International Telecommunication Union

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Radiocommunication Sector of ITU

Recommendation ITU-R P.533-10

(10/2009)

Method for the prediction of the performance of HF circuits

P Series

Radiowave propagation

International Telecommunication Union

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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.533-10

Method for the prediction of the performance of HF circuits*, **

(1978-1982-1990-1992-1994-1995-1999-2001-2005-2007-2009)

Scope

This Recommendation provides methods for the prediction of available frequencies, of signal levels and of the predicted reliability for both analogue and digital modulated systems at HF, taking account not only of the signal to noise ratio but also of the expected time and frequency spreads of the channel.

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[1],

recommends

1 that the information contained in Annex 1 should be used for the 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.

** *Note by the BR Secretariat* – Pages 1, 3, 18 and 23 (equation of § 3) were amended editionally in English in February 2008.

1 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 prediction 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. The method includes an estimation of the parameters of the channel transfer function for use for the prediction of performance of digital systems. Methods are given for the assessment of circuit reliability. 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”.

In equatorial regions, in the evening hours (local time), it is possible to have distortions in the predicted results due to regional ionospheric structural instabilities which are not fully accounted for by this method.

Part 1

Frequency availability

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.

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)

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

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.

3.3 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 monthly median 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. These representations 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:

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

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 § 3.2.

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_{n_0} 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 Within the month probability of ionospheric propagation support

In some cases it may be sufficient to predict the probability of having sufficient ionization to support propagation over the path, without taking into account system and antenna characteristics and performance requirements. In such cases the probability that the MUF exceeds the working frequency is required. Sections 3.3 and 3.5 above give the median values of MUF(50) for E and F2 propagation.

For F2 modes the lower decile ratio, δ_l, of the MUF exceeded for 90% of the days of the month, MUF(90), to MUF(50) is given in Recommendation ITU-R P.1239, Table 2, as a function of local time, latitude, season and sunspot number.

For cases where the working frequency, f, is less than MUF(50), the probability of ionospheric support is given by:

$$F_{prob} = 130 - \frac{80}{1 + \text{MUF}(50)/(f \cdot \delta_l)} \quad \text{or} = 100\text{, whichever is the smaller} \tag{9}$$

The upper decile ratio, δ_u, of the MUF exceeded for 10% of the days of the month, MUF(10) to MUF(50) is given in Recommendation ITU-R P.1239, Table 3, as a function of local time, latitude, season and sunspot number.

For cases where the working frequency, f, is greater than MUF(50), the probability of ionospheric support is given by:

$$F_{prob} = \frac{80}{1 + f/(\text{MUF}(50) \cdot \delta_u)} - 30 \quad \text{or} = 0\text{, whichever is the larger} \tag{10}$$

In the case of E modes the appropriate factors for the interdecile range are 1.05 and 0.95 respectively.

The distribution of the operational MUF at a given hour within a month may be obtained by applying the distribution given in § 3.6.

Note that the operational MUFs exceeded for 90% and 10% of days of the month are defined as the optimum working frequency and the highest probable frequency respectively.

3.7 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. The relationship between the operational and basic MUFs will depend on the systems and antenna characteristics and on the path length geographic and other considerations, and should be determined from practical experience of the circuit performance. Where this experience is not available, 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 appropriate factors given in Recommendation ITU-R P.1239, Tables 2 and 3, in the case of the F modes. In the case of E modes the appropriate factors are 1.05 and 0.95 respectively.

4 E-layer maximum screening frequency (f_s)

E-layer screening of F2 modes is considered for paths up to 9 000 km (see Table 1b). 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.

$$f_s = 1.05 \text{ foE} \sec i \tag{11}$$

with:

$$i = \arcsin\left(\frac{R_0 \cos \Delta_F}{R_0 + h_r}\right) \tag{12}$$

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 (13)).

Part 2

Median sky-wave field strength

5 Median sky-wave field strength

The predicted field strength is the monthly median over all days of the month. The prediction procedure is in three parts, dependent on the path length.

5.1 Elevation angle

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

$$\Delta = \arctan\left(\cot \frac{d}{2\,R_0} - \frac{R_0}{R_0 + h_r} \operatorname{cosec} \frac{d}{2\,R_0}\right) \qquad (13)$$

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:

$$h_r = h \text{ or } 800 \text{ km, whichever is the smaller} \qquad (14)$$

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

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

$G = 19.25$ for $x_r > 3.7$

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

$$h_r = h \text{ or } 800 \text{ km, whichever is the smaller} \quad (15)$$

where:

$h = A_2 + B_2\, b$ for $B_2 \geq 0$

$= A_2 + B_2$ 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 $x \leq 3.33$:

$$h_r = 115 + H\,J + U\,d \text{ or } 800 \text{ km, whichever is the smaller} \quad (16)$$

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.

5.2 Paths up to 7000 km

5.2.1 Modes considered

Up to three E modes (for paths up to 4000 km) and up to six F2 modes are selected, each of which meets all of the following separate criteria:

– mirror-reflection heights:
  – for E modes, from a height $h_r = 110$ km;
  – for F2 modes, from a height h_r determined from equation (2), where M(3 000)F2 is evaluated at the mid-path (path lengths up to d_{max} (km)), or at the control point given in Table 1c) for which foF2 has the lower value (path lengths from d_{max} to 9 000 km);
– E modes – the lowest-order mode with hop length up to 2000 km, and the next two higher-order modes;
– F2 modes – the lowest-order mode with a hop length up to d_{max} (km) and the next five higher-order modes, which have an E-layer maximum screening frequency evaluated as described in § 4 which is less than the operating frequency.

5.2.2 Field strength determination

For each mode w selected in § 5.2.1, the median field strength is given by:

$$E_w = 136.6 + P_t + G_t + 20 \log f - L_b \qquad \text{dB}(1\ \mu\text{V/m}) \tag{17}$$

where:

- f: transmitting frequency (MHz)
- P_t: transmitter power (dB(1 kW))
- G_t: transmitting antenna gain at the required azimuth angle and elevation angle (Δ) relative to an isotropic antenna (dB)
- L_b: the ray path basic transmission loss for the mode under consideration given by:

$$L_b = 32.45 + 20 \log f + 20 \log p' + L_i + L_m + L_g + L_h + L_z \tag{18}$$

with:

- p': virtual slant range (km)

$$p' = 2R_0 \sum_1^n \left[\frac{\sin(d/2R_0)}{\cos[\Delta + (d/2R_0)]} \right] \tag{19}$$

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

$$L_i = \frac{n(1 + 0.0067 R_{12}) \cdot \sec i}{(f + f_L)^2} \cdot \frac{1}{k} \sum_{j=1}^{k} AT_{noon} \cdot \frac{F(\chi_j)}{F(\chi_{jnoon})} \cdot \varphi_n \left(\frac{f_v}{\text{foE}} \right) \tag{20}$$

with:

$$F(\chi) = \cos^p (0.881\ \chi) \text{ or } 0.02\text{, whichever is greater} \tag{21}$$

where:

$$f_v = f \cos i \tag{22}$$

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 magnetic dip (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:

$$L_m = 0 \tag{23}$$

For E modes for $f > f_b$:

$$L_m = 130\,[(f / f_b) - 1]^2 \quad \text{dB} \tag{24}$$

or 81 dB whichever is the smaller.

For F2 modes for $f > f_b$:

$$L_m = 36\,[(f / f_b) - 1]^{1/2} \quad \text{dB} \tag{25}$$

or 62 dB whichever is the smaller.

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

For an n-hop mode:

$$L_g = 2(n - 1) \quad \text{dB} \tag{26}$$

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 given in § 5.2.

NOTE 1 – It should be noted that the value of L_z is dependent on the elements of the prediction method, so that any changes in those elements should be accompanied by revision of the L_z value.

Discounting modes screened by the E layer, the overall resultant equivalent median sky-wave field strength, E_s, is taken as the root-sum-squared field strength for N modes where N is chosen to encompass the F2 and E modes for which predictions have been made, i.e.:

$$E_{ts} = 10 \log_{10} \sum_{w=1}^{N} 10^{E_{tw}/10} \qquad \text{dB(1 µV/m)} \qquad (27)$$

For the prediction of the performance of digitally modulated systems, the equivalent median sky-wave field strength for each mode is taken into account, see § 10.2.

FIGURE 1

The absorption factor, *AT*$_{noon}$

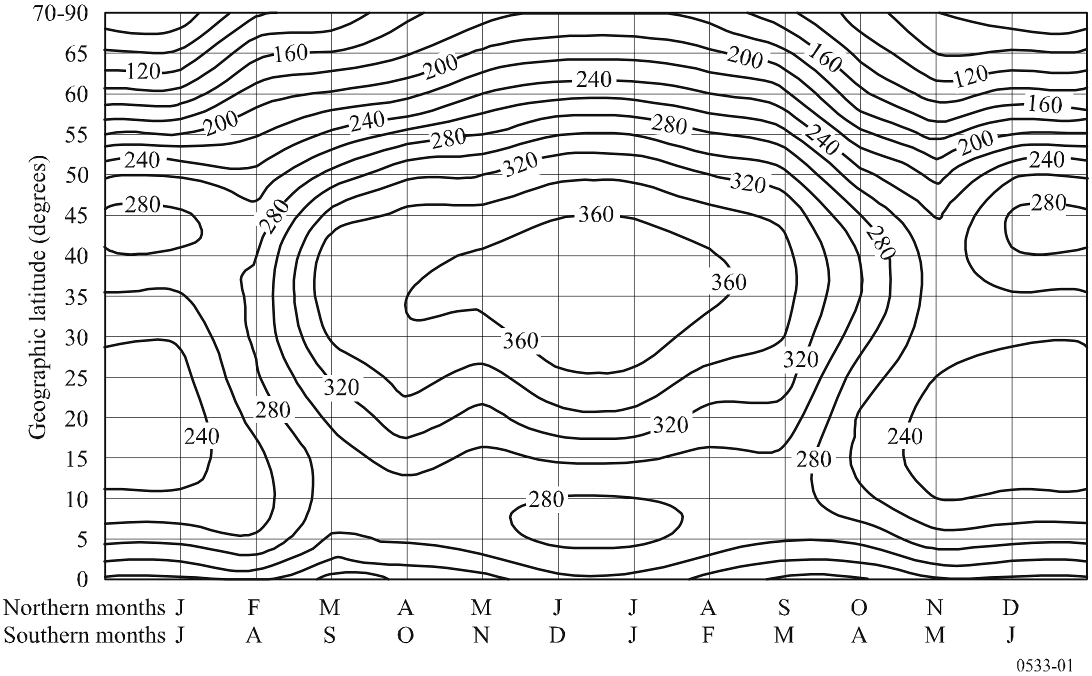

FIGURE 2

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

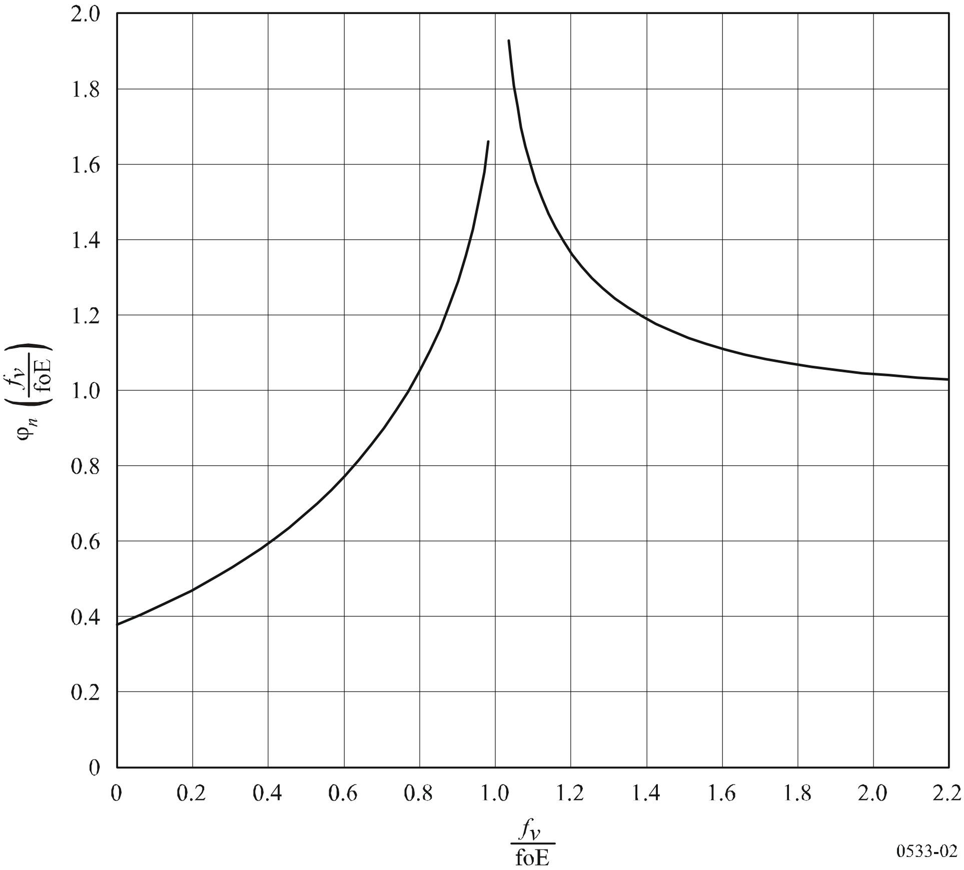

FIGURE 3

The diurnal absorption exponent, *p*

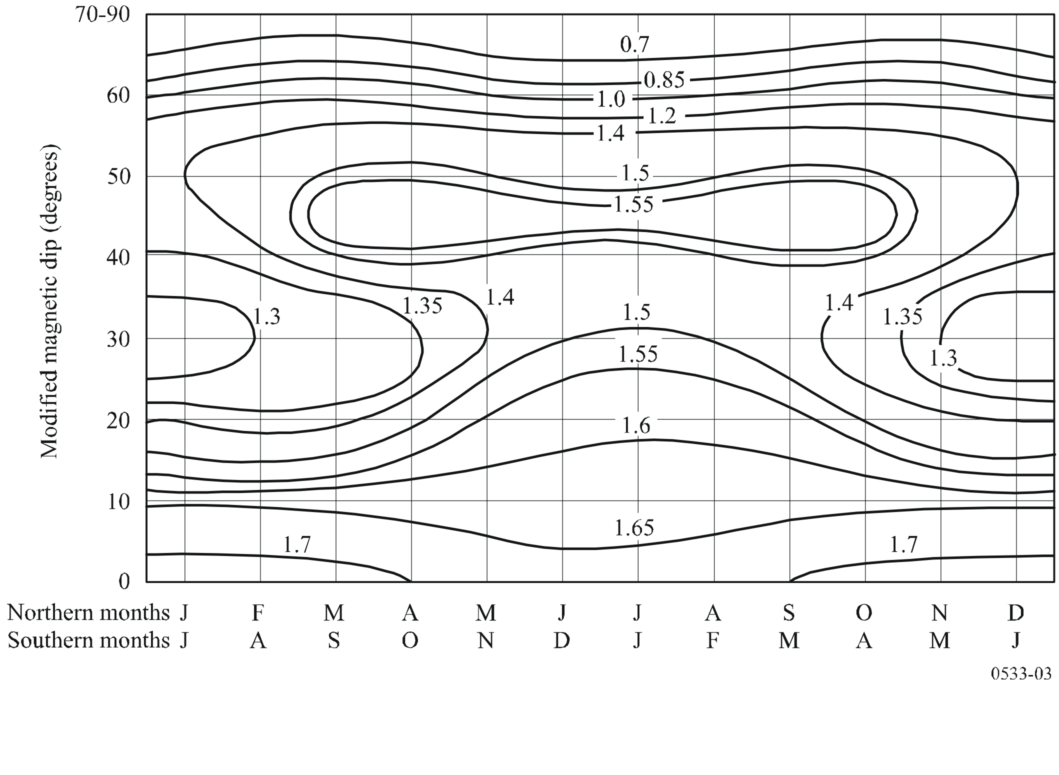

TABLE 2

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	Winter
$72.5° \le G_n < 77.5°$	3.4	8.3	8.6	0.9	0.5	2.5	3.0	3.0	Winter
$67.5° \le G_n < 72.5°$	6.2	15.6	12.8	2.3	1.5	4.6	7.0	5.0	Winter
$62.5° \le G_n < 67.5°$	7.0	16.0	14.0	3.6	2.0	6.8	9.8	6.6	Winter
$57.5° \le G_n < 62.5°$	2.0	4.5	6.6	1.4	0.8	2.7	3.0	2.0	Winter
$52.5° \le G_n < 57.5°$	1.3	1.0	3.2	0.3	0.4	1.8	2.3	0.9	Winter
$47.5° \le G_n < 52.5°$	0.9	0.6	2.2	0.2	0.2	1.2	1.5	0.6	Winter
$42.5° \le G_n < 47.5°$	0.4	0.3	1.1	0.1	0.1	0.6	0.7	0.3	Winter
$77.5° \le G_n$	1.4	2.5	7.4	3.8	1.0	2.4	2.4	3.3	Equinox
$72.5° \le G_n < 77.5°$	3.3	11.0	11.6	5.1	2.6	4.0	6.0	7.0	Equinox
$67.5° \le G_n < 72.5°$	6.5	12.0	21.4	8.5	4.8	6.0	10.0	13.7	Equinox
$62.5° \le G_n < 67.5°$	6.7	11.2	17.0	9.0	7.2	9.0	10.9	15.0	Equinox
$57.5° \le G_n < 62.5°$	2.4	4.4	7.5	5.0	2.6	4.8	5.5	6.1	Equinox
$52.5° \le G_n < 57.5°$	1.7	2.0	5.0	3.0	2.2	4.0	3.0	4.0	Equinox
$47.5° \le G_n < 52.5°$	1.1	1.3	3.3	2.0	1.4	2.6	2.0	2.6	Equinox
$42.5° \le G_n < 47.5°$	0.5	0.6	1.6	1.0	0.7	1.3	1.0	1.3	Equinox
$77.5° \le G_n$	2.2	2.7	1.2	2.3	2.2	3.8	4.2	3.8	Summer
$72.5° \le G_n < 77.5°$	2.4	3.0	2.8	3.0	2.7	4.2	4.8	4.5	Summer
$67.5° \le G_n < 72.5°$	4.9	4.2	6.2	4.5	3.8	5.4	7.7	7.2	Summer
$62.5° \le G_n < 67.5°$	6.5	4.8	9.0	6.0	4.8	9.1	9.5	8.9	Summer
$57.5° \le G_n < 62.5°$	3.2	2.7	4.0	3.0	3.0	6.5	6.7	5.0	Summer
$52.5° \le G_n < 57.5°$	2.5	1.8	2.4	2.3	2.6	5.0	4.6	4.0	Summer
$47.5° \le G_n < 52.5°$	1.6	1.2	1.6	1.5	1.7	3.3	3.1	2.6	Summer
$42.5° \le G_n < 47.5°$	0.8	0.6	0.8	0.7	0.8	1.6	1.5	1.3	Summer

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	
$72.5° \le G_n < 77.5°$	2.5	4.5	4.3	0.8	0.3	1.6	2.0	4.8	W
$67.5° \le G_n < 72.5°$	5.5	5.0	7.0	1.9	0.5	3.0	4.5	9.6	i
$62.5° \le G_n < 67.5°$	5.3	7.0	5.9	2.0	0.7	4.0	4.5	10.0	n
$57.5° \le G_n < 62.5°$	1.6	2.4	2.7	0.6	0.4	1.7	1.8	3.5	t
$52.5° \le G_n < 57.5°$	0.9	1.0	1.3	0.1	0.1	1.0	1.5	1.4	e
$47.5° \le G_n < 52.5°$	0.6	0.6	0.8	0.1	0.1	0.6	1.0	0.5	r
$42.5° \le G_n < 47.5°$	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	E
$72.5° \le G_n < 77.5°$	1.8	2.9	4.1	5.7	1.5	3.2	5.6	3.6	q
$67.5° \le G_n < 72.5°$	3.7	5.6	7.7	8.1	3.5	5.0	9.5	7.3	u
$62.5° \le G_n < 67.5°$	3.9	5.2	7.6	9.0	5.0	7.5	10.0	7.9	i
$57.5° \le G_n < 62.5°$	1.4	2.0	3.2	3.8	1.8	4.0	5.4	3.4	n
$52.5° \le G_n < 57.5°$	0.9	0.9	1.8	2.0	1.3	3.1	2.7	2.0	o
$47.5° \le G_n < 52.5°$	0.6	0.6	1.2	1.3	0.8	2.0	1.8	1.3	x
$42.5° \le G_n < 47.5°$	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	
$72.5° \le G_n < 77.5°$	1.9	4.6	2.9	1.3	2.2	1.3	2.8	2.7	S
$67.5° \le G_n < 72.5°$	4.4	6.3	5.9	1.9	3.3	1.7	4.4	4.5	u
$62.5° \le G_n < 67.5°$	5.5	8.5	7.6	2.6	4.2	3.2	5.5	5.7	m
$57.5° \le G_n < 62.5°$	2.8	3.8	3.7	1.4	2.7	1.6	4.5	3.2	m
$52.5° \le G_n < 57.5°$	2.2	2.4	2.2	1.0	2.2	1.2	4.4	2.5	e
$47.5° \le G_n < 52.5°$	1.4	1.6	1.4	0.6	1.4	0.8	2.9	1.6	r
$42.5° \le G_n < 47.5°$	0.7	0.8	0.7	0.3	0.7	0.4	1.4	0.8	

5.3 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_l is given by:

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

$$- 36.4 + P_t + G_{tl} + G_{ap} - L_y \qquad \text{dB(1 } \mu\text{V/m)} \qquad (28)$$

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

$$E_0 = 139.6 - 20 \log p' \qquad \text{dB}(1\ \mu\text{V/m}) \tag{29}$$

where p' is calculated using equations (19) and (13) 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:

$$G_{ap} = 10 \log \frac{D}{R_0 \left|\sin (D / R_0)\right|} \qquad \text{dB} \tag{30}$$

As G_{ap} from the above formula tends to infinity when D is a multiple of $\pi\, R_0$, 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 – It should be noted that the value of L_y is dependent on the elements of the prediction method, so that any changes in those elements should be accompanied by revision of the L_y value

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:

$$f_M = K \cdot f_g \qquad \text{MHz} \tag{31}$$

$$K = 1.2 + W \frac{f_g}{f_{g,\,noon}} + X \left[\sqrt[3]{\frac{f_{g,\,noon}}{f_g}} - 1 \right] + Y \left[\frac{f_{g,\,min}}{f_{g,\,noon}} \right]^2 \tag{32}$$

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:

$$f_L = \left(5.3 \times I \left[\frac{(1 + 0.009 R_{12}) \sum_{1}^{2n} \cos^{0.5} \chi}{\cos i_{90} \, \log_e \left[\frac{9.5 \times 10^6}{p'} \right]} \right]^{1/2} - f_H \right) \cdot A_w \qquad \text{MHz} \qquad (33)$$

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 $f_L \leq 2 f_{LN}$

where:

$$f_{LN} = \sqrt{\frac{D}{3000}} \qquad \text{MHz} \tag{34}$$

During the next three hours f_L is calculated from:

$$f_L = 2 f_{LN} \, e^{-0.23t} \tag{35}$$

where t is the time in hours after t_r. For subsequent hours $f_L = f_{LN}$ until the time when equation (33) gives a higher value.

5.4 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_s and E_l. E_s is the root-sum-squared field strength given by equation (27) and E_l refers to a composite mode as given by equation (28).

$$E_i = 100 \log_{10} X_i \qquad \text{dB(1 μV/m)} \tag{36}$$

with

$$X_i = X_s + \frac{D - 7000}{2000} (X_l - X_s)$$

where:

$$X_s = 10^{0.01 E_s}$$

and

$$X_l = 10^{0.01 E_l}$$

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 § 5.2, for a given mode w having sky-wave field strength E_w (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:

$$P_{rw} = E_w + G_{rw} - 20 \log_{10} f - 107.2 \qquad \text{dBW} \tag{37}$$

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:

$$P_r = 10 \log_{10} \sum_{w=1}^{N} 10^{P_{rw}/10} \qquad \text{dBW} \tag{38}$$

For distance ranges beyond 9 000 km, where field strength is calculated by the method of § 5.3, the field strength E_l is for the resultant of the composite modes. In this case P_r is determined using equation (37), 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 7000 to 9000 km, the power is determined from equation (36) using the powers corresponding to E_s and E_l.

Part 3

The prediction of system performance

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. The resultant external noise factor is given as F_a (dB(k T b)) at frequency f (MHz) where k is the Boltzmann constant and T is a reference temperature of 288 K. In general, when using some other practical reception antenna the resultant noise factor may differ from this value of F_a. However, since complete noise measurement data for different antennas is not available, it is appropriate to assume that the F_a value obtained from Recommendation ITU-R P.372 applies, as a first approximation. Hence the monthly median signal-to-noise ratio (S/N) (dB) achieved within a bandwidth b (Hz) is:

$$S/N = P_r - F_a - 10 \log_{10} b + 204 \quad (39)$$

where:

P_r: median available receiver power determined from § 6.

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

The sky-wave field strength, available receiver power and signal-to-noise ratio may be determined for a specified percentage of time in terms of the within-an-hour and day-to-day deviations of the signals and the noise. In the absence of other data, signal fading allowances may be taken as 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 also taken as those given in Recommendation ITU-R P.372 although these 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.

The signal-to-noise ratio exceeded for 90% of the time is given by:

$$S/N_{90} = S/N_{50} - (S^2_{wh} + S^2_{dd} + N^2_{dd})^{1/2} \quad (40)$$

where:

S_{wh}: wanted signal lower decile deviation from the hourly median field strength arising from within the hour changes (dB)

S_{dd}: wanted signal lower decile deviation from the monthly median field strength arising from day-to-day changes (dB)

N_{dd}: background noise upper decile deviation from the monthly median field strength arising from day-to-day changes (dB).

For other time percentages the deviations may be obtained from the information for a log-normal distribution given in Recommendation ITU-R P.1057.

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)

10.1 The reliability of analogue modulated systems

The BCR is defined in Recommendation ITU-R P.842, where the reliability is the probability (in that Recommendation given as a percentage) that the specified performance criterion (i.e. the specified signal-to-noise) is achieved. 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 is as described in § 8. The procedure is set out in Recommendation ITU-R P.842.

10.2 The reliability of digitally modulated systems, taking account of the time and frequency spreading of the received signal

For modulation systems which are robust in respect of the expected time and frequency spreading, the reliability is the percentage of time for which the required signal-to-noise is expected, using the procedure described in § 8.

In general, for digitally modulated systems, account should be taken of the time and frequency spreading of the received signal.

10.2.1 System parameters

A simplified representation of the channel transfer function is used. For the modulation method concerned the estimation of reliability is based on four parameters:

– *Required signal-to-noise ratio, S/N_r*: The ratio of the power sum of the hourly median signal modes to the noise, which is required to achieve the specified performance for the circumstances where all signal modes are within the time and frequency windows, T_w and F_w.

– *Amplitude ratio, A*: For each propagating mode the hourly median value of the field strength will be predicted, taking account of transmitter power and of the antenna gain for that mode. The strongest mode at that hour will be determined and the amplitude ratio, A, is the ratio of the strength of a sub-dominant mode to that of the dominant mode, which will just affect the system performance if it arrives with a time delay beyond T_w or a frequency spread greater than F_w.

– *Time window, T_w*: The time interval within which signal modes will contribute to system performance and beyond which will reduce system performance.
– *Frequency window, F_w*: The frequency interval within which signal modes will contribute to system performance and beyond which will reduce system performance.

10.2.2 Time delay

The time delay of an individual mode is given by:

$$\tau = (p'/c) \times 10^3 \qquad \text{ms} \qquad (41)$$

where:

p': virtual slant range (km) given by equations (13) and (19), and the reflection height, h_r, determined as in § 5.1

c: speed of light (km/s) in free space.

The differential time delay between modes may be determined from the time delays of each mode.

10.2.3 Reliability prediction procedure

For the prediction of reliability the following procedure is used:

For path lengths up to 9 000 km:

Step 1: The strength of the dominant mode, E_w, is determined using the methods given in § 5.2 and § 5.3.

Step 2: All other active modes with strengths exceeding ($E_w - A$ (dB)) are identified.

Step 3: Of the modes identified in Steps 1 or 2, the first arriving mode is identified, and all modes within the time window, T_w, measured from the first arriving mode, are identified.

Step 4: For path lengths up to 7 000 km, a power summation of the modes arriving within the window is made, or for path lengths between 7 000 and 9 000 km the interpolation procedure given in § 5.4 is used, and the basic circuit reliability, BCR, is determined using the procedure in § 10.1. This uses the procedure of Table 1 of Recommendation ITU-R P.842. The required signal-to-noise ratio, S/N_r is used in Step 10 of that table.

Step 5: If any of the active modes identified in Step 2 above have differential time delays beyond the time window, T_w, the reduction in reliability due to these modes is determined using a method similar to that for overall circuit reliability given in Table 3 of Recommendation ITU-R P.842, replacing the relative protection ratios of Step 3 of Table 3 by the ratio A and ignoring the day-to-day variability by setting to 0 dB all parameters in Steps 5 and 8. The degradation in reliability due to multimode interference , *MIR*, is that obtained in Step 12 of Table 3. The overall circuit reliability in the absence of scattering (corresponding to Recommendation ITU-R P.842, Table 3, Step 14 is ((*BCR*) × (*MIR*)/100)%.

Note that it may be necessary to reconsider the values for the decile deviations given in Steps 6 and 9 of Table 3, since the probability distribution may be different for the consideration of individual modes.

Step 6: Outside the regions and times where scattering is expected, the frequency shift due to bulk motion of the reflecting layers is expected to be of the order of 1 Hz and this method assumes that such frequency shifts are negligible.

For path lengths beyond 9 000 km:

The strength of the composite signal is as obtained in § 5.3. It is assumed that the modes making up this composite signal are contained within a time delay spread of 3 ms at 7 000 km, increasing linearly to 5 ms at 20 000 km. If the time window specified for the system is smaller than this time delay spread, then it is predicted that the system will not meet its performance requirements.

10.3 Equatorial scattering

In addition to the procedure given in § 10.2 above, the following steps should be undertaken to calculate the spreading due to scatter, invoking the model for equatorial scattering given in Appendix 1:

Step 7: The potential time spread due to scattering is given in Appendix 1, § 1, this time scattering function at increasing times is applied to each F region mode within the time window and the scattering strength $p_{Tspread}$, found at the edge of the time window, T_w.

Step 8: The potential frequency spread due to scattering is given in Appendix 1, § 2, this frequency scattering function, $p_{Fspread}$, is applied to the dominant F region mode and the frequency scattering strength is found symmetrically at the edges of the frequency window, F_w.

Step 9: If the ratio of any $p_{Tspread}$ and/or $p_{Fspread}$ to the level of the specular component of the dominant mode, p_m, as determined in Step 1 above, at the edges of the windows exceeds the ratio, A, the probability of occurrence of scattering should be determined at the control points for the F Region modes as given in Appendix 1, § 3. Where more than one control point is considered for a propagation mode, the largest probability should be taken.

Step 10: The overall circuit reliability is given by the function:

$$((BCR) \times (MIR) \times (100 - prob_{occ})/10\,000)\% \qquad (42)$$

where the probability of scattering occurrence, $prob_{occ}$, is defined in Appendix 1.

Appendix 1
to Annex 1

A model for equatorial scattering of HF signals

1 The time scattering model for the available power from the scattered component $p_{Tspread}$ is given by a half-normal distribution:

$$p_{Tspread} = 0.056\,p_m\ \mathrm{e}^{\frac{-(\tau-\tau_m)^2}{2T_{spread}^2}}$$

for τ greater than τ_m,

where:

p_m: available received power from specular reflection of the mode

τ: time delay being considered

τ_m: time delay of the specular mode

T_{spread}: standard deviation of the time spread in this half distribution, taken as 1 ms.

2 For frequency spreading the scatter is symmetrical around the transmitted frequency with a similar form of variation as for time spreading:

$$p_{Fspread} = 0.056\,p_m \;\mathrm{e}^{\frac{-(f-f_m)^2}{2F_{spread}^2}}$$

where:

f: frequency being considered

f_m: transmitted centre frequency

F_{spread}: standard deviation of the frequency spread, taken as 3 Hz.

3 The probability of occurrence of scattering on a day within a month $prob_{occc}$ is given by:

$$prob_{occ} = F_{\lambda_d} F_{T_l} F_R F_S$$

where:

$$F_{\lambda_d} = 1 \qquad \text{for} \quad 0° < |\lambda_d| < 15°$$

$$F_{\lambda_d} = \left(\frac{25-|\lambda_d|}{10}\right)^2 \left(\frac{|\lambda_d|-10}{5}\right) \qquad \text{for } 15° < |\lambda_d| < 25°$$

$$F_{\lambda_d} = 0 \qquad \text{for } 25° < |\lambda_d| < 90°$$

where λ_d is the magnetic dip

$$F_{T_l} = 1 \qquad \text{for } 00 < T_l < 03$$

$$F_{T_l} = \left(\frac{7-T_l}{4}\right)^2 \left(\frac{T_l-1}{2}\right) \qquad \text{for } 03 < T_l < 07$$

$$F_{T_l} = 0 \qquad \text{for } 07 < T_l < 19$$

$$F_{T_l} = (T_l-19)^2(41-2T_l) \qquad \text{for } 19 < T_l < 20$$

$$F_{T_l} = 1 \qquad \text{for } 20 < T_l < 24$$

where:

T_l: local time at the control point (h)

$F_R =$ $(0.1 + 0.008R_{12})$ or 1, whichever is the smaller, and R_{12} is the sunspot number

and

$$F_S = 0.55 + 0.45 \sin\left(60°(m-1.5)\right)$$

where m is the month number.

4 The prediction procedure would be to determine the levels of the time- and frequency-scattered components at the limits of the time and frequency windows specified for the modulation system in use. If the ratio of the greater of these two levels to the level of the specular component of the dominant mode is within the limits specified for inter-symbol interference for the system, then the system is predicted to fail with a probability given by the probability of scattering occurrence.