RECOMMENDATION ITU-R P.533-7

HF propagation prediction method*

(Question ITU-R 223/3)

(1978-1982-1990-1992-1994-1995-1999-2001)

The ITU Radiocommunication Assembly,

considering

a) that tests against ITU-R Data Bank D1 show that the method of Annex 1 of this Recommendation has comparable accuracy to the other more complex methods;

b) that information on the performance characteristics of transmitting and receiving antennas is required for the practical application of this method**;

c) that associated computer codes have been formulated and made available to the Radiocommunication Bureau,

recommends

1 that the information contained in Annex 1 should be used in computerized prediction of sky-wave propagation at frequencies between 2 and 30 MHz;

2 that administrations and ITU-R should endeavour to improve prediction methods to enhance operational facilities and to improve accuracy.

ANNEX 1

CONTENTS

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* A computer program (REC533) associated with the prediction procedures described in this Recommendation is available from that part of the ITU-R website dealing with Radiocommunication Study Group 3.

** Detailed information on a range of antennas with an associated computer program is available from the ITU; for details see Recommendation ITU-R BS.705.

1 Introduction

This propagation prediction method for use in the estimation of reliability and compatibility between frequencies of about 2 MHz and 30 MHz derives from a method first proposed in 1983 by Interim Working Party 6/12 of the ex-CCIR with later refinements following considerations by the Second Session of the World Administrative Radio Conference for the Planning of HF Bands Allocated to the Broadcasting Service (Geneva, 1987) (WARC HFBC-87), the ex-CCIR, ITU-R, broadcasting and other organizations. The procedure applies a ray-path analysis for path lengths up to 7 000 km, composite mode empirical formulations from the fit to measured data beyond 9 000 km and a smooth transition between these two approaches over the 7 000-9 000 km distance range.

Monthly median basic MUF, incident sky-wave field strength and available receiver power from a lossless receiving antenna of given gain are determined. Signal strengths are standardized against an ITU-R measurement data bank. The method requires the determination of a number of ionospheric characteristics and propagation parameters at specified “control points”.

2 Location of control points

Propagation is assumed to be along the great-circle path between the transmitter and receiver locations via E modes (up to 4 000 km range) and F2 modes (for all distances). Depending on path length and reflecting layer, control points are selected as indicated in Table 1.

TABLE 1

Locations of control points for the determination of basic MUF, E-layer screening, ray-path mirror-reflection heights and ionospheric absorption

a) Basic MUF and associated electron gyrofrequency

Path length, *D* (km)	**E modes**	**F2 modes**
$0 < D \leq 2\,000$	M	M
$2\,000 < D \leq 4\,000$	$T + 1\,000$, $R - 1\,000$	–
$2\,000 < D \leq d_{max}$	–	M
$D > d_{max}$	–	$T + d_0 / 2$, $R - d_0 / 2$

b) E-layer screening

Path length, *D* (km)	**F2 modes**
$0 < D \leq 2\,000$	M
$2\,000 < D < 9\,000$	$T + 1\,000$, $R - 1\,000$

c) Ray-path mirror-reflection heights

Path length, *D* (km)	**F2 modes**
$0 < D \leq d_{max}$	M
$d_{max} < D < 9\,000$	$T + d_0 / 2$, M, $R - d_0 / 2$

d) Ionospheric absorption and associated electron gyrofrequency

Path length, *D* (km)	**E modes**	**F2 modes**
$0 < D \leq 2\,000$	M	M
$2\,000 < D \leq 4\,000$	$T + 1\,000$, M, $R - 1\,000$	–
$2\,000 < D \leq d_{max}$	–	$T + 1\,000$, M, $R - 1\,000$
$d_{max} < D < 9\,000$	–	$T + 1\,000$, $T + d_0 / 2$, M, $R - d_0 / 2$, $R - 1\,000$

M: path mid-point
T: transmitter location
R: receiver location
d_{max}: maximum hop length for F2 mode
d_0: hop length of lowest-order mode

Distances are quoted in kilometres.

3 Basic and operational maximum usable frequencies

The estimation of operational MUF, the highest frequency that would permit acceptable operation of a radio service, is in two stages: first, the estimation of basic MUF from a consideration of ionospheric parameters and second, the determination of a correction factor to allow for propagation mechanisms at frequencies above the basic MUF.

3.1 Basic maximum usable frequencies

The basic MUFs of the various propagation modes are evaluated in terms of the corresponding ionospheric layer critical frequencies and a factor related to hop length. Where both E and F2 modes are considered the higher of the two basic MUFs of the lowest-order E and F2 modes give the basic MUF for the path.

3.2 E-layer critical frequency (foE)

foE is determined as defined in Recommendation ITU-R P.1239.

3.3 E-layer basic MUF

foE is evaluated at the control points noted in Table 1a) and for path lengths of 2 000-4 000 km the lower value is selected. The basic MUF of an *n*-hop E mode over a path of length *D* is given by:

$$n\ \mathrm{E}(D)\mathrm{MUF} = \mathrm{foE} \cdot \sec i_{110} \qquad (1)$$

where i_{110} is the angle of incidence at a mid-hop mirror-reflection height of 110 km for a hop of length $d = D/n$.

The E-layer basic MUF for the path is the value of E(D)MUF for the lowest-order E-mode.

3.4 F2-layer characteristics

Numerical representations of the ionospheric characteristics foF2 and M(3000)F2, for solar-index values $R_{12} = 0$ and 100, and for each month are taken from Recommendation ITU-R P.1239 where the magnetic field is evaluated at a height of 300 km. The Oslo coefficients are used to determine these values for the required times and for the control points given in Table 1a). Linear interpolation or extrapolation is applied for the prevailing index values between $R_{12} = 0$ and 150 (see Recommendation ITU-R P.371). For higher sunspot activity, R_{12} is set equal to 150 in the case of foF2 only.

3.5 F2-layer basic MUF

3.5.1 Lowest-order mode

3.5.1.1 Paths up to d_{max} (km)

The order, n_0, of the lowest-order mode is determined by geometrical considerations, using the mirror reflection height h_r derived at the mid-path control point from the equation:

$$h_r = \frac{1490}{\mathrm{M(3000)F2}} - 176 \text{ km or 500 km, whichever is the smaller} \qquad (2)$$

For this mode, the F2-layer basic MUF, which is also the F2-layer basic MUF for the path, is calculated as:

$$n_0 \text{ F2}(D)\text{MUF} = \left[1 + \left(\frac{C_d}{C_{3000}}\right)(B-1)\right] \cdot \text{foF2} + \frac{f_H}{2}\left(1 - \frac{d}{d_{max}}\right) \tag{3}$$

where:

f_H: value of electron gyrofrequency, for a height of 300 km, determined at each of the appropriate control points given in Table 1a)

$$C_d = 0.74 - 0.591\, Z - 0.424\, Z^2 - 0.090\, Z^3 + 0.088\, Z^4 + 0.181\, Z^5 + 0.096\, Z^6 \tag{4}$$

with $Z = 1 - 2d/d_{max}$

$$d_{max} = 4\,780 + (12\,610 + 2\,140/x^2 - 49\,720/x^4 + 688\,900/x^6)\ (1/B - 0.303) \tag{5}$$

$$B = \text{M(3000)F2} - 0.124 + [[\text{M(3000)F2}]^2 - 4] \cdot \left[0.0215 + 0.005 \sin\left(\frac{7.854}{x} - 1.9635\right)\right] \tag{6}$$

where:

$d =$ D/n_0 and d_{max} are in kilometres

C_{3000}: value of C_d for $D = 3\,000$ km

$x =$ foF2/foE, or 2, whichever is the larger

foE is calculated as in § 3.3.

3.5.1.2 Paths longer than d_{max} (km)

The basic MUF of the lowest-order mode n_0 F2(D)MUF for path length D is taken equal to the lower of the F2(d_{max})MUF values determined from equation (3) for the two control points given in Table 1a). This is also the basic MUF for the path.

3.5.2 Higher-order modes (paths up to 9 000 km)

3.5.2.1 Paths up to d_{max} (km)

The F2-layer basic MUF for an n-hop mode is calculated using equations (3) to (6) at the midpath control point given in Table 1a) for hop length $d = D/n$.

3.5.2.2 Paths longer than d_{max} (km)

The F2-layer basic MUF for an n-hop mode is calculated in terms of F2(d_{max})MUF and a distance scaling factor dependent on the respective hop lengths of the mode in question and the lowest possible order mode.

$$n \text{ F2}(D)\text{MUF} = \text{F2}(d_{max})\text{MUF} \cdot M_n \,/\, M_{n_0} \tag{7}$$

where M_n/M_{n0} is derived using equation (3) as follows:

$$\frac{M_n}{M_{n_0}} = \frac{n\text{ F2}(d)\text{MUF}}{n_0 \text{ F2}(D)\text{MUF}} \tag{8}$$

The lower of the values calculated at the two control points of Table 1a) is selected.

3.6 The path operational MUF

The path operational MUF is the greater of the operational MUF for F2 modes and the operational MUF for E modes. For F2 modes, the operational MUF = basic MUF. R_{op} where R_{op} is given in Table 1 to Recommendation ITU-R P.1240. For E modes the operational MUF is equal to the basic MUF.

An estimate of the operational MUF exceeded for 10% and 90% of the days is determined by multiplying the median operational MUF by the factors 1.15 and 0.85 respectively in the case of the F modes and 1.05 and 0.95 respectively in the case of E modes.

4 E-layer maximum screening frequency (f_s)

E-layer screening of F2 modes is considered for paths up to 9 000 km. The foE value at the mid-point of the path (for paths up to 2 000 km), or the higher one of the foE values at the two control points 1 000 km from each end of the path (for paths longer than 2 000 km), is taken for the calculation of the maximum screening frequency (see Table 1b)).

$$f_s = 1.05 \text{ foE} \sec i \tag{9}$$

with:

$$i = \arcsin\left(\frac{R_0 \cos \Delta_F}{R_0 + h_r}\right) \tag{10}$$

where:

i: angle of incidence at height $h_r = 110$ km

R_0: radius of the Earth, 6 371 km

Δ_F: elevation angle for the F2-layer mode (determined from equation (11)).

5 Median sky-wave field strength

The predicted field strength is the monthly median over all days of the month.

5.1 Paths up to 7 000 km

5.1.1 Modes considered

Up to three E modes (for paths up to 4 000 km only) and up to six F2 modes are selected, each of which meets all of the following separate criteria:

E modes – being the lowest-order mode with hop length up to 2 000 km, or one of the next two higher-order modes;

– having an elevation angle ≥ 3° as given from equation (11) for mirror-reflection from a height $h_r = 110$ km.

F2 modes – being the lowest-order mode with a hop length up to d_0 (km) or one of the next five higher-order modes;

– having an elevation angle ≥ 3° as given from equation (11) for mirror-reflection from a height h_r determined from equation (2) where M(3000)F2 is evaluated at the mid-path (paths up to d_{max} (km)) or at the control point given in Table 1c) for which foF2 has the lower value (paths d_{max} to 9 000 km);

– having an E-layer maximum screening frequency evaluated as described in § 4 which is less than the operating frequency.

5.1.2 Elevation angle

The elevation angle which applies for all frequencies, including those above the basic MUF, is given by:

$$\Delta = \arctan\left(\cot \frac{d}{2\,R_0} - \frac{R_0}{R_0 + h_r} \operatorname{cosec} \frac{d}{2\,R_0} \right) \tag{11}$$

where:

d: hop length of an n-hop mode given by $d = D/n$

h_r: equivalent plane-mirror reflection height

for E modes $h_r = 110$ km

for F2 modes h_r is taken as a function of time, location and hop length.

The mirror reflection height for F2 modes, h_r, is calculated as follows, where:

$$x = \text{foF2/foE} \qquad \text{and} \qquad H = \frac{1490}{\text{M(3000)F2} + \Delta M} - 316$$

with:

$$\Delta M = \frac{0.18}{y - 1.4} + \frac{0.096(R_{12} - 25)}{150}$$

and $y = x$ or 1.8, whichever is the larger.

a) For $x > 3.33$ and $x_r = f/\text{foF2} \geq 1$, where f is the wave frequency:

$$h_r = h \text{ or 800 km, whichever is the smaller} \tag{12}$$

where:

$h = A_1 + B_1\, 2.4^{-a}$ for B_1 and $a \geq 0$

$= A_1 + B_1$ otherwise

with $A_1 = 140 + (H - 47)\, E_1$

$B_1 = 150 + (H - 17)\, F_1 - A_1$

$E_1 = -0.09707\, x_r^3 + 0.6870\, x_r^2 - 0.7506\, x_r + 0.6$

F_1 is such that:

$F_1 = -1.862\, x_r^4 + 12.95\, x_r^3 - 32.03\, x_r^2 + 33.50\, x_r - 10.91$ for $x_r \leq 1.71$

$F_1 = 1.21 + 0.2\, x_r$ for $x_r > 1.71$

and a varies with distance d and skip distance d_s as:

$$a = (d - d_s) / (H + 140)$$

where: $d_s = 160 + (H + 43)\, G$

$$G = -2.102\, x_r^4 + 19.50\, x_r^3 - 63.15\, x_r^2 + 90.47\, x_r - 44.73 \qquad \text{for } x_r \leq 3.7$$

$$G = 19.25 \qquad \text{for } x_r > 3.7$$

b) For $x > 3.33$ and $x_r < 1$:

$$h_r = h \text{ or 800 km, whichever is the smaller} \qquad (13)$$

where:

$$h = A_2 + B_2\, b \qquad \text{for } B_2 \geq 0$$

$$= A_2 + B_2 \qquad \text{otherwise}$$

with $A_2 = 151 + (H - 47)\, E_2$

$$B_2 = 141 + (H - 24)\, F_2 - A_2$$

$$E_2 = 0.1906\, Z^2 + 0.00583\, Z + 0.1936$$

$$F_2 = 0.645\, Z^2 + 0.883\, Z + 0.162$$

where: $Z = x_r$ or 0.1, whichever is the larger and b varies with normalized distance d_f, Z and H as follows:

$$b = -7.535\, d_f^4 + 15.75\, d_f^3 - 8.834\, d_f^2 - 0.378\, d_f + 1$$

where: $d_f = \dfrac{0.115\, d}{Z(H + 140)}$ or 0.65; whichever is the smaller

c) For $x \leq 3.33$:

$$h_r = 115 + H\,J + U\,d \text{ or 800 km, whichever is the smaller} \qquad (14)$$

with $J = -0.7126\, y^3 + 5.863\, y^2 - 16.13\, y + 16.07$

and $U = 8 \times 10^{-5}\, (H - 80)\, (1 + 11\, y^{-2.2}) + 1.2 \times 10^{-3}\, H\, y^{-3.6}$

In the case of paths up to d_{max} (km) h_r is evaluated at the mid-point of the path: for longer paths it is determined for all the control points given in Table 1c) and the mean value is used.

5.1.3 Field strength determination

For each mode w selected in § 5.1.1, the median field strength is given by:

$$E_{tw} = 136.6 + P_t + 20 \log f - L_t \qquad \text{dB}(1\ \mu\text{V/m}) \qquad (15)$$

where:

f: transmitting frequency (MHz)

P_t: transmitter power (dB(1 kW))

L_t: the ray path transmission loss for the mode under consideration given by:

$$L_t = 32.45 + 20 \log f + 20 \log p' - G_t + L_i + L_m + L_g + L_h + L_z \qquad (16)$$

with:

p': virtual slant range (km)

$$p' = 2R_0 \sum_{1}^{n} \left[\frac{\sin(d/2R_0)}{\cos[\Delta + (d/2R_0)]} \right] \tag{17}$$

G_t : transmitting antenna gain at the required azimuth angle and elevation angle (Δ) relative to an isotropic antenna (dB)

L_i : absorption loss (dB) for an n-hop mode given by:

$$L_i = \frac{n(1 + 0.0067 R_{12}) \cdot \sec i}{(f + f_L)^2} \cdot \frac{1}{k} \sum_{j=1}^{k} AT_{noon} \cdot \frac{F(\chi_j)}{F(\chi_{jnoon})} \cdot \varphi_n\left(\frac{f_v}{\text{foE}}\right) \tag{18}$$

with:

$$F(\chi) = \cos^p (0.881\ \chi) \text{ or } 0.02, \text{ whichever is greater} \tag{19}$$

where:

$$f_v = f \cos i \tag{20}$$

and

i: angle of incidence at 110 km

k: number of control points (from Table 1d))

f_L: mean of the values of electron gyrofrequency, about the longitudinal component of the Earth's magnetic field for a height of 100 km, determined at the control points given in Table 1d)

χ_j: solar zenith angle at the j-th control point or 102° whichever is the smaller. The equation-of-time, for the middle of the month in question, is incorporated in the calculation of this parameter

χ_{jnoon}: value of χ_j at local noon

AT_{noon}: absorption factor at local noon and $R_{12} = 0$ given as a function of geographic latitude and month from Fig. 1

$\varphi_n\left(\frac{f_v}{\text{foE}}\right)$: absorption layer penetration factor given as a function of the ratio of equivalent vertical-incidence wave frequency f_v to foE from Fig. 2

p : diurnal absorption exponent given as a function of modified dip latitude (see Recommendation ITU-R P.1239, Annex 1) and month from Fig. 3.

For frequencies above the basic MUF, the absorption continues to vary with frequency and is calculated assuming the same ray-paths as those at the basic MUF.

L_m: "above-the-MUF" loss.

For frequency f equal to or less than the basic MUF (f_b) of the given mode:

$$L_m = 0 \tag{21}$$

For E modes for $f > f_b$:

$$L_m = 130\,[(f/f_b) - 1]^2 \qquad \text{dB} \tag{22}$$

or 81 dB whichever is the smaller.

For F2 modes for $f > f_b$:

$$L_m = 36 \left[(f / f_b) - 1 \right]^{1/2} \qquad \text{dB} \tag{23}$$

or 62 dB whichever is the smaller.

L_g: summed ground-reflection loss at intermediate reflection points:

For an n-hop mode:

$$L_g = 2(n - 1) \qquad \text{dB} \tag{24}$$

L_h: factor to allow for auroral and other signal losses, given in Table 2. Each value is evaluated in terms of the geomagnetic latitude G_n (N or S of equator) and local time t for an Earth-centred dipole with pole at 78.5° N, 68.2° W: mean values for the control points of Table 1d) are taken.

In the Northern Hemisphere, winter is taken as December-February, equinox as March-May and September-November and summer as June-August. In the Southern Hemisphere, the months for winter and summer are interchanged.

For $G_n < 42.5°$, $L_h = 0$ dB

L_z: term containing those effects in sky-wave propagation not otherwise included in this method. The present recommended value is 9.9 dB (see also, definition of L_y given in § 5.2).

FIGURE 1

Absorption factor, AT_{noon}

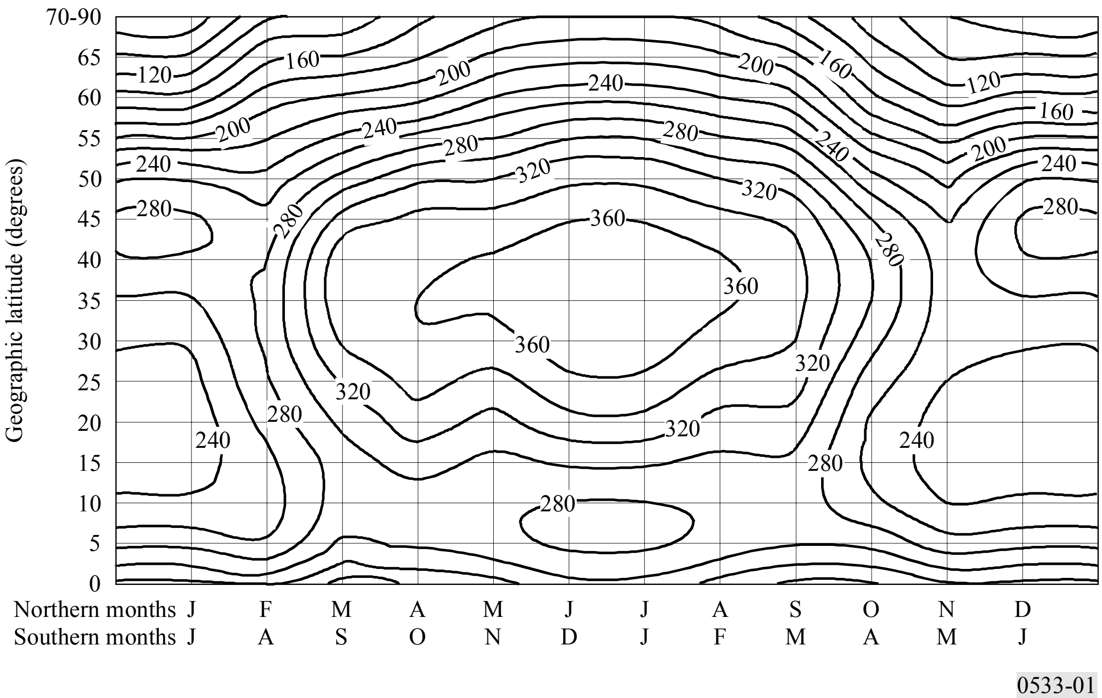


FIGURE 2

The absorption layer penetration factor, $\varphi_n\left(\frac{f_v}{foE}\right)$

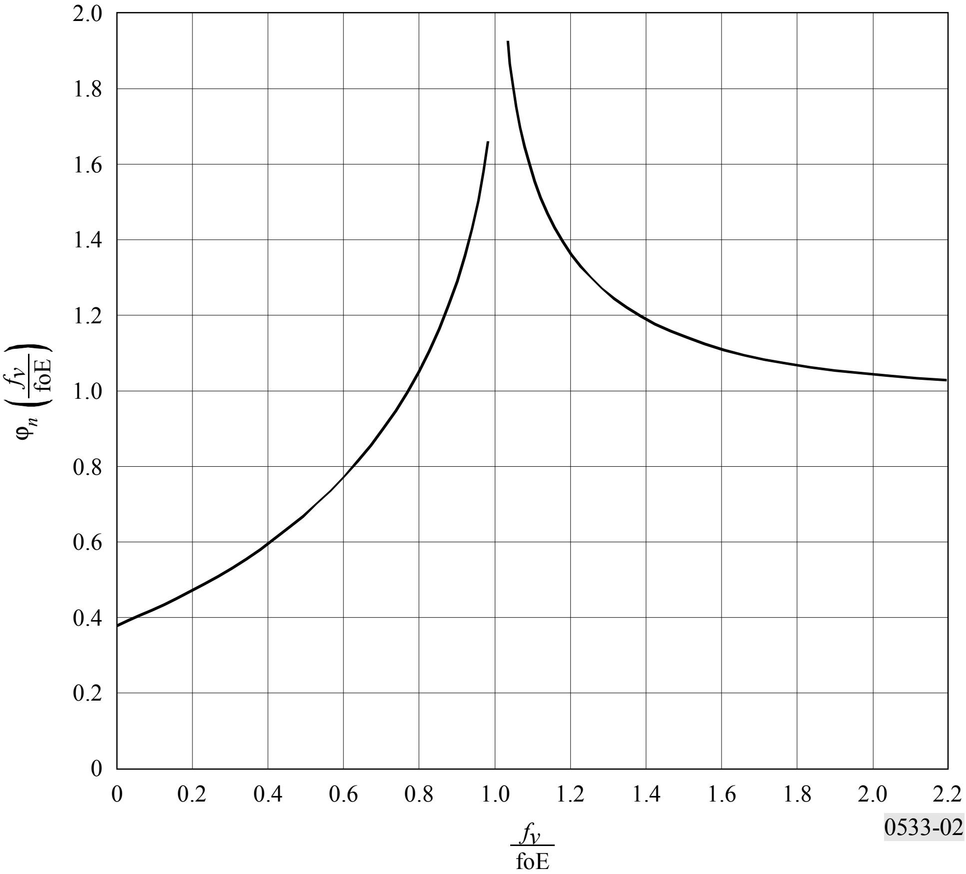
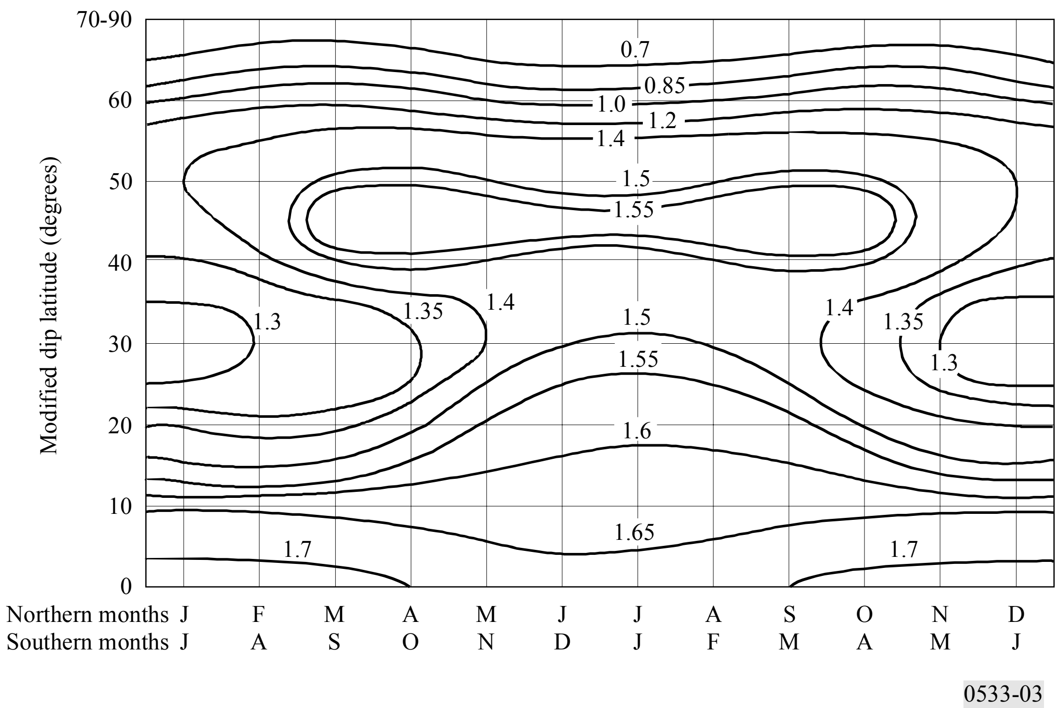


FIGURE 3

Diurnal absorption exponent, *p*



Discounting modes screened by the E layer, the resultant equivalent median sky-wave field strength, E_{ts}, is taken as the root-sum-squared field strength for N modes where N is chosen to encompass up to the three selected strongest F2 modes and also, in the case of path lengths up to 4 000 km, the two strongest E modes i.e.:

$$E_{ts} = 10 \log_{10} \sum_{w=1}^{N} 10^{E_{tw}/10} \qquad \text{dB(1 μV/m)} \qquad (25)$$

TABLE 2

Values of L_h giving auroral and other signal losses (dB)

	a) Transmission ranges less than or equal to 2 500 km								
	Mid-path local time, t								
G_n	$01 \le t < 04$	$04 \le t < 07$	$07 \le t < 10$	$10 \le t < 13$	$13 \le t < 16$	$16 \le t < 19$	$19 \le t < 22$	$22 \le t < 01$	
$77.5° \le G_n$	2.0	6.6	6.2	1.5	0.5	1.4	1.5	1.0	
$72.5° \le G_n < 77.5°$	3.4	8.3	8.6	0.9	0.5	2.5	3.0	3.0	W
$67.5° \le G_n < 72.5°$	6.2	15.6	12.8	2.3	1.5	4.6	7.0	5.0	I
$62.5° \le G_n < 67.5°$	7.0	16.0	14.0	3.6	2.0	6.8	9.8	6.6	n
$57.5° \le G_n < 62.5°$	2.0	4.5	6.6	1.4	0.8	2.7	3.0	2.0	t
$52.5° \le G_n < 57.5°$	1.3	1.0	3.2	0.3	0.4	1.8	2.3	0.9	e
$47.5° \le G_n < 52.5°$	0.9	0.6	2.2	0.2	0.2	1.2	1.5	0.6	r
$42.5° \le G_n < 47.5°$	0.4	0.3	1.1	0.1	0.1	0.6	0.7	0.3	
$77.5° \le G_n$	1.4	2.5	7.4	3.8	1.0	2.4	2.4	3.3	E
$72.5° \le G_n < 77.5°$	3.3	11.0	11.6	5.1	2.6	4.0	6.0	7.0	q
$67.5° \le G_n < 72.5°$	6.5	12.0	21.4	8.5	4.8	6.0	10.0	13.7	u
$62.5° \le G_n < 67.5°$	6.7	11.2	17.0	9.0	7.2	9.0	10.9	15.0	i
$57.5° \le G_n < 62.5°$	2.4	4.4	7.5	5.0	2.6	4.8	5.5	6.1	n
$52.5° \le G_n < 57.5°$	1.7	2.0	5.0	3.0	2.2	4.0	3.0	4.0	o
$47.5° \le G_n < 52.5°$	1.1	1.3	3.3	2.0	1.4	2.6	2.0	2.6	x
$42.5° \le G_n < 47.5°$	0.5	0.6	1.6	1.0	0.7	1.3	1.0	1.3	
$77.5° \le G_n$	2.2	2.7	1.2	2.3	2.2	3.8	4.2	3.8	
$72.5° \le G_n < 77.5°$	2.4	3.0	2.8	3.0	2.7	4.2	4.8	4.5	S
$67.5° \le G_n < 72.5°$	4.9	4.2	6.2	4.5	3.8	5.4	7.7	7.2	u
$62.5° \le G_n < 67.5°$	6.5	4.8	9.0	6.0	4.8	9.1	9.5	8.9	m
$57.5° \le G_n < 62.5°$	3.2	2.7	4.0	3.0	3.0	6.5	6.7	5.0	m
$52.5° \le G_n < 57.5°$	2.5	1.8	2.4	2.3	2.6	5.0	4.6	4.0	e
$47.5° \le G_n < 52.5°$	1.6	1.2	1.6	1.5	1.7	3.3	3.1	2.6	r
$42.5° \le G_n < 47.5°$	0.8	0.6	0.8	0.7	0.8	1.6	1.5	1.3	

TABLE 2 (*end*)

	b) Transmission ranges greater than 2 500 km								
	Mid-path local time, t								
	$01 \le t < 04$	$04 \le t < 07$	$07 \le t < 10$	$10 \le t < 13$	$13 \le t < 16$	$16 \le t < 19$	$19 \le t < 22$	$22 \le t < 01$	
G_n									
$77.5° \le G_n$	1.5	2.7	2.5	0.8	0.0	0.9	0.8	1.6	Winter
$72.5° \le G_n < 77.5°$	2.5	4.5	4.3	0.8	0.3	1.6	2.0	4.8	
$67.5° \le G_n < 72.5°$	5.5	5.0	7.0	1.9	0.5	3.0	4.5	9.6	
$62.5° \le G_n < 67.5°$	5.3	7.0	5.9	2.0	0.7	4.0	4.5	10.0	
$57.5° \le G_n < 62.5°$	1.6	2.4	2.7	0.6	0.4	1.7	1.8	3.5	
$52.5° \le G_n < 57.5°$	0.9	1.0	1.3	0.1	0.1	1.0	1.5	1.4	
$47.5° \le G_n < 52.5°$	0.6	0.6	0.8	0.1	0.1	0.6	1.0	0.5	
$42.5° \le G_n < 47.5°$	0.3	0.3	0.4	0.0	0.0	0.3	0.5	0.4	
$77.5° \le G_n$	1.0	1.2	2.7	3.0	0.6	2.0	2.3	1.6	Equinox
$72.5° \le G_n < 77.5°$	1.8	2.9	4.1	5.7	1.5	3.2	5.6	3.6	
$67.5° \le G_n < 72.5°$	3.7	5.6	7.7	8.1	3.5	5.0	9.5	7.3	
$62.5° \le G_n < 67.5°$	3.9	5.2	7.6	9.0	5.0	7.5	10.0	7.9	
$57.5° \le G_n < 62.5°$	1.4	2.0	3.2	3.8	1.8	4.0	5.4	3.4	
$52.5° \le G_n < 57.5°$	0.9	0.9	1.8	2.0	1.3	3.1	2.7	2.0	
$47.5° \le G_n < 52.5°$	0.6	0.6	1.2	1.3	0.8	2.0	1.8	1.3	
$42.5° \le G_n < 47.5°$	0.3	0.3	0.6	0.6	0.4	1.0	0.9	0.6	
$77.5° \le G_n$	1.9	3.8	2.2	1.1	2.1	1.2	2.3	2.4	Summer
$72.5° \le G_n < 77.5°$	1.9	4.6	2.9	1.3	2.2	1.3	2.8	2.7	
$67.5° \le G_n < 72.5°$	4.4	6.3	5.9	1.9	3.3	1.7	4.4	4.5	
$62.5° \le G_n < 67.5°$	5.5	8.5	7.6	2.6	4.2	3.2	5.5	5.7	
$57.5° \le G_n < 62.5°$	2.8	3.8	3.7	1.4	2.7	1.6	4.5	3.2	
$52.5° \le G_n < 57.5°$	2.2	2.4	2.2	1.0	2.2	1.2	4.4	2.5	
$47.5° \le G_n < 52.5°$	1.4	1.6	1.4	0.6	1.4	0.8	2.9	1.6	
$42.5° \le G_n < 47.5°$	0.7	0.8	0.7	0.3	0.7	0.4	1.4	0.8	

5.1.4 Time delay

The time delay of an individual mode is given by:

$$\tau = (p'/c) \times 10^3 \qquad \text{ms} \tag{26}$$

where:

p' : virtual slant range (km) given by equation (17)

c : velocity of light (km/s).

The values of time delay for each individual mode may be used in conjunction with the predicted field strength for each mode as determined according to the procedure in § 5.1.3, to give the median time-delay profile.

5.2 Paths longer than 9 000 km

In this method, predictions are made by dividing the path into the minimum number, n, of equal length hops, none of which exceeds 4 000 km.

The resultant median field strength E_{tl} is given by:

$$E_{tl} = E_0 \left[1 - \frac{(f_M + f_H)^2}{(f_M + f_H)^2 + (f_L + f_H)^2} \left[\frac{(f_L + f_H)^2}{(f + f_H)^2} + \frac{(f + f_H)^2}{(f_M + f_H)^2} \right] \right]$$

$$- 36.4 + P_t + G_{tl} + G_{ap} - L_y \qquad \text{dB(1 } \mu\text{V/m)} \qquad (27)$$

E_0 is the free-space field strength for 3 MW e.i.r.p. In this case:

$$E_0 = 139.6 - 20 \log p' \qquad \text{dB(1 } \mu\text{V/m)} \qquad (28)$$

where p' is calculated using equations (17) and (11) with $h_r = 300$ km

G_{tl}: largest value of transmitting antenna gain at the required azimuth in the elevation range 0° to 8° (dB)

G_{ap}: increase in field strength due to focusing at long distances given as:

$$G_{ap} = 10 \log \frac{D}{R_0 \, |\sin (D / R_0)|} \qquad \text{dB} \qquad (29)$$

As G_{ap} from the above formula tends to infinity when D is a multiple of πR_0, it is limited to the value of 15 dB

L_y: a term similar in concept to L_z. The present recommended value is –3.7 dB.

NOTE 1 – It should be noted that the values of L_y and L_z are dependent on the elements of the prediction method, so that any changes in those elements should be accompanied by revision of the L_y and L_z values

f_H: mean of the values of electron gyrofrequency determined at the control points given in Table 1a)

f_M: upper reference frequency. It is determined separately for the two control points indicated in Table 1a) and the lower value is taken:

$$f_M = K \cdot f_g \qquad \text{MHz} \qquad (30)$$

$$K = 1.2 + W \frac{f_g}{f_{g,\,noon}} + X \left[\sqrt[3]{\frac{f_{g,\,noon}}{f_g}} - 1 \right] + Y \left[\frac{f_{g,\,min}}{f_{g,\,noon}} \right]^2 \qquad (31)$$

f_g : F2(4000)MUF = 1.1 F2(3000)MUF

$f_{g,noon}$: value of f_g for a time corresponding to local noon

$f_{g,min}$: lowest value of f_g which occurs during the 24 h.

W, *X* and *Y* are given in Table 3. The azimuth of the great-circle path is determined at the centre of the whole path and this angle is used for linear interpolation in angle between the East-West and North-South values.

TABLE 3

Values of *W*, *X* and *Y* used for the determination of the correction factor *K*

	W	*X*	*Y*
East-West	0.1	1.2	0.6
North-South	0.2	0.2	0.4

f_L: lower reference frequency:

$$f_L \left(5.3 \times I \left[\frac{(1 + 0.009 R_{12}) \sum_{1}^{2n} \cos^{0.5} \chi}{\cos i_{90} \log_e \left[\frac{9.5 \times 10^6}{p'} \right]} \right]^{1/2} - f_H \right) \cdot A_w \quad \text{MHz} \qquad (32)$$

where R_{12} does not saturate for high values.

In the summation, χ is determined for each traverse of the ray-path through the height of 90 km. When $\chi > 90°$, $\cos^{0.5}\chi$ is taken as zero.

i_{90}: angle of incidence at a height of 90 km

I : given in Table 4.

TABLE 4

Values of *I* used in the equation for f_L

Geographic latitudes		Month											
One terminal	Other terminal	J	F	M	A	M	J	J	A	S	O	N	D
> 35° N	> 35° N	1.1	1.05	1	1	1	1	1	1	1	1	1.05	1.1
> 35° N	35° N-35° S	1.05	1.02	1	1	1	1	1	1	1	1	1.02	1.05
> 35° N	> 35° S	1.05	1.02	1	1	1.02	1.05	1.05	1.02	1	1	1.02	1.05
35° N-35° S	35° N-35° S	1	1	1	1	1	1	1	1	1	1	1	1
35° N-35° S	> 35° S	1	1	1	1	1.02	1.05	1.05	1.02	1	1	1	1
> 35° S	> 35° S	1	1	1	1	1.05	1.1	1.1	1.05	1	1	1	1

A_w: winter-anomaly factor determined at the path mid-point which is unity for geographic latitudes 0° to 30° and at 90° and reaches the maximum values given in Table 5 at 60°. The values at intermediate latitudes are found by linear interpolation.

TABLE 5

Values of the winter-anomaly factor A_w, at 60° geographic latitude used in the equation for f_L

Hemisphere	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
Northern	1.30	1.15	1.03	1	1	1	1	1	1	1.03	1.15	1.30
Southern	1	1	1	1.03	1.15	1.30	1.30	1.15	1.03	1	1	1

The values of f_L are calculated at each hour until the local time t_r when $f_L \leq 2f_{LN}$

where:

$$f_{LN} = \sqrt{\frac{D}{3000}} \quad \text{MHz} \tag{33}$$

During the next three hours f_L is calculated from:

$$f_L = 2\, f_{LN}\, \mathrm{e}^{-0.23t} \tag{34}$$

where t is the time in hours after t_r. For subsequent hours $f_L = f_{LN}$ until the time when equation (32) gives a higher value.

5.3 Paths between 7 000 and 9 000 km

In this distance range the median sky-wave field strength E_{ti} is determined by interpolation between values E_{ts} and E_{tl}. E_{ts} is the root-sum-squared field strength given by equation (25) for up to the three strongest of the possible six F2 modes meeting the three criteria given in § 5.1.1. E_{tl} refers to a composite mode as given by equation (27).

$$E_{ti} = 100 \log_{10} X_i \quad \text{dB(1 µV/m)} \tag{35}$$

with

$$X_i = X_s + \frac{D - 7\,000}{2\,000}(X_l - X_s)$$

where: $X_s = 10^{0.01 E_{ts}}$

and $X_l = 10^{0.01 E_{tl}}$

The basic MUF for the path is equal to the lower of the F2(d_{max})MUF values given from equation (3) for the two control points noted in Table 1a).

6 Median available receiver power

For distance ranges up to 7 000 km, where field strength is calculated by the method of § 5.1, for a given mode w having sky-wave field strength E_{tw} (dB(1 μV/m)) at frequency f (MHz), the corresponding available signal power P_{rw} (dBW) from a lossless receiving antenna of gain G_{rw} (dB relative to an isotropic radiator) in the direction of signal incidence is:

$$P_{rw} = E_{tw} + G_{rw} - 20 \log_{10} f - 107.2 \qquad \text{dBW} \tag{36}$$

The resultant median available signal power P_r (dBW) is given by summing the powers arising from the different modes, each mode contribution depending on the receiving antenna gain in the direction of incidence of that mode. For N modes contributing to the summation:

$$P_r = 10 \log_{10} \sum_{w=1}^{N} 10^{P_{rw}/10} \qquad \text{dBW} \tag{37}$$

For distance ranges beyond 9 000 km, where field strength is calculated by the method of § 5.2, the field strength E_{tl} is for the resultant of the composite modes. In this case P_r is determined using equation (36), where G_{rw} is the largest value of receiving antenna gain at the required azimuth in the elevation range 0° to 8°.

In the intermediate range 7 000 to 9 000 km, the power is determined from equation (35) using the powers corresponding to E_{ts} and E_{tl}.

7 Monthly median signal-to-noise ratio

Recommendation ITU-R P.372 provides values of median atmospheric noise power for reception on a short vertical lossless monopole antenna above perfect ground and also gives corresponding man-made noise and cosmic noise intensities. Let the resultant external noise factor be F_a (dB(kTb)) at frequency f (MHz) where reception is on such an ideal short lossless vertical monopole over a perfectly conducting ground plane with k the Boltzmann constant and T a reference temperature of 288 K. Then, in general, when using some other practical reception antenna the resultant noise factor may differ from this value of F_a (see Recommendation ITU-R P.372). However, in the absence of complete noise measurement data for different antennas, as a first approximation, it is appropriate to assume that the same F_a applies. Hence the monthly median signal-to-noise ratio S/N (dB) achieved within a bandwidth b (Hz) is:

$$S/N = P_r - F_a - 10 \log_{10} b + 204 \tag{38}$$

8 Sky-wave field strength, available receiver signal power and signal-to-noise ratios for other percentages of time

Use is made of equations (11) and (12) of Report ITU-R P.266 to determine the sky-wave field strength, available receiver power and signal-to-noise ratio for a specified percentage of time in terms of the within-an-hour and day-to-day decile deviations of the signals and the noise. Signal fading allowances are those adopted by WARC HFBC-87 with a short-term upper decile deviation of 5 dB and a lower decile deviation of 8 dB. For long-term signal fading the decile deviations are taken as a function of the ratio of operating frequency to the path basic MUF as given in Table 2 of Recommendation ITU-R P.842.

In the case of atmospheric noise, the decile deviations of noise power arising from day-to-day variability are taken from Recommendation ITU-R P.372. No allowance for within-an-hour variability is currently applied. For man-made noise, in the absence of direct information on temporal variability, the decile deviations are taken as those given in Recommendation ITU-R P.372 which strictly relate to a combination of temporal and spatial variability. The combined within-an-hour and day-to-day decile variability of galactic noise is taken as ±2 dB.

9 Lowest usable frequency (LUF)

The LUF is defined in Recommendation ITU-R P.373. Consistent with this definition, this is evaluated as the lowest frequency, expressed to the nearest 0.1 MHz, at which a required signal-to-noise ratio is achieved by the monthly median signal-to-noise.

10 Basic circuit reliability (BCR)

The BCR is defined in Recommendation ITU-R P.842. For analogue systems, it is evaluated on the basis of signal-to-noise ratios incorporating within-an-hour and day-to-day decile variations of both signal field strength and noise background. Distribution about the median uses a distribution formulation from Recommendation ITU-R P.842. Expressions which involve time spread and frequency dispersion parameters are also given for digital modulation systems.