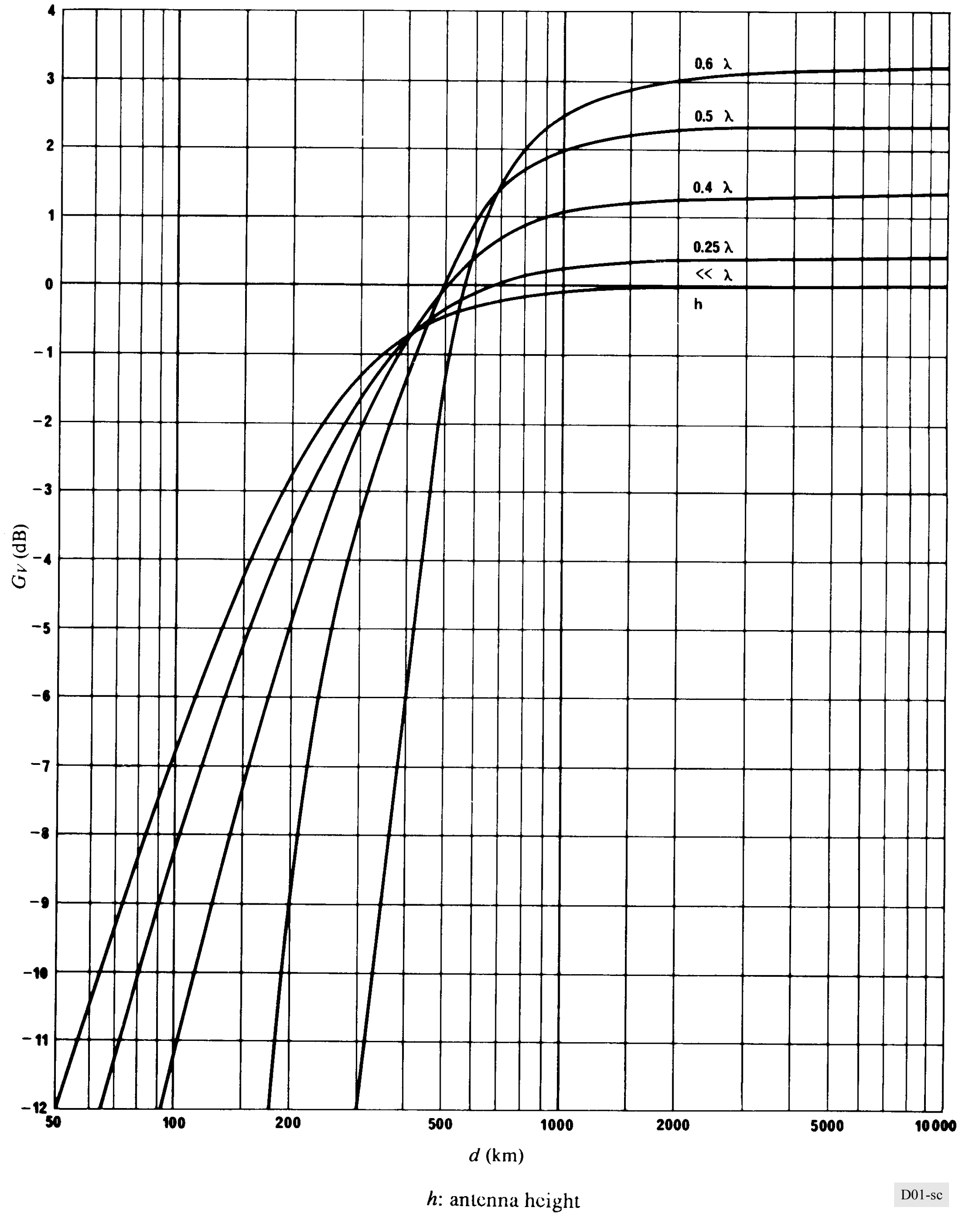
6.5 dB greater at LF,

8 dB greater at MF,

than the value of E_0 given in § 2.

FIGURE 1

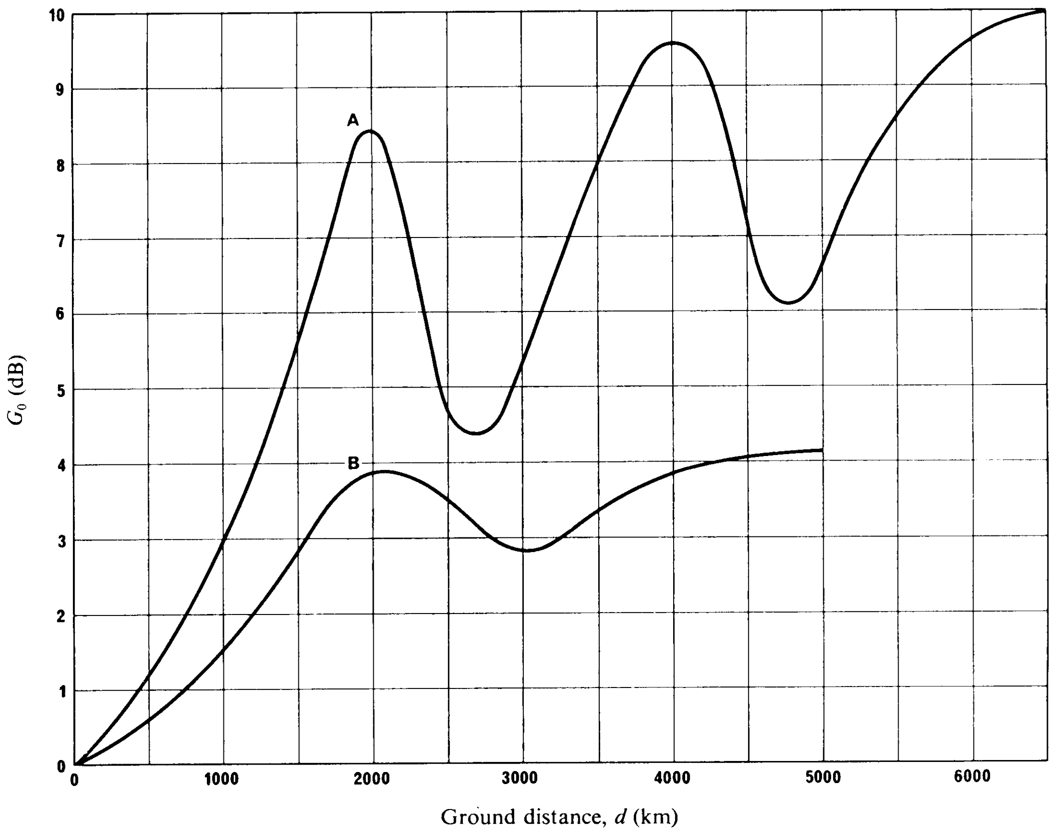
Transmitting antenna gain factor for single monopoles (G_V) over perfect earth



h: antenna height

FIGURE 2

Sea gain (G_0) for a single terminal on the coast



A: MF band B: LF band

FIGURE 3

Hourly loss factor (L_t)

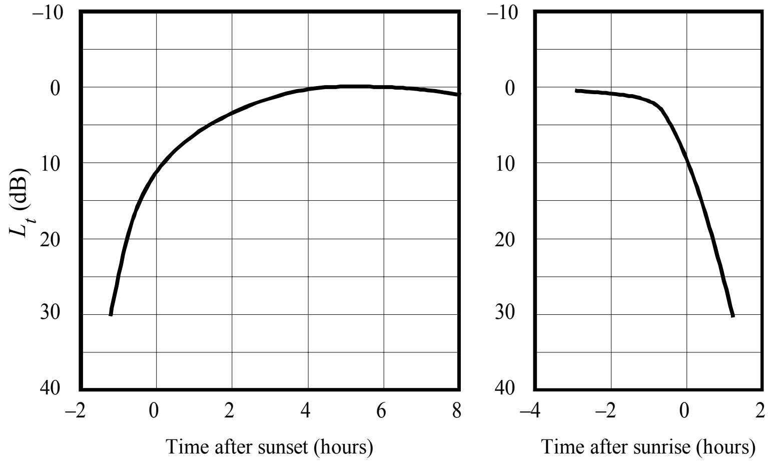
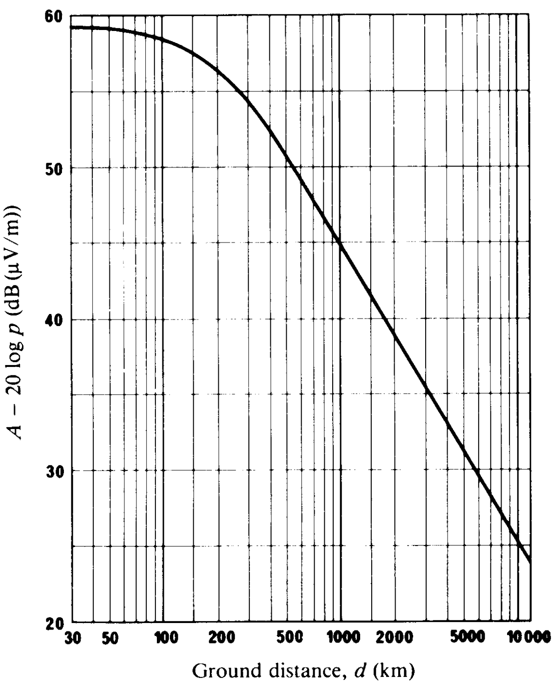


FIGURE 4

Basic field strength



The curves show $A - 20 \log p$
Where $A = 106.6 - 2 \sin \Phi$
$\Phi = 40°$
$p = (d^2 + 40\,000)^{1/2}$

D04-sc

FIGURE 5

Curves showing E_0 for 200 kHz, when G_S, L_p and R are all zero, for constant geomagnetic latitudes

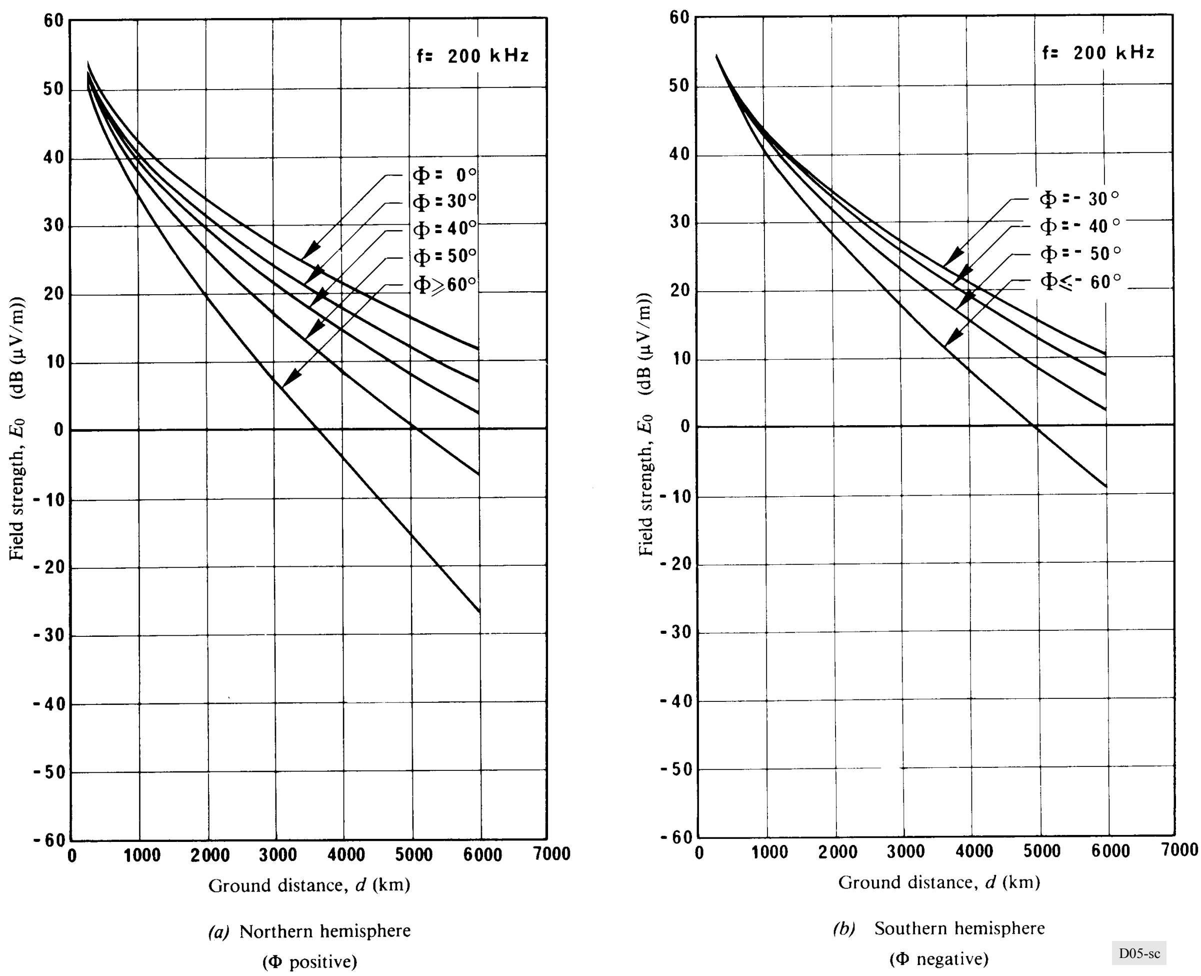
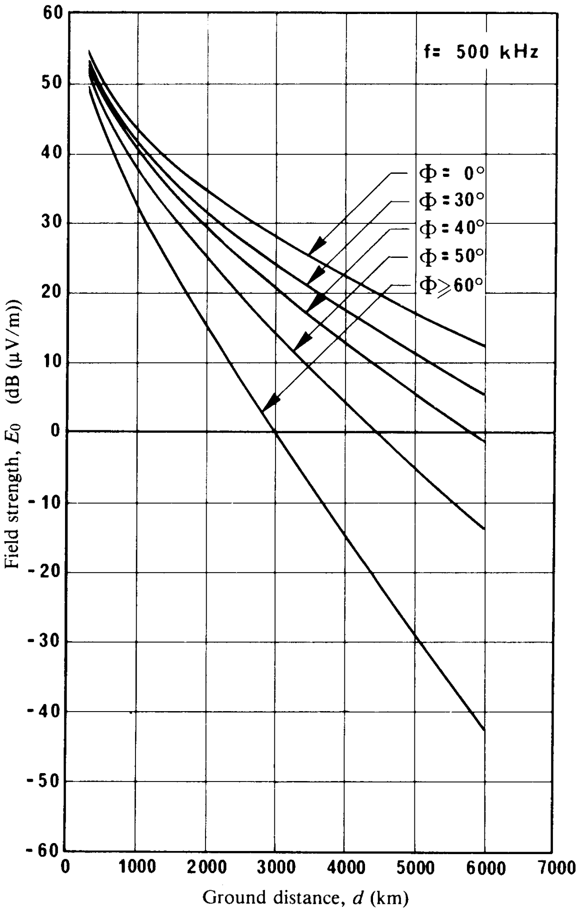
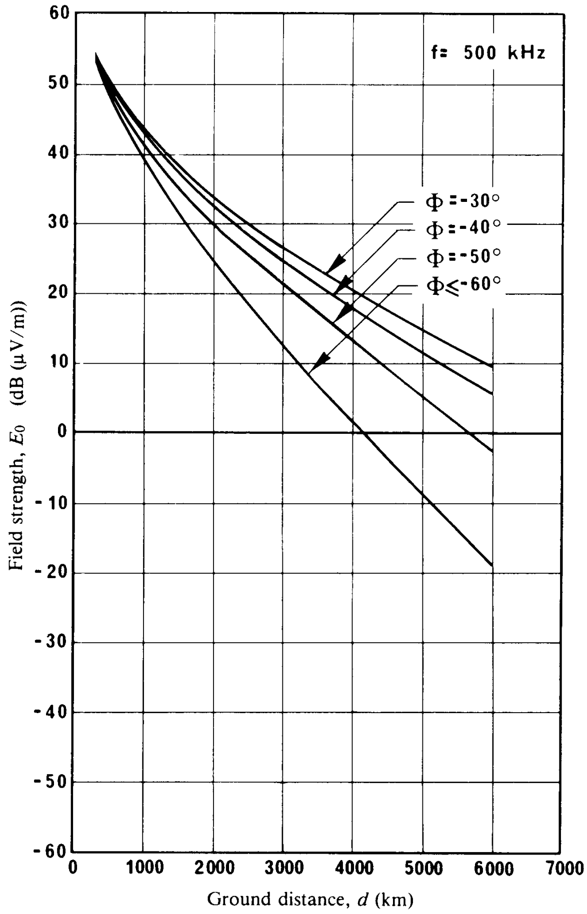


FIGURE 6

Curves showing E_0 for 500 kHz, when G_S, L_p and R are all zero, for constant geomagnetic latitudes



(a) Northern hemisphere
(Φ positive)



(b) Southern hemisphere
(Φ negative)

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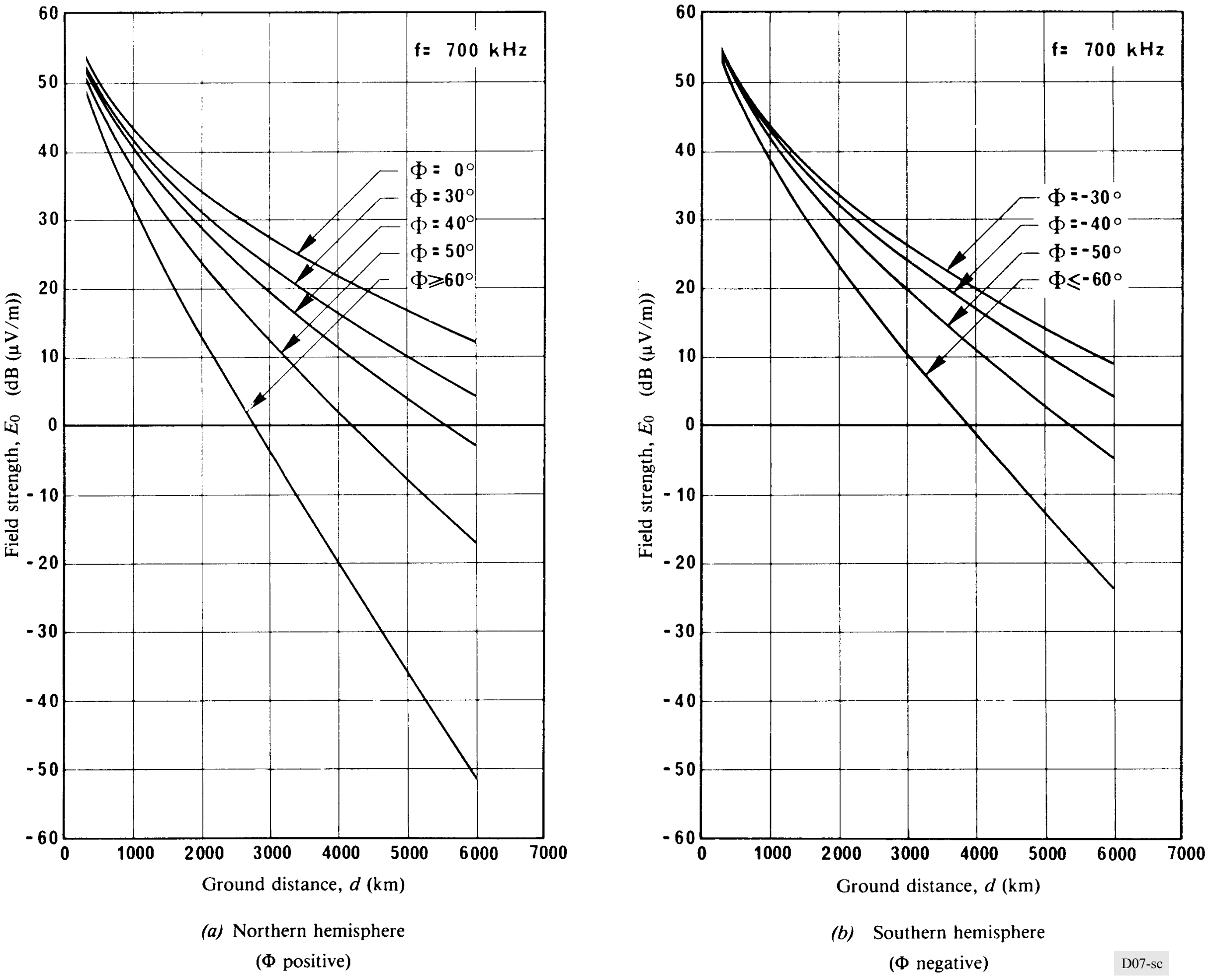
FIGURE 7

Curves showing E_0 for 700 kHz, when G_S, L_p and R are all zero, for constant geomagnetic latitudes

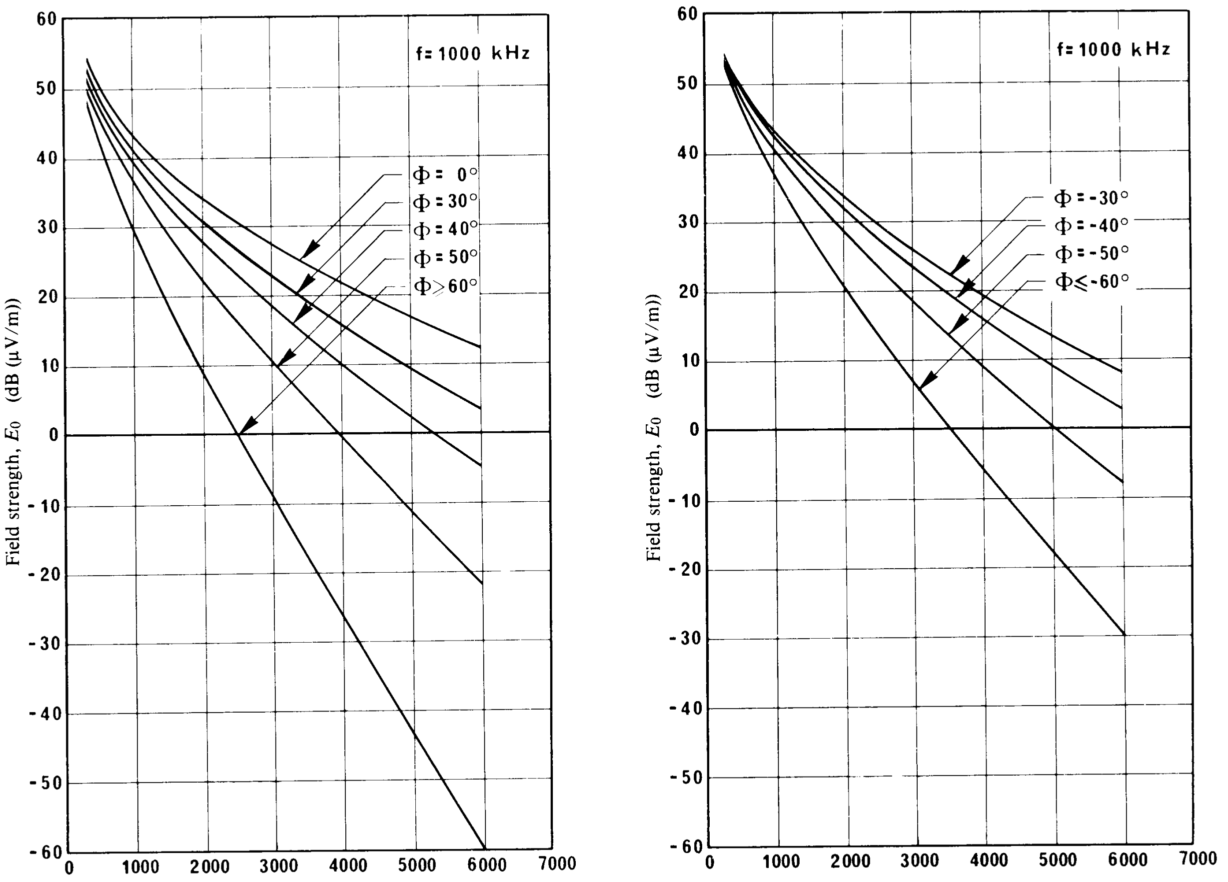


(a) Northern hemisphere
(Φ positive)

(b) Southern hemisphere
(Φ negative)

FIGURE 8

Curves showing E_0 for 1 000 kHz, when G_S, L_p and R are all zero, for constant geomagnetic latitudes



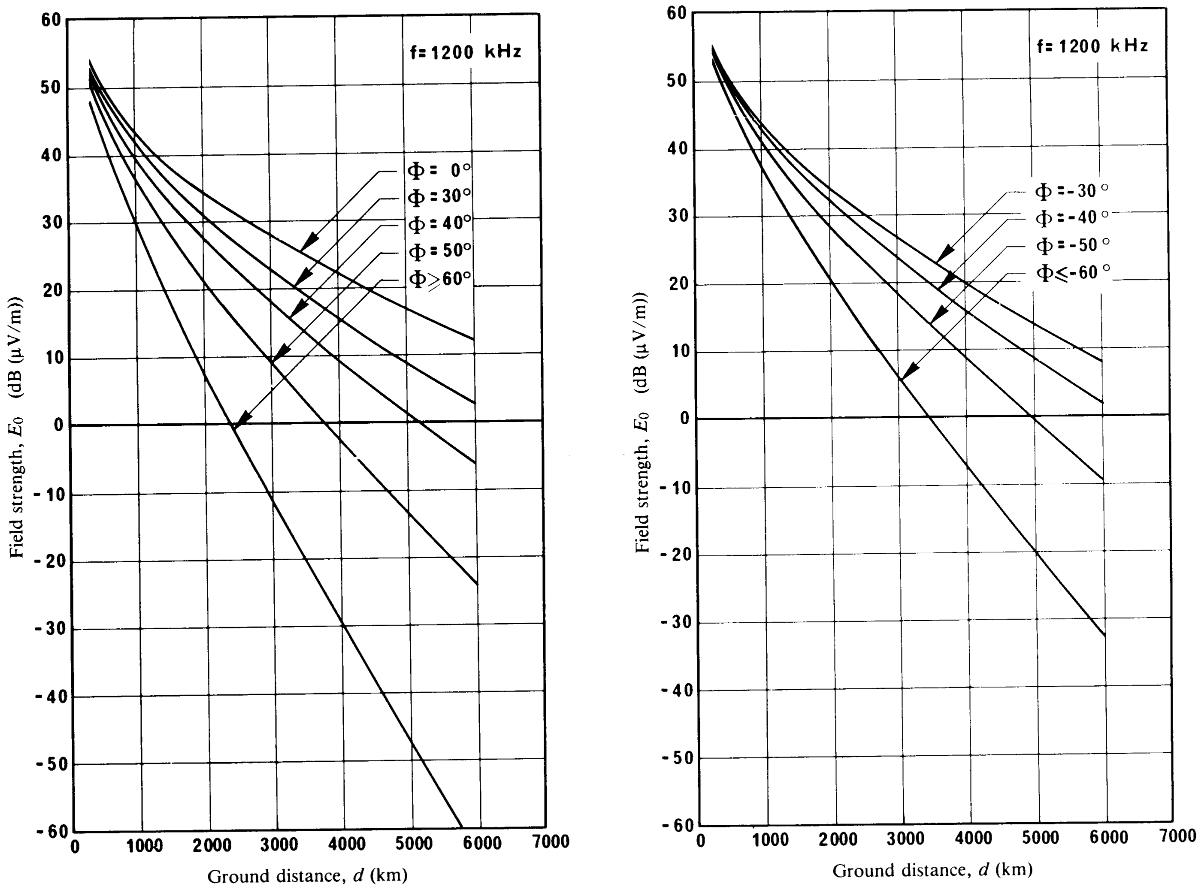
(a) Northern hemisphere
(Φ positive)

(b) Southern hemisphere
(Φ negative)

D08-sc

FIGURE 9

Curves showing E_0 for 1 200 kHz, when G_S, L_p and R are all zero, for constant geomagnetic latitudes

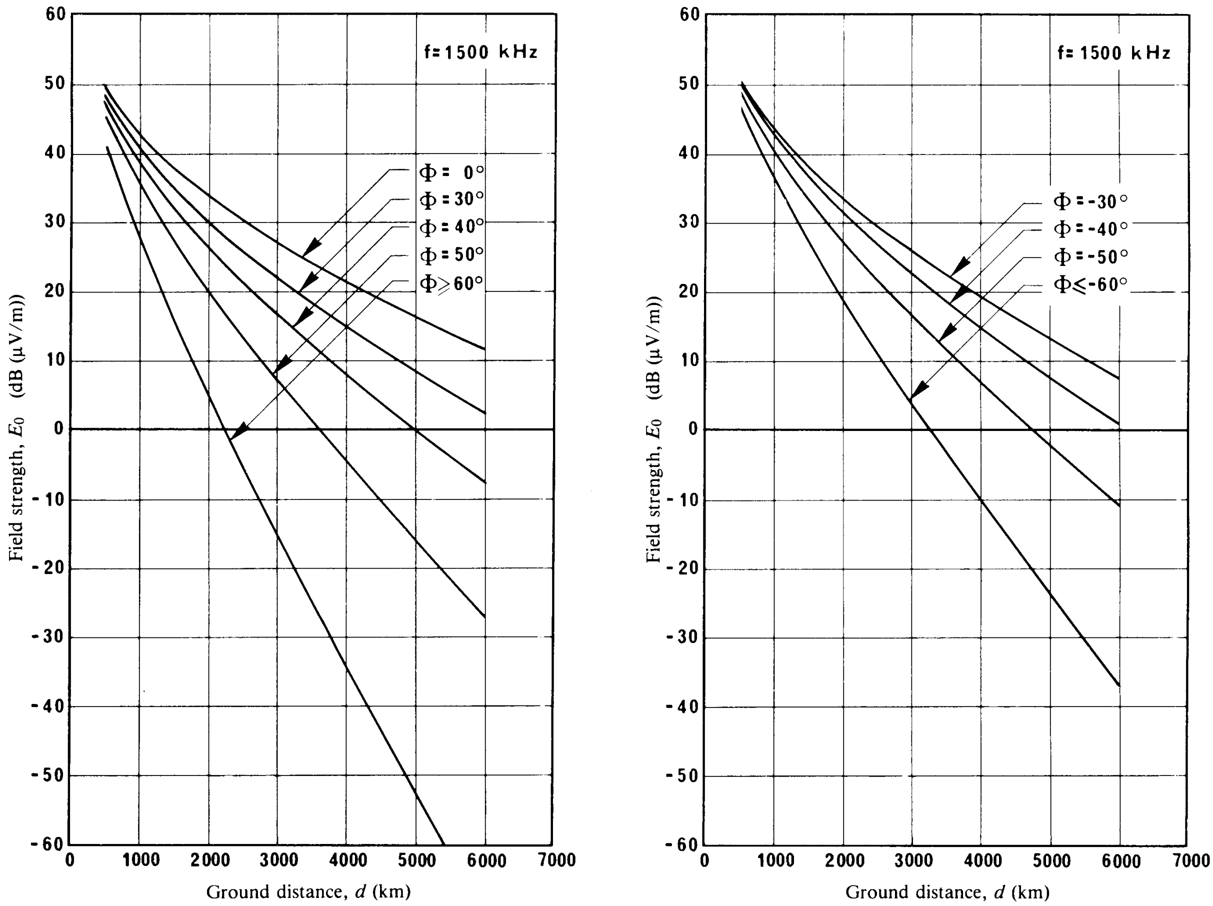


(a) Northern hemisphere (Φ positive)

(b) Southern hemisphere (Φ negative)

FIGURE 10

Curves showing E_0 for 1 500 kHz, when G_S, L_p and R are all zero, for constant geomagnetic latitudes



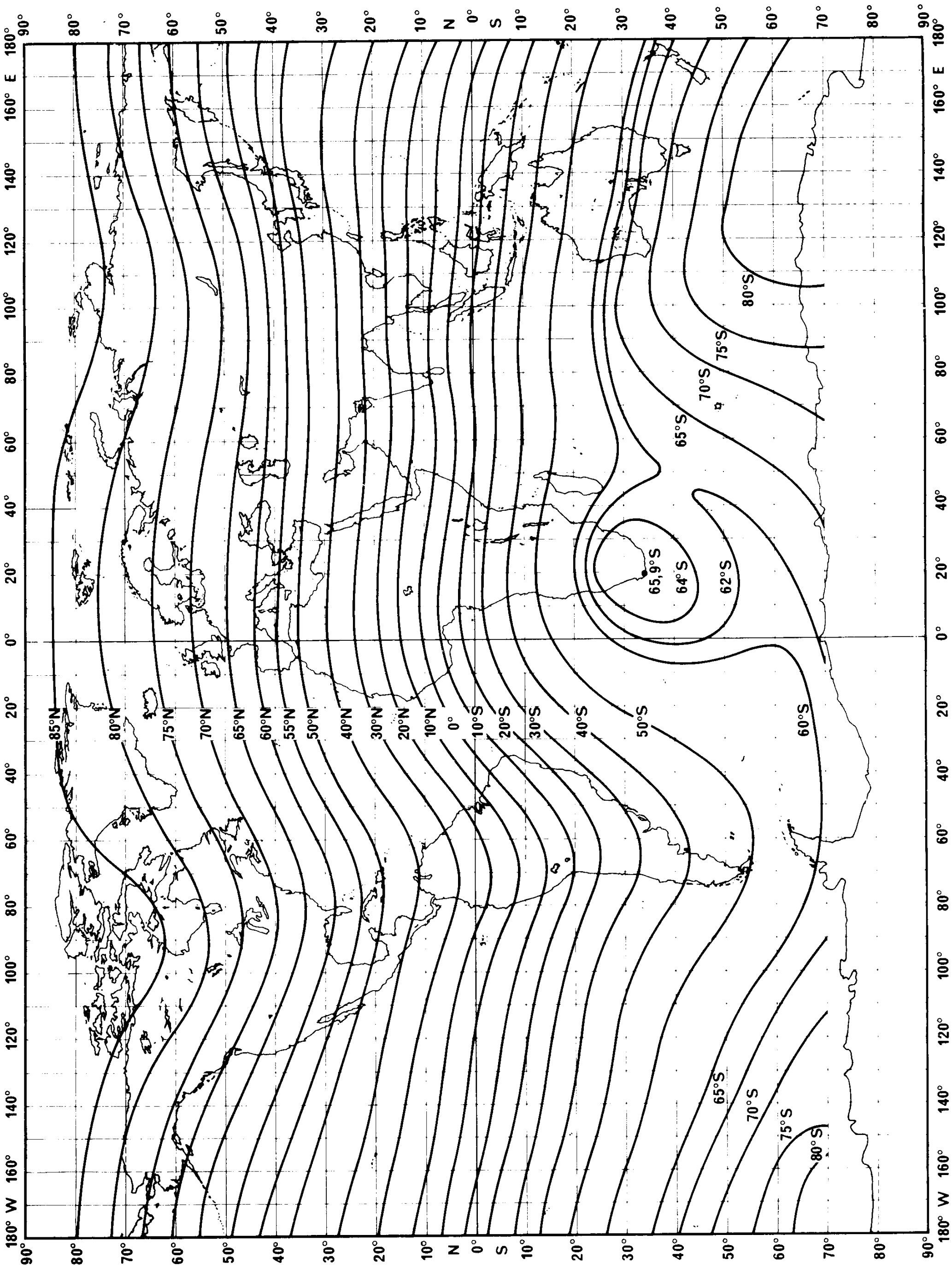
(a) Northern hemisphere (Φ positive)

(b) Southern hemisphere (Φ negative)

D10-sc

FIGURE 11

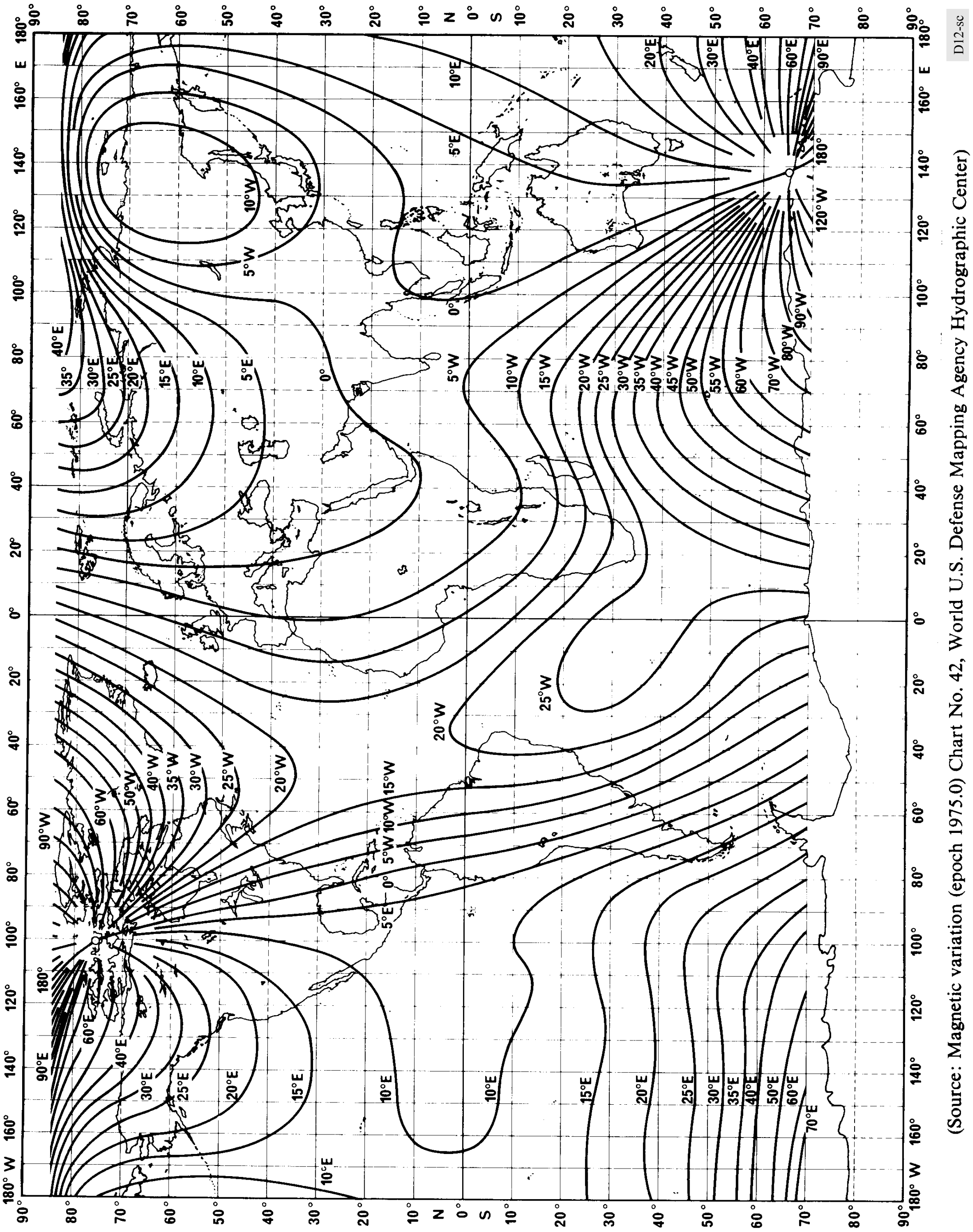
Map of magnetic dip (epoch 1975.0)



(Source: Magnetic inclination or dip (epoch 1975.0) Chart No. 30 World U.S. Defense Mapping Agency Hydrographic Center)

FIGURE 12

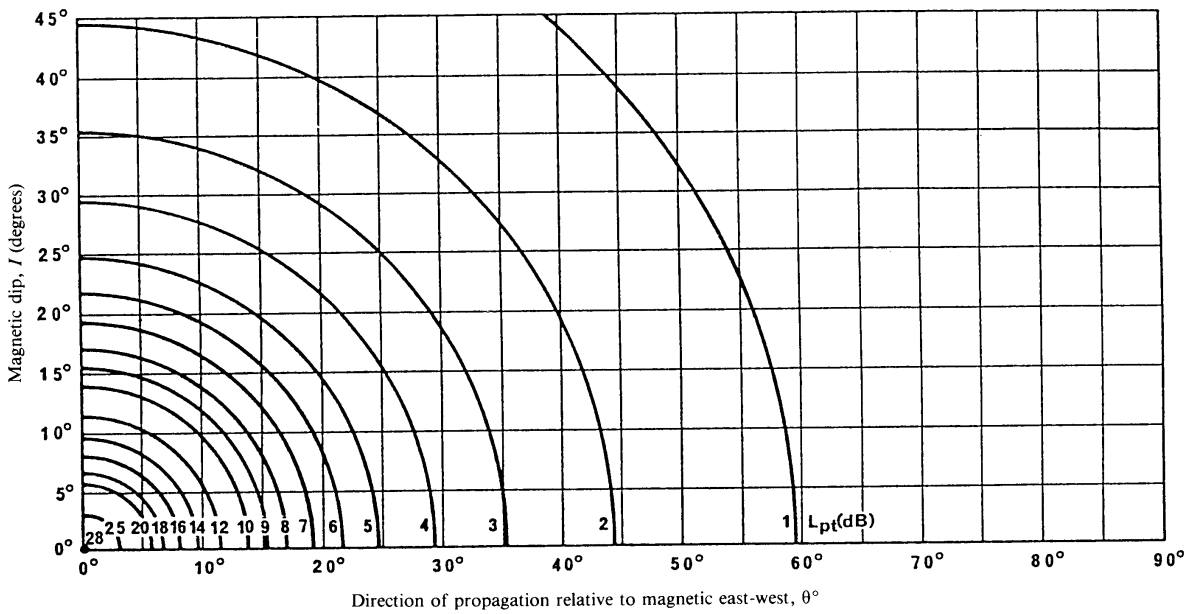
Map of magnetic declination (epoch 1975.0)



(Source: Magnetic variation (epoch 1975.0) Chart No. 42, World U.S. Defense Mapping Agency Hydrographic Center)

FIGURE 13

Excess polarization coupling loss L_p (for a single terminal)



$$L_p = 180\,(36 + \theta^2 + I^2)^{-\frac{1}{2}} - 2$$

D13-sc

FIGURE 14a

Values of r_1 for various frequencies

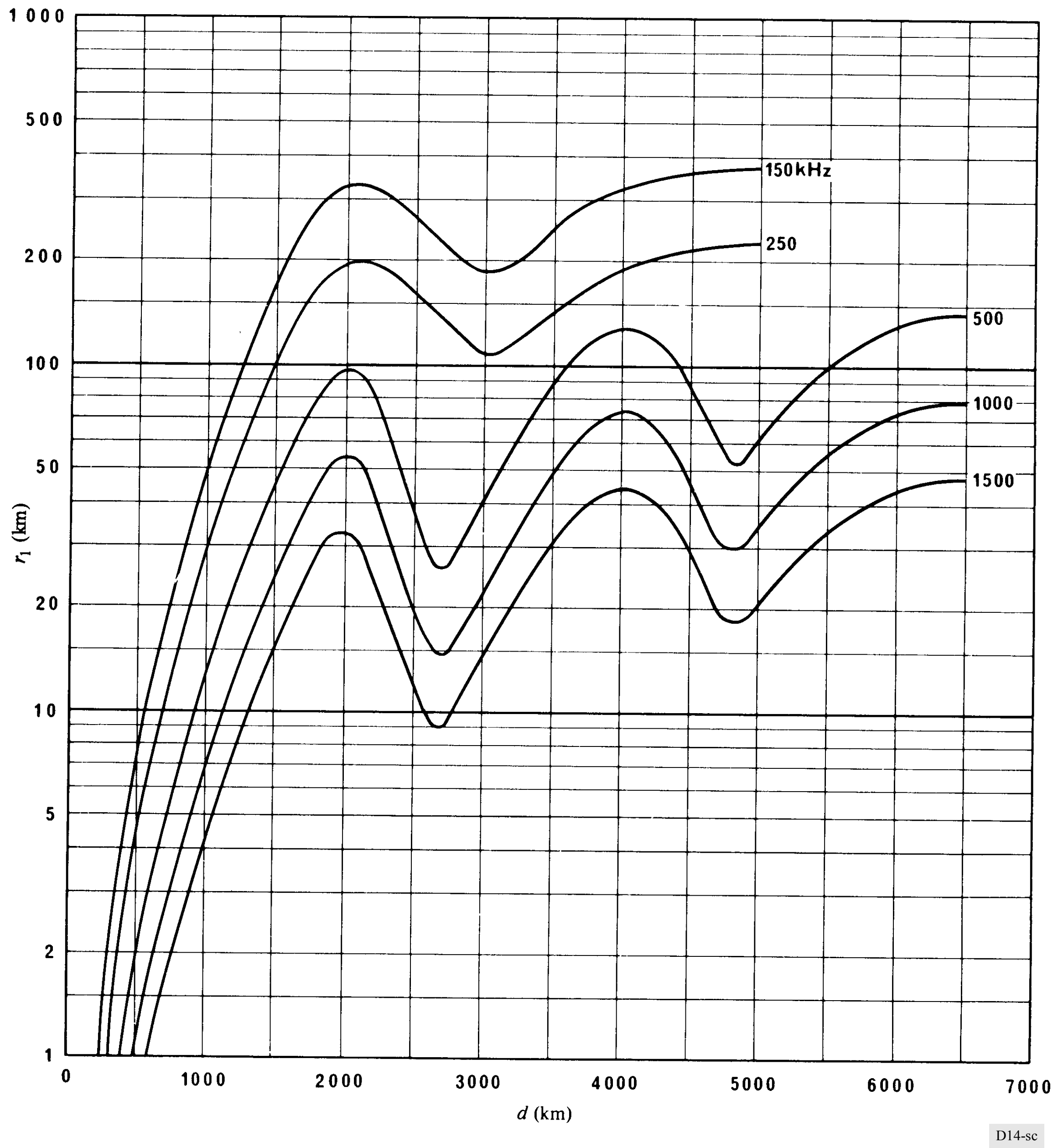


FIGURE 14b

Values of r_2 for various frequencies

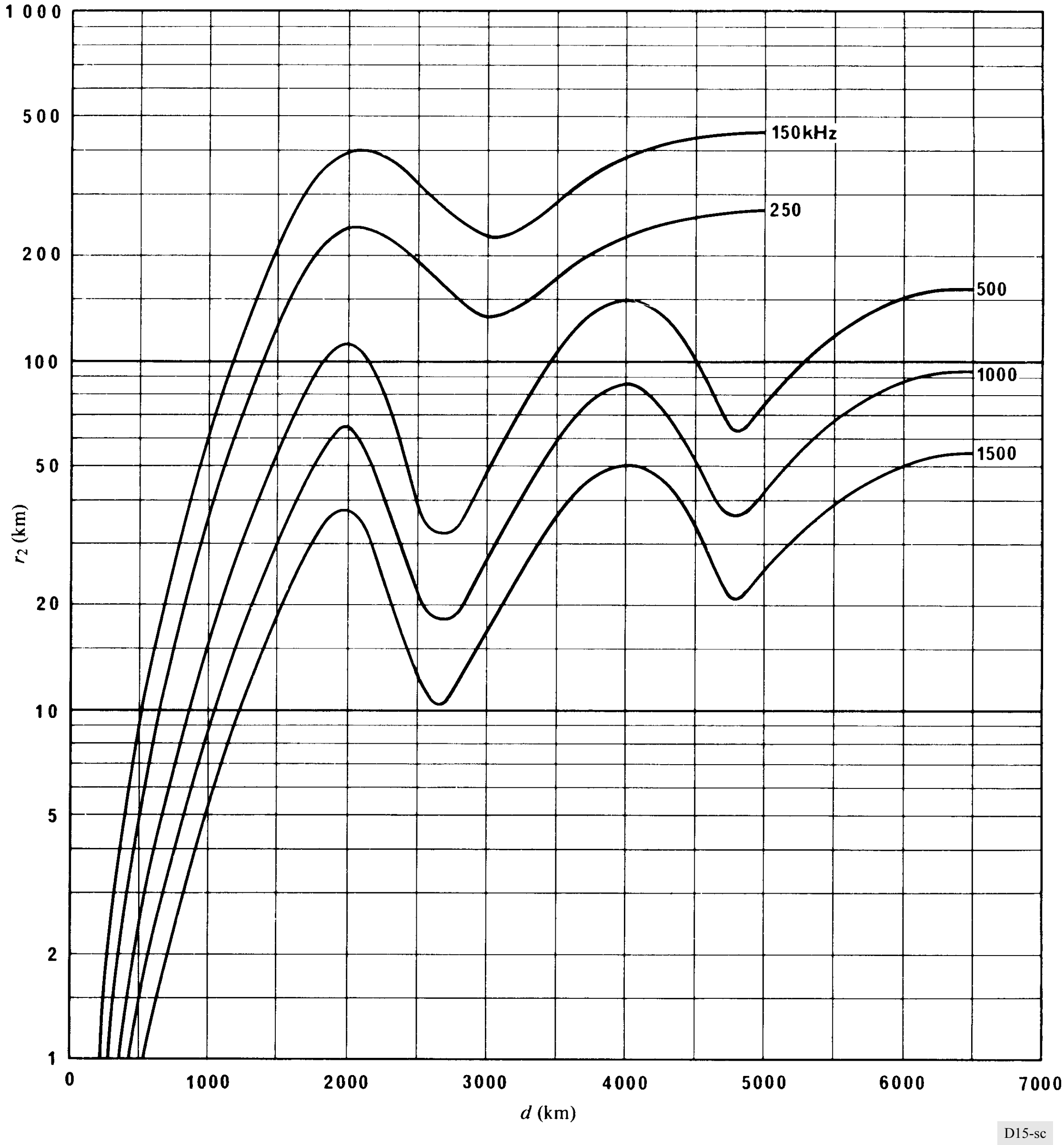
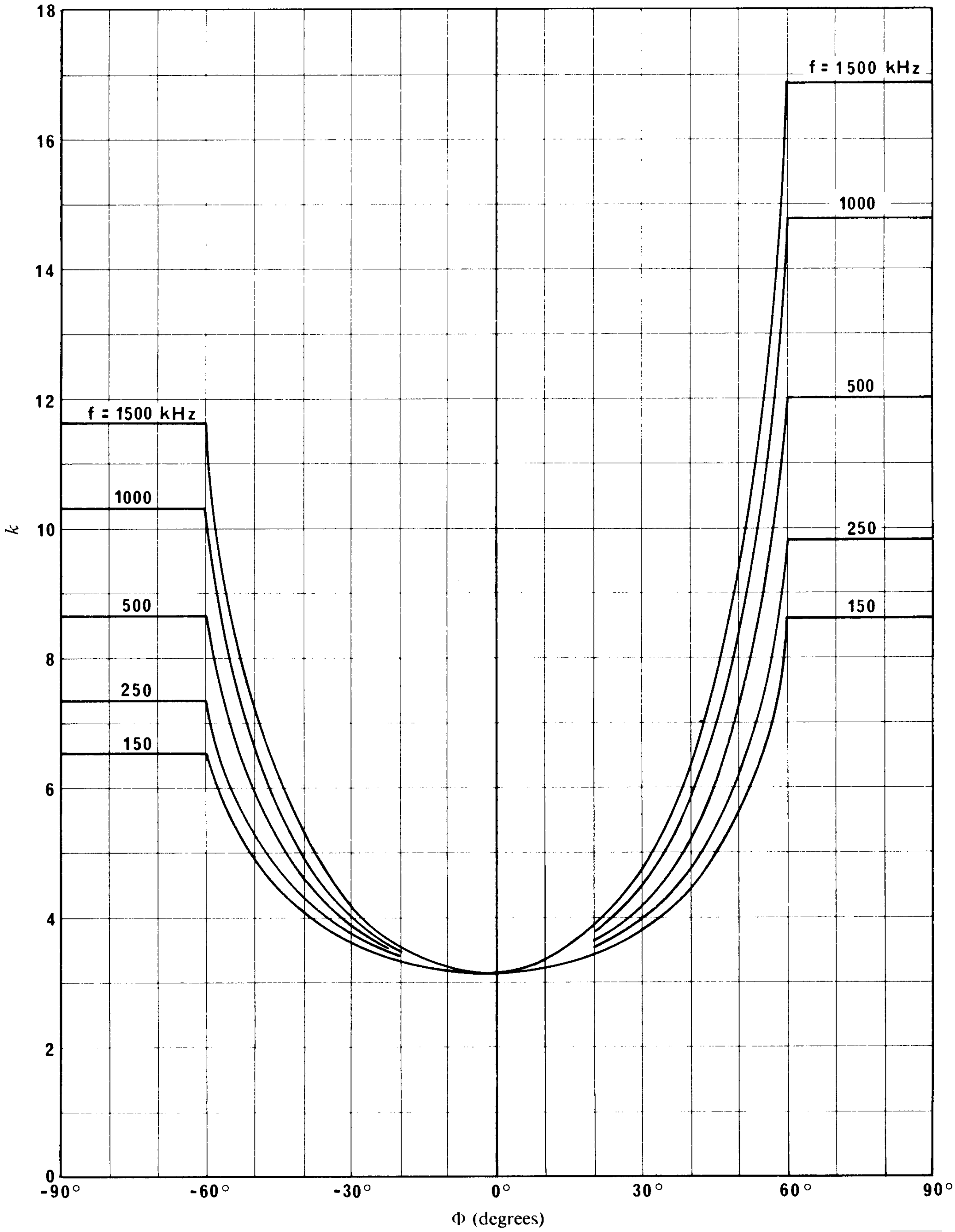


FIGURE 15

Basic loss factor

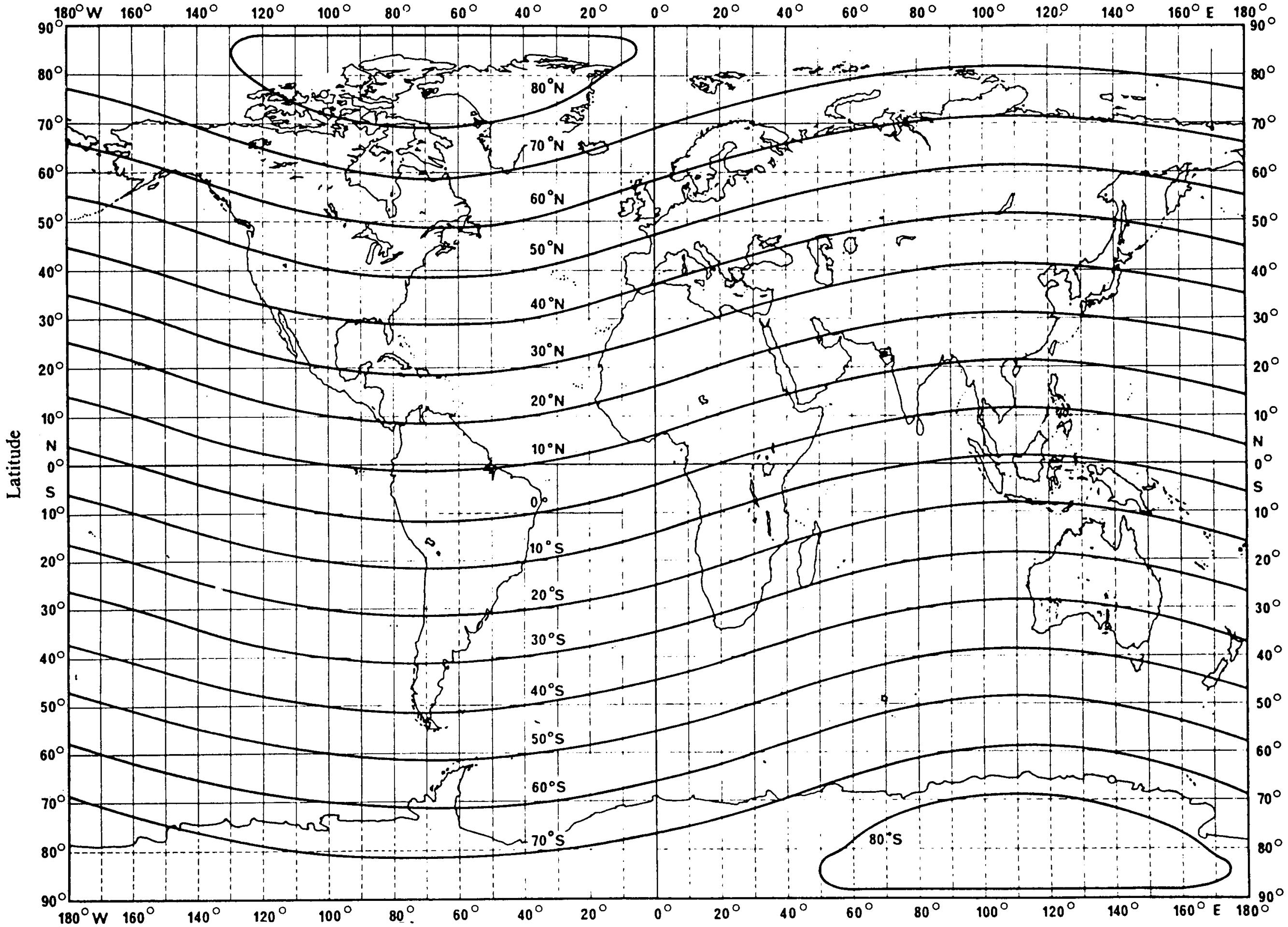


$$k = 3.2 + 0.19\, f^{0.4} \tan^2(\Phi + 3)$$

$$-60° \leqslant \Phi \leqslant 60°$$

FIGURE 16

Geomagnetic latitudes



$\Phi = \arcsin [\sin \alpha \cdot \sin 78.5° + \cos \alpha \cdot \cos 78.5° \cdot \cos (69° + \beta)]$

Φ: geomagnetic latitude

α: geographic latitude

β: geographic longitude

North and East coordinates are considered positive, and South and West coordinates negative.

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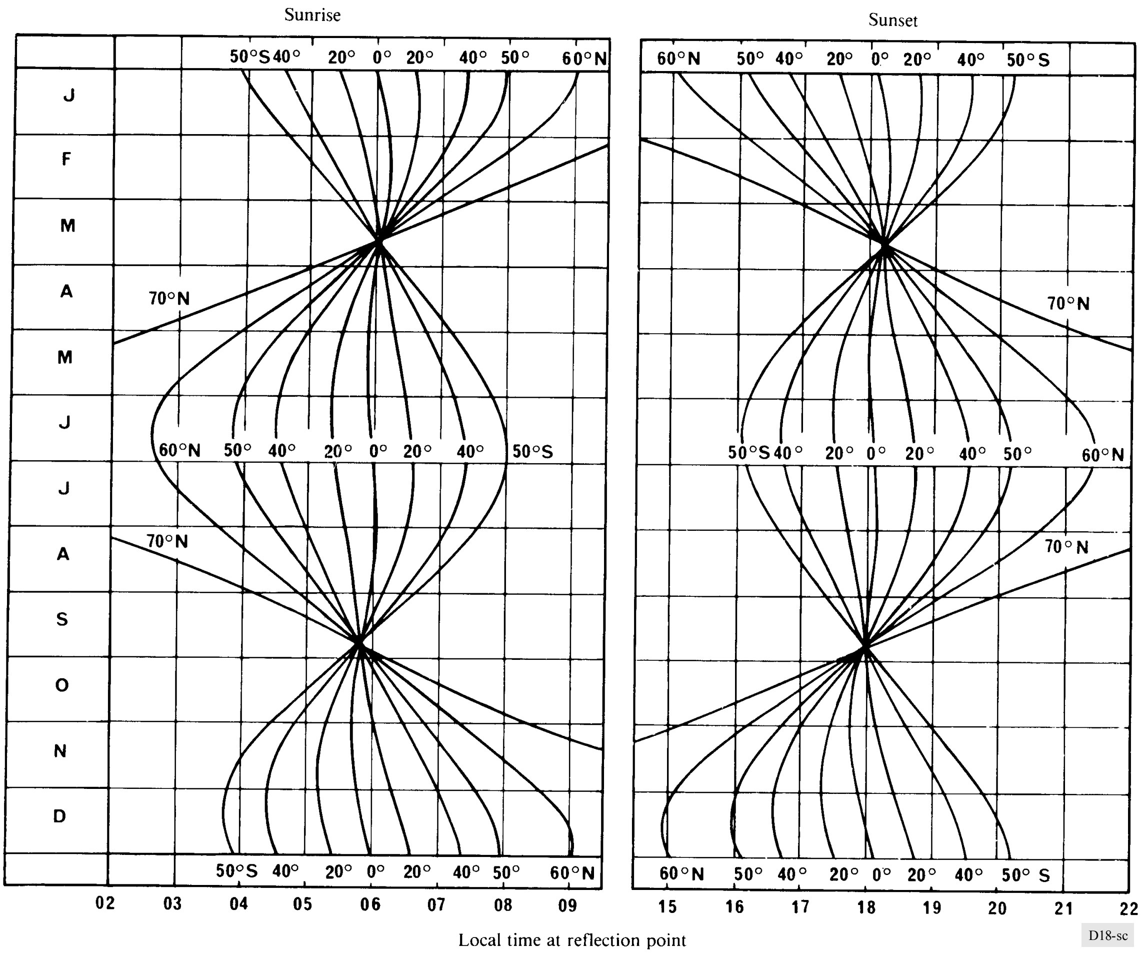
FIGURE 17

Times of sunrise and sunset for various months and geographical latitudes



APPENDIX 1

This Appendix contains equations that may be used in lieu of Figs. 3 and 17 for hourly loss factor, and sunset and sunrise times respectively. For the purpose of this Appendix, the following additional symbols are used.

List of symbols

α : geographic latitude of a point on the path (degrees)

β : geographic longitude of a point on the path (degrees)

S : local mean time of sunset or sunrise at a point (hours).

North and East coordinates are considered positive, and South and West coordinates negative.

1. Hourly loss factor: L_t

These equations may be used instead of the curves in Fig. 3, within the stated limits of t. For hours between these times (i.e. near midnight) set $L_t = 0$.

$$L_t \text{ (sunset)} = 12.40 - 9.248\, t + 2.892\, t^2 - 0.3343\, t^3 \qquad \text{for } -1 < t \text{ (sunset)} < 4, \text{ and}$$

$$L_t \text{ (sunrise)} = 9.6 + 12.2\, t + 5.62\, t^2 + 0.86\, t^3 \qquad \text{for } -3 < t \text{ (sunrise)} < 1;$$

where t is the time in hours relative to sunset or sunrise at the path mid-point.

2. Sunset and sunrise times

For non-polar locations, i.e. such that $|\alpha| < 65°$, the times of sunset and sunrise can be calculated as follows, to an accuracy of ± 2 min.

N: day of year, in days; e.g. 1 January = 1

S': approximate local time of event, e.g. sunset = 1800 h, sunrise = 0600 h

Z: Sun's zenith distance (degrees) = 90.8333°(90°50′) for sunset or sunrise.

Step 1: Calculate observer's longitude, B:

$$B = \beta / 15 \qquad \text{h}$$

Step 2: Calculate the time of event, Y:

$$Y = N + (S' - B)/24 \qquad \text{days}$$

Step 3: Calculate Sun's mean anomaly, M:

$$M = 0.985600\, Y - 3.289 \qquad \text{degrees}$$

Step 4: Calculate Sun's longitude, L:

$$L = M + 1.916 \sin M + 0.020 \sin 2M + 282.634 \qquad \text{degrees}$$

Note in which quadrant L occurs.

Step 5: Calculate Sun's right ascension, RA:

$$\tan RA = 0.91746 \tan L$$

Note that RA must be in the same quadrant as L.

Step 6: Calculate Sun's declination s:

$\sin s = 0.39782 \sin L$, from which:

$$\cos s = + \sqrt{1 - \sin^2 s}$$

Note that $\sin s$ may be positive or negative but $\cos s$ must always be positive.

Step 7: Calculate Sun's local hour angle H:

$$\cos H = x = (\cos Z - \sin s \cdot \sin \alpha) / (\cos s \cdot \cos \alpha)$$

Note that if $| x | > 1$, there is no sunset or sunrise.

From $\cos H$, obtain H in degrees; for sunrise $180 < H < 360$; for sunset $0 < H < 180$.

Step 8: Calculate local mean time of event, S :

$$S = H / 15 + RA / 15 - 0.065710 \; Y - 6.622$$

Note that S is expressed in hours and that multiples of 24 should be added or subtracted until $0 < S < 24$.

Note that S is the local time at the point concerned. The corresponding standard time is $S - B + \beta_m/15$ h where β_m is the longitude of the standard meridian for the desired time zone (degrees) so that, for example, universal time $= S - B$.

ANNEX 1

Accuracy of method

The method applies for paths of length 50 to 12 000 km in the LF and MF bands. However, at LF it has only been verified for paths up to 5 000 km. The accuracy of prediction varies from region to region and may be improved in certain regions by applying modifications such as those discussed below.

The asymmetry so evident in the basic loss factor (Fig. 15) might have been removed if "corrected geomagnetic latitude" had been used rather than geomagnetic latitude. In any case, the method should be used with caution for geomagnetic latitudes greater than 60°.

Field strengths measured in the United States of America and Brazil tend to be greater at higher frequencies; the frequency variation given by equation (11) is in the opposite sense. For these and other reasons, the method should be used provisionally in Region 2.

Equation (6) which describes how G_S is modified by the distance s_2 to the next section of land is derived from theory and must therefore be regarded as tentative until measurements are available.

The method predicts the field strength which is likely to be observed if the transmitter and receiver are situated on ground of average conductivity, typically 3 to 10 mS/m. In certain areas (e.g. see Recommendation 832), the effective ground conductivity can be as low as 0.5 mS/m or as high as 40 mS/m. If the ground conductivity at either terminal is an order of magnitude smaller than 10 mS/m, then the field strength may be up to 10 dB smaller. If the ground conductivity at both terminals is an order of magnitude smaller, then the field-strength reduction will be doubled. The amount of attenuation is a function of path length and is greatest for waves approaching grazing incidence. The method may be improved by using a correction for ground conductivity when it differs significantly from that for average ground, for example by using the information contained in Reports 265 and 575.

The method assumes that reflection takes place only via the E layer, or that E-layer reflections predominate. However, if $f >$ (foE) sec i, where foE is the critical frequency of the E layer and i is the angle of incidence at the E layer, then the wave will penetrate the E layer and be reflected from the F layer. This is most likely to occur at the highest frequencies in the MF band at ground distances less than 500 km, especially late at night and during the sunspot minimum period. The method can still be used provided p is calculated for an F-layer reflection height of 220 km and the cymomotive force V is calculated for the corresponding angle of elevation.

Measurements made in the United States of America suggest that Fig. 3 (hourly loss factor) is likely to be accurate for frequencies near 1 000 kHz in a year of low solar activity. As the frequency deviates in either direction from about 1 000 kHz, particularly during transition hours, appreciable errors may result. These measurements also suggest that the magnitude of the effect of solar activity at two hours after sunset is considerably greater than that at six hours after sunset. Thus, in a year of high solar activity, the difference between field strengths at six hours after sunset and two hours after sunset can be considerably greater than that shown in Fig. 3.

At night, MF sky-waves propagating in temperate latitudes are strongest in spring and autumn and are weakest in summer and winter, the summer minimum being the more pronounced. The overall variation may be as much as 15 dB at the lowest frequencies in the MF band, decreasing to about 3 dB at the upper end of the band. At LF the seasonal variation at night has the opposite trend, with a pronounced summer maximum. The seasonal variation is much smaller in tropical latitudes.

At LF in Europe the median day-time field strength in winter is 10 dB less than the night-time value of E_0 given in § 2. In summer the day-time field strength is 30 dB less than E_0. The field strength exceeded for 10% of the total time on a series of days in winter, during short periods centred on a specific time, is 5 dB greater than the median day-time value given above.

At MF in Europe the median day-time field strength in winter is 25 dB less than the night-time value of E_0 given in § 2. In summer the day-time field strength is about 60 dB less than E_0.

In spring and autumn in Europe, day-time field strengths at LF and MF have values between the summer and winter values.