



Recommendation ITU-R P.530-17
(12/2017)

**Propagation data and prediction methods
required for the design of terrestrial
line-of-sight systems**

P Series
Radiowave propagation



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

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RECOMMENDATION ITU-R P.530-17

Propagation data and prediction methods required for the design of terrestrial line-of-sight systems

(Question ITU-R 204/3)

(1978-1982-1986-1990-1992-1994-1995-1997-1999-2001-2001-2005-2007-2009-2012-2013-2015-2017)

Scope

This Recommendation provides prediction methods for the propagation effects that should be taken into account in the design of digital fixed line-of-sight links, both in clear-air and rainfall conditions. It also provides link design guidance in clear step-by-step procedures including the use of mitigation techniques to minimize propagation impairments. The final outage predicted is the base for other Recommendations addressing error performance and availability.

The ITU Radiocommunication Assembly,

considering

- a) that for the proper planning of terrestrial line-of-sight systems, it is necessary to have appropriate propagation prediction methods and data;
- b) that methods have been developed that allow the prediction of some of the most important propagation parameters affecting the planning of terrestrial line-of-sight systems;
- c) that as far as possible these methods have been tested against available measured data and have been shown to yield an accuracy that is both compatible with the natural variability of propagation phenomena and adequate for most present applications in system planning,

recommends

that the prediction methods and other techniques set out in Annex 1 be adopted for planning terrestrial line-of-sight systems in the respective ranges of parameters indicated.

Annex 1**1 Introduction**

Several propagation effects must be considered in the design of line-of-sight radio-relay systems. These include:

- diffraction fading due to obstruction of the path by terrain obstacles under adverse propagation conditions;
- attenuation due to atmospheric gases;
- fading due to atmospheric multipath or beam spreading (commonly referred to as defocusing) associated with abnormal refractive layers;
- fading due to multipath arising from surface reflection;
- attenuation due to precipitation or solid particles in the atmosphere;

- variation of the angle-of-arrival at the receiver terminal and angle-of-launch at the transmitter terminal due to refraction;
- reduction in cross-polarization discrimination (XPD) in multipath or precipitation conditions;
- signal distortion due to frequency selective fading and delay during multipath propagation.

One purpose of this Annex is to present in concise step-by-step form simple prediction methods for the propagation effects that must be taken into account in the majority of fixed line-of-sight links, together with information on their ranges of validity. Another purpose of this Annex is to present other information and techniques that can be recommended in the planning of terrestrial line-of-sight systems.

Prediction methods based on specific climate and topographical conditions within an administration's territory may be found to have advantages over those contained in this Annex.

With the exception of the interference resulting from reduction in XPD, the Annex deals only with effects on the wanted signal. Some overall allowance is made in § 2.3.6 for the effects of intra-system interference in digital systems, but otherwise the subject is not treated. Other interference aspects are treated in separate Recommendations, namely:

- inter-system interference involving other terrestrial links and earth stations in Recommendation ITU-R P.452;
- inter-system interference involving space stations in Recommendation ITU-R P.619.

To optimize the usability of this Annex in system planning and design, the information is arranged according to the propagation effects that must be considered, rather than to the physical mechanisms causing the different effects.

It should be noted that the term “worst month” used in this Recommendation is equivalent to the term “any month” (see Recommendation ITU-R P.581).

2 Propagation loss

The propagation loss on a terrestrial line-of-sight path relative to the free-space loss (see Recommendation ITU-R P.525) is the sum of different contributions as follows:

- attenuation due to atmospheric gases;
- diffraction fading due to obstruction or partial obstruction of the path;
- fading due to multipath, beam spreading and scintillation;
- attenuation due to variation of the angle-of-arrival/launch;
- attenuation due to precipitation;
- attenuation due to sand and dust storms.

Each of these contributions has its own characteristics as a function of frequency, path length and geographic location. These are described in the paragraphs that follow.

Sometimes propagation enhancement is of interest. In such cases it is considered following the associated propagation loss.

2.1 Attenuation due to atmospheric gases

Some attenuation due to absorption by oxygen and water vapour is always present, and should be included in the calculation of total propagation loss at frequencies above about 10 GHz. The attenuation on a path of length d (km) is given by:

$$A_a = \gamma_a d \quad \text{dB} \quad (1)$$

The specific attenuation γ_a (dB/km) should be obtained using Recommendation ITU-R P.676.

NOTE 1 – On long paths at frequencies above about 20 GHz, it may be desirable to take into account known statistics of water vapour density and temperature in the vicinity of the path. Information on water vapour density is given in Recommendation ITU-R P.836.

2.2 Diffraction fading

Variations in atmospheric refractive conditions cause changes in the effective Earth's radius or k -factor from its median value of approximately 4/3 for a standard atmosphere (see Recommendation ITU-R P.310). When the atmosphere is sufficiently sub-refractive (large positive values of the gradient of refractive index, low k -factor values), the ray paths will be bent in such a way that the Earth appears to obstruct the direct path between transmitter and receiver, giving rise to the kind of fading called diffraction fading. This fading is the factor that determines the antenna heights.

k -factor statistics for a single point can be determined from measurements or predictions of the refractive index gradient in the first 100 m of the atmosphere (see Recommendation ITU-R P.453 on effects of refraction). These gradients need to be averaged in order to obtain the effective value of k for the path length in question, k_e . Values of k_e exceeded for 99.9% of the time are discussed in terms of path clearance criteria in the following section.

2.2.1 Diffraction loss dependence on path clearance

Diffraction loss will depend on the type of terrain and the vegetation. For a given path ray clearance, the diffraction loss will vary from a minimum value for a single knife-edge obstruction to a maximum for smooth spherical Earth. Methods for calculating diffraction loss for these two cases and also for paths with irregular terrain are discussed in Recommendation ITU-R P.526. These upper and lower limits for the diffraction loss are shown in Fig. 1.

The diffraction loss over average terrain can be approximated for losses greater than about 15 dB by the formula:

$$A_d = -20 h / F_1 + 10 \quad \text{dB} \quad (2)$$

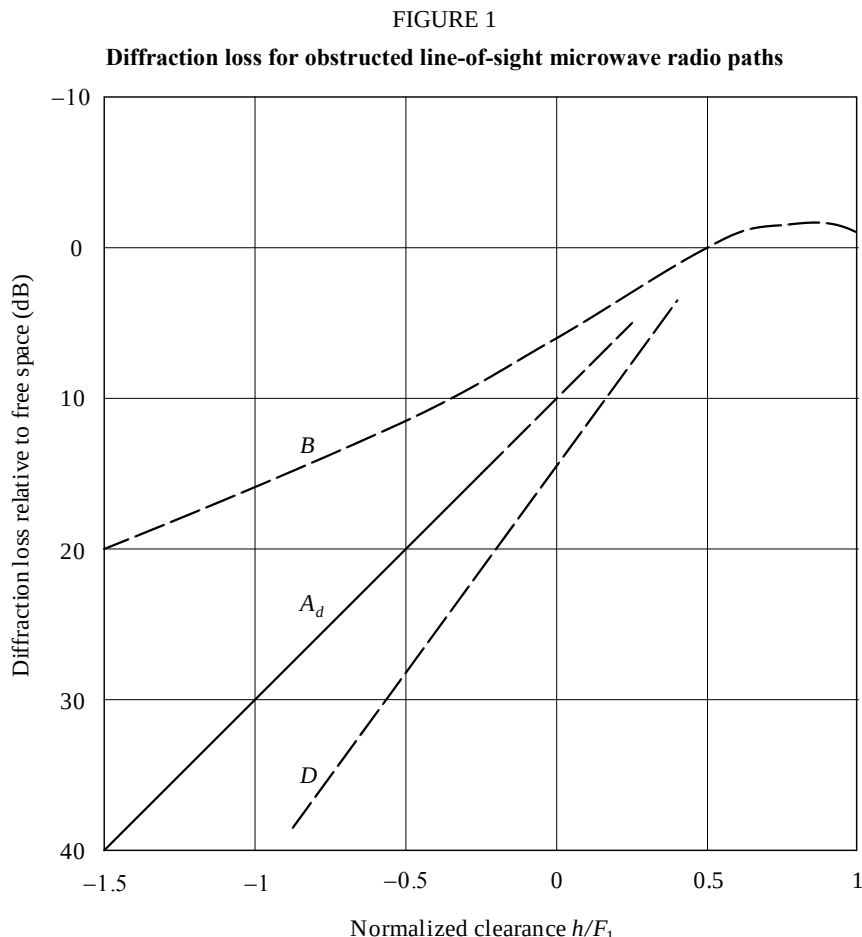
where h is the height difference (m) between most significant path blockage and the path trajectory (h is negative if the top of the obstruction of interest is above the virtual line-of-sight) and F_1 is the radius of the first Fresnel ellipsoid given by:

$$F_1 = 17.3 \sqrt{\frac{d_1 d_2}{f d}} \quad \text{m} \quad (3)$$

with:

- f : frequency (GHz)
- d : path length (km)
- d_1 and d_2 : distances (km) from the terminals to the path obstruction.

A curve, referred to as A_d , based on equation (2) is also shown in Fig. 1. This curve, strictly valid for losses larger than 15 dB, has been extrapolated up to 6 dB loss to fulfil the need of link designers.



B: theoretical knife-edge loss curve
D: theoretical smooth spherical Earth loss curve, at 6.5 GHz and $k_e = 4/3$
 A_d : empirical diffraction loss based on equation (2) for intermediate terrain
 h : amount by which the radio path clears the Earth's surface
 F_1 : radius of the first Fresnel zone

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2.2.2 Planning criteria for path clearance

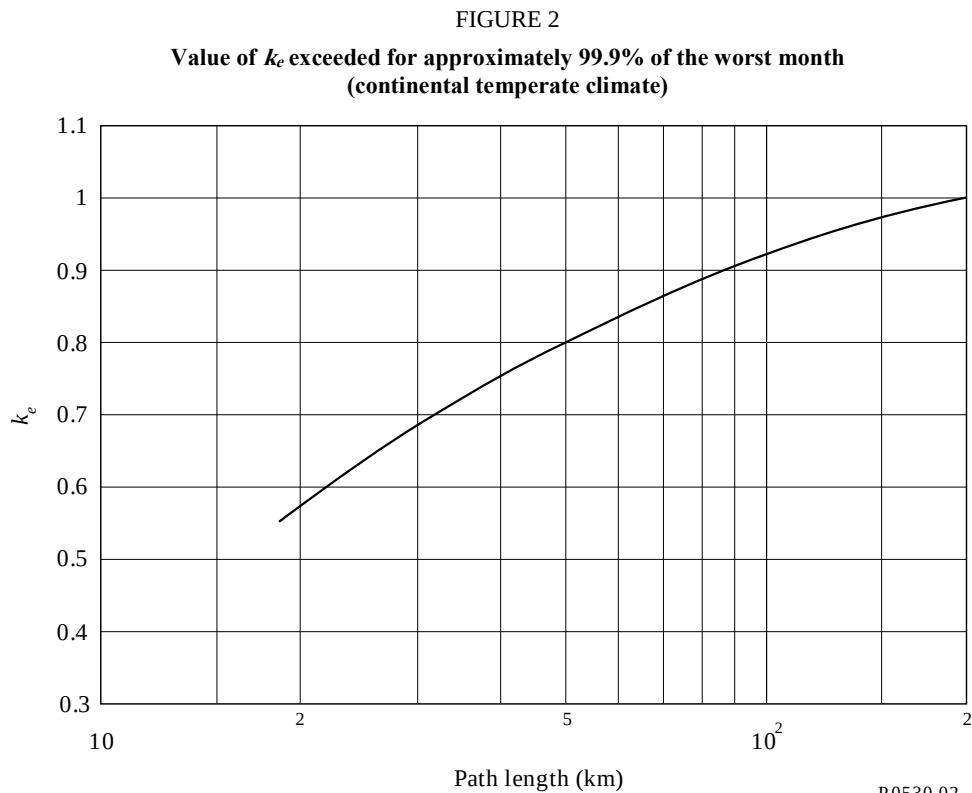
At frequencies above about 2 GHz, diffraction fading of this type has in the past been alleviated by installing antennas that are sufficiently high, so that the most severe ray bending would not place the receiver in the diffraction region when the effective Earth radius is reduced below its normal value. Diffraction theory indicates that the direct path between the transmitter and the receiver needs a clearance above ground of at least 60% of the radius of the first Fresnel zone to achieve free-space propagation conditions. Recently, with more information on this mechanism and the statistics of k_e that are required to make statistical predictions, some administrations are installing antennas at heights that will produce some small known outage.

In the absence of a general procedure that would allow a predictable amount of diffraction loss for various small percentages of time and therefore a statistical path clearance criterion, the following procedure is advised for temperate and tropical climates.

2.2.2.1 Non-diversity antenna configurations

Step 1: Determine the antenna heights required for the appropriate median value of the point k -factor (see § 2.2; in the absence of any data, use $k = 4/3$) and $1.0 F_1$ clearance over the highest obstacle (temperate and tropical climates).

Step 2: Obtain the value of k_e from Fig. 2 for the path length in question.



Step 3: Calculate the antenna heights required for the value of k_e obtained from Step 2 and the following Fresnel zone clearance radii:

Temperate climate	Tropical climate
0.0 F_1 (i.e. grazing) if there is a single isolated path obstruction	0.6 F_1 for path lengths greater than about 30 km
0.3 F_1 if the path obstruction is extended along a portion of the path	

Step 4: Use the larger of the antenna heights obtained by Steps 1 and 3 (see Note 1).

In cases of uncertainty as to the type of climate, the more conservative clearance rule (see Note 1) for tropical climates may be followed or at least a rule based on an average of the clearances for temperate and tropical climates. Smaller fractions of F_1 may be necessary in Steps 1 and 3 above for frequencies less than about 2 GHz in order to avoid unacceptably large antenna heights.

At frequencies above about 13 GHz, the estimation accuracy of the obstacle height begins to approach the radius of the Fresnel zone. This estimation accuracy should be added to the above clearance.

NOTE 1 – Although these rules are conservative from the viewpoint of diffraction loss due to sub-refractive fading, it must be made clear that an overemphasis on minimizing unavailability due to diffraction loss in sub-refractive conditions may result in a worse degradation of performance and availability in multipath conditions. It is not currently possible to give general criteria for the trade-off to be made between the two conditions. Among the relevant factors are the system fading margins available.

2.2.2.2 Two or three antenna space-diversity configurations

Step 1: Calculate the height of the upper antenna using the procedure for single antenna configurations noted above.

Step 2: Calculate the height of the lower antenna for the appropriate median value of the point k -factor (in the absence of any data use $k = 4/3$) and the following Fresnel zone clearances (see Note 1):

0.6 F_1 to 0.3 F_1 if the path obstruction is extended along a portion of the path;

0.3 F_1 to 0.0 F_1 if there are one or two isolated obstacles on the path profile.

One of the lower values in the two ranges noted above may be chosen if necessary to avoid increasing heights of existing towers or if the frequency is less than 2 GHz.

Alternatively, the clearance of the lower antenna may be chosen to give about 6 dB of diffraction loss during normal refractivity conditions (i.e. during the middle of the day; see § 8), or some other loss appropriate to the fade margin of the system, as determined by test measurements. Measurements should be carried out on several different days to avoid anomalous refractivity conditions.

In this alternative case the diffraction loss can also be estimated using Fig. 1 or equation (2).

Step 3: Verify that the spacing of the two antennas satisfies the requirements for diversity under multipath fading conditions (see § 6.2.1), and if not, modify accordingly.

NOTE 1 – These ranges of clearance were chosen to give a diffraction loss ranging from about 3 dB to 6 dB and to reduce the occurrence of surface multipath fading (see § 6.1.3). Of course, the profiles of some paths will not allow the clearance to be reduced to this range, and other means must be found to ameliorate the effects of multipath fading.

On paths in which surface multipath fading from one or more stable surface reflection is predominant (e.g. overwater or very flat surface areas), it may be desirable to first calculate the height of the upper antenna using the procedure in § 2.2.2.1, and then calculate the minimum optimum spacing for the diversity antenna to protect against surface multipath (see § 6.1.3).

In extreme situations (e.g. very long overwater paths), it may be necessary to employ three-antenna diversity configurations. In this case the clearance of the lowest antenna can be based on the clearance rule in Step 2, and that of the middle antenna on the requirement for optimum spacing with the upper antenna to ameliorate the effects of surface multipath (see § 6.2.1).

2.3 Fading and enhancement due to multipath and related mechanisms

Various clear-air fading mechanisms caused by extremely refractive layers in the atmosphere must be taken into account in the planning of links of more than a few kilometres in length; beam spreading (commonly referred to as defocusing), antenna decoupling, surface multipath, and atmospheric multipath. Most of these mechanisms can occur by themselves or in combination with each other (see Note 1). A particularly severe form of frequency selective fading occurs when beam spreading of the direct signal combines with a surface reflected signal to produce multipath fading. Scintillation fading due to smaller scale turbulent irregularities in the atmosphere is always present with these mechanisms but at frequencies below about 40 GHz its effect on the overall fading distribution is not significant.

NOTE 1 – Antenna decoupling governs the minimum beamwidth of the antennas that should be chosen.

A method for predicting the single-frequency (or narrow-band) fading distribution at large fade depths in the average worst month in any part of the world is given in § 2.3.1. This method does not make use of the path profile and can be used for initial planning, licensing, or design purposes. A second method in § 2.3.2 that is suitable for all fade depths employs the method for large fade depths and an interpolation procedure for small fade depths.

A method for predicting signal enhancement is given in § 2.3.3. The method uses the fade depth predicted by the method in § 2.3.1 as the only input parameter. Finally, a method for converting average worst month to average annual distributions is given in § 2.3.4.

2.3.1 Method for small percentages of time

Multipath fading and enhancement only need to be calculated for path lengths longer than 5 km, and can be set to zero for shorter paths.

Step 1: For the path location in question, estimate the geoclimatic factor K for the average worst month from fading data for the geographic area of interest if these are available (see Attachment 1).

If measured data for K are not available, and a detailed link design is being carried out (see Note 1), estimate the geoclimatic factor for the average worst month from:

$$K = 10^{-4.4 - 0.0027 dN_1} (10 + s_a)^{-0.46} \quad (4)$$

where:

- dN_1 is point refractivity gradient in the lowest 65 m of the atmosphere not exceeded for 1% of an average year, and s_a is the area terrain roughness
- dN_1 : provided in Recommendation ITU-R P.453-10. The correct value for the latitude and longitude at path centre should be obtained from the values for the four closest grid points by bilinear interpolation
- s_a : defined as the standard deviation of terrain heights (m) within a 110 km × 110 km area with a 30 s resolution (e.g. the Globe “gtopo30” data). The value for the mid-path may be obtained from an area roughness map with 0.5 × 0.5 degree resolution of geographical coordinates using bi-linear interpolation. The map is available from the ITU-R Study Group 3 website.

If a quick calculation of K is required for planning applications (see Note 1), a fairly accurate estimate can be obtained from:

$$K = 10^{-4.6 - 0.0027 dN_1} \quad (5)$$

Step 2: From the antenna heights h_e and h_r ((m) above sea level), calculate the magnitude of the path inclination $|\varepsilon_p|$ (mrad) from:

$$|\varepsilon_p| = |h_r - h_e| / d \quad (6)$$

where d is the path length (km).

Step 3: For detailed link design applications (see Notes 1 and 2), calculate the percentage of time p_w that fade depth A (dB) is exceeded in the average worst month from:

$$p_w = Kd^{3.4}(1 + |\varepsilon_p|)^{-1.03} f^{0.8} \times 10^{-0.00076h_L - A/10} \quad \% \quad (7)$$

where:

f : frequency (GHz)

h_L : altitude of the lower antenna (i.e. the smaller of h_e and h_r);

and where the geoclimatic factor K is obtained from equation (4).

For quick planning applications as desired (see Notes 1 and 2), calculate the percentage of time p_w that fade depth A (dB) is exceeded in the average worst month from:

$$p_w = Kd^{3.1}(1 + |\varepsilon_p|)^{-1.29} f^{0.8} \times 10^{-0.00089h_L - A/10} \quad \% \quad (8)$$

where K is obtained from equation (5).

NOTE 1 – The overall standard deviations of error in predictions using equations (4) and (7), and (5) and (8), are 5.7 dB and 5.9 dB, respectively (including the contribution from year-to-year variability). Within the wide range of paths included in these figures, a minimum standard deviation of error of 5.2 dB applies to overland paths for which $h_L < 700$ m, and a maximum value of 7.3 dB for overwater paths. The small difference between the overall standard deviations, however, does not accurately reflect the improvement in predictions that is available using equations (4) and (7) for links over very rough terrain (e.g. mountains) or very smooth terrain (e.g. overwater paths). Standard deviations of error for mountainous links ($h_L > 700$ m), for example, are reduced by 0.6 dB, and individual errors for links over high mountainous regions by up to several decibels.

NOTE 2 – Equations (7) and (8), and the associated equations (4) and (5) for the geoclimatic factor K , were derived from multiple regressions on fading data for 251 links in various geoclimatic regions of the world with path lengths d in the range of 7.5 to 185 km, frequencies f in the range of 450 MHz to 37 GHz, path inclinations $|\varepsilon_p|$ up to 37 mrad, lower antenna altitudes h_L in the range of 17 to 2 300 m, refractivity gradients dN_1 in the range of –860 to –150 N-unit/km, and area surface roughnesses s_a in the range of 6 to 850 m (for $s_a < 1$ m, use a lower limit of 1 m).

Equations (7) and (8) are also expected to be valid for frequencies to at least 45 GHz. The results of a semi-empirical analysis indicate that the lower frequency limit is inversely proportional to path length. A rough estimate of this lower frequency limit, f_{min} , can be obtained from:

$$f_{min} = 15 / d \quad \text{GHz} \quad (9)$$

2.3.2 Method for all percentages of time

The method given below for predicting the percentage of time that any fade depth is exceeded combines the deep fading distribution given in the preceding section and an empirical interpolation procedure for shallow fading down to 0 dB.

Step 1: Using the method in § 2.3.1 calculate the multipath occurrence factor, p_0 (i.e. the intercept of the deep-fading distribution with the percentage of time-axis):

$$p_0 = Kd^{3.4}(1 + |\varepsilon_p|)^{-1.03} f^{0.8} \times 10^{-0.00076h_L} \quad \% \quad (10)$$

for detailed link design applications, with K obtained from equation (4), and

$$p_0 = Kd^{3.1}(1 + |\varepsilon_p|)^{-1.29} f^{0.8} \times 10^{-0.00089h_L} \quad \% \quad (11)$$

for quick planning applications, with K obtained from equation (5). Note that equations (10) and (11) are equivalent to equations (7) and (8), respectively, with $A = 0$.

Step 2: Calculate the value of fade depth, A_t , at which the transition occurs between the deep-fading distribution and the shallow-fading distribution as predicted by the empirical interpolation procedure:

$$A_t = 25 + 1.2 \log p_0 \quad \text{dB} \quad (12)$$

The procedure now depends on whether A is greater or less than A_t .

Step 3a: If the required fade depth, A , is equal to or greater than A_t :

Calculate the percentage of time that A is exceeded in the average worst month:

$$p_w = p_0 \times 10^{-A/10} \quad \% \quad (13)$$

Note that equation (13) is equivalent to equation (7) or (8), as appropriate.

Step 3b: If the required fade depth, A , is less than A_t :

Calculate the percentage of time, p_t , that A_t is exceeded in the average worst month:

$$p_t = p_0 \times 10^{-A_t/10} \quad \% \quad (14)$$

Note that equation (14) is equivalent to equation (7) or (8), as appropriate, with $A = A_t$.

Calculate q'_a from the transition fade A_t and transition percentage time p_t :

$$q'_a = -20 \log_{10} \left\{ -\ln \left[\left(100 - p_t \right) / 100 \right] \right\} / A_t \quad (15)$$

Calculate q_t from q'_a and the transition fade A_t :

$$q_t = (q'_a - 2) \left/ \left[\left(1 + 0.3 \times 10^{-A_t/20} \right) 10^{-0.016 A_t} \right] - 4.3 \left(10^{-A_t/20} + A_t/800 \right) \right. \quad (16)$$

Calculate q_a from the required fade A :

$$q_a = 2 + \left[1 + 0.3 \times 10^{-A/20} \right] \left[10^{-0.016 A} \right] \left[q_t + 4.3 \left(10^{-A/20} + A/800 \right) \right] \quad (17)$$

Calculate the percentage of time, p_w , that the fade depth A (dB) is exceeded in the average worst month:

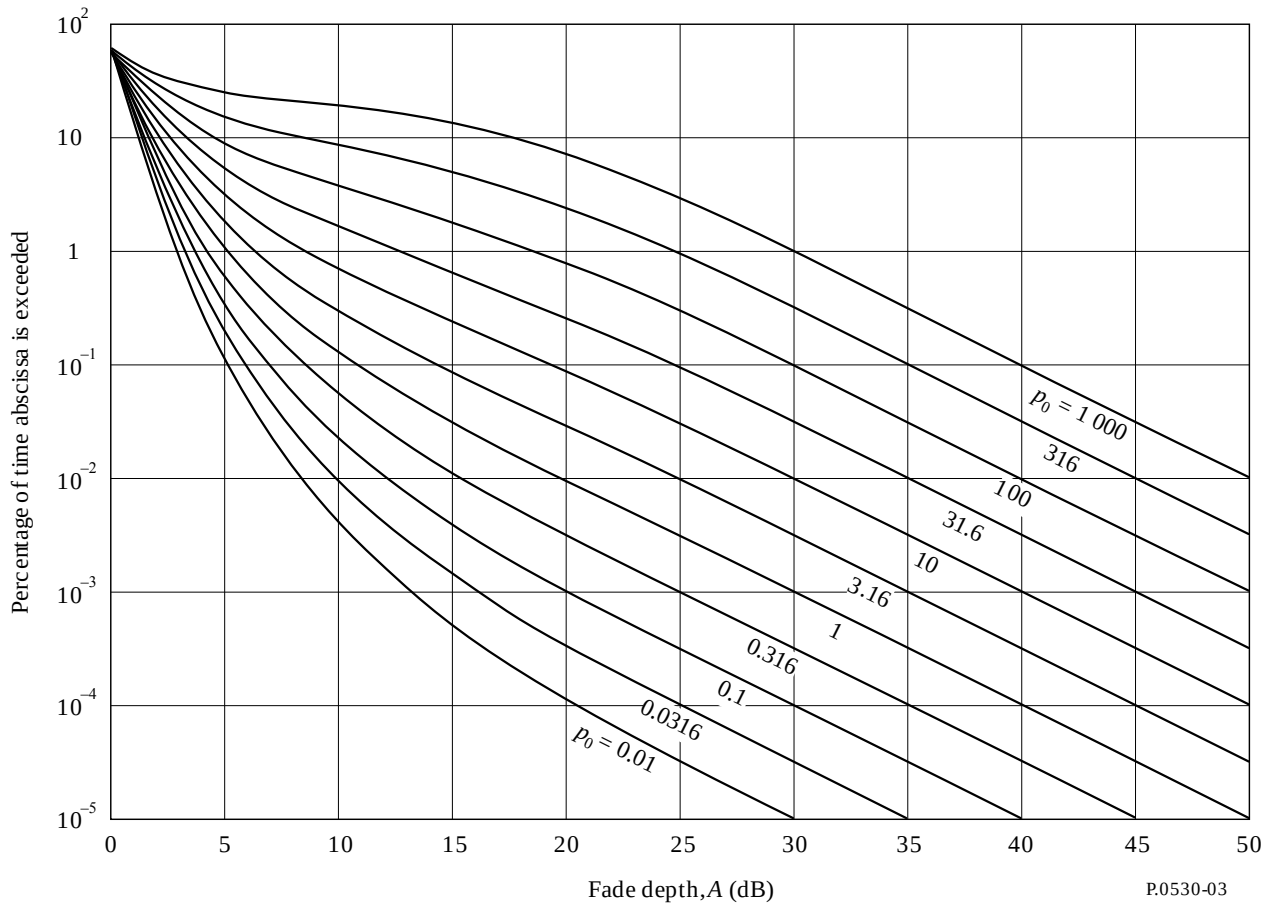
$$p_w = 100 \left[1 - \exp \left(-10^{-q_a A/20} \right) \right] \quad \% \quad (18)$$

Provided that $p_0 < 2000$, the above procedure produces a monotonic variation of p_w versus A which can be used to find A for a given value of p_w using simple iteration.

With p_0 as a parameter, Fig. 3 gives a family of curves providing a graphical representation of the method.

FIGURE 3

Percentage of time, p_w , fade depth, A , exceeded in average worst month,
with p_0 (in equation (10) or (11), as appropriate)
ranging from 0.01 to 1 000



2.3.3 Prediction method for enhancement

Large enhancements are observed during the same general conditions of frequent ducts that result in multipath fading. Average worst month enhancement above 10 dB should be predicted using:

$$p_w = 100 - 10^{(-1.7 + 0.2 A_{0.01} - E)/3.5} \% \quad \text{for } E > 10 \text{ dB} \quad (19)$$

where E (dB) is the enhancement not exceeded for $p\%$ of the time and $A_{0.01}$ is the predicted deep fade depth using equation (7) or (8), as appropriate, exceeded for $p_w = 0.01\%$ of the time.

For the enhancement between 10 and 0 dB use the following step-by-step procedure:

Step 1: Calculate the percentage of time p'_w with enhancement less or equal to 10 dB ($E' = 10$) using equation (19).

Step 2: Calculate q'_e using:

$$q'_e = -\frac{20}{E'} \left(\log_{10} \left[-\ln \left(1 - \frac{100 - p'_w}{58.21} \right) \right] \right) \quad (20)$$

Step 3: Calculate the parameter q_s from:

$$q_s = 2.05q'_e - 20.3 \quad (21)$$

Step 4: Calculate q_e for the desired E using:

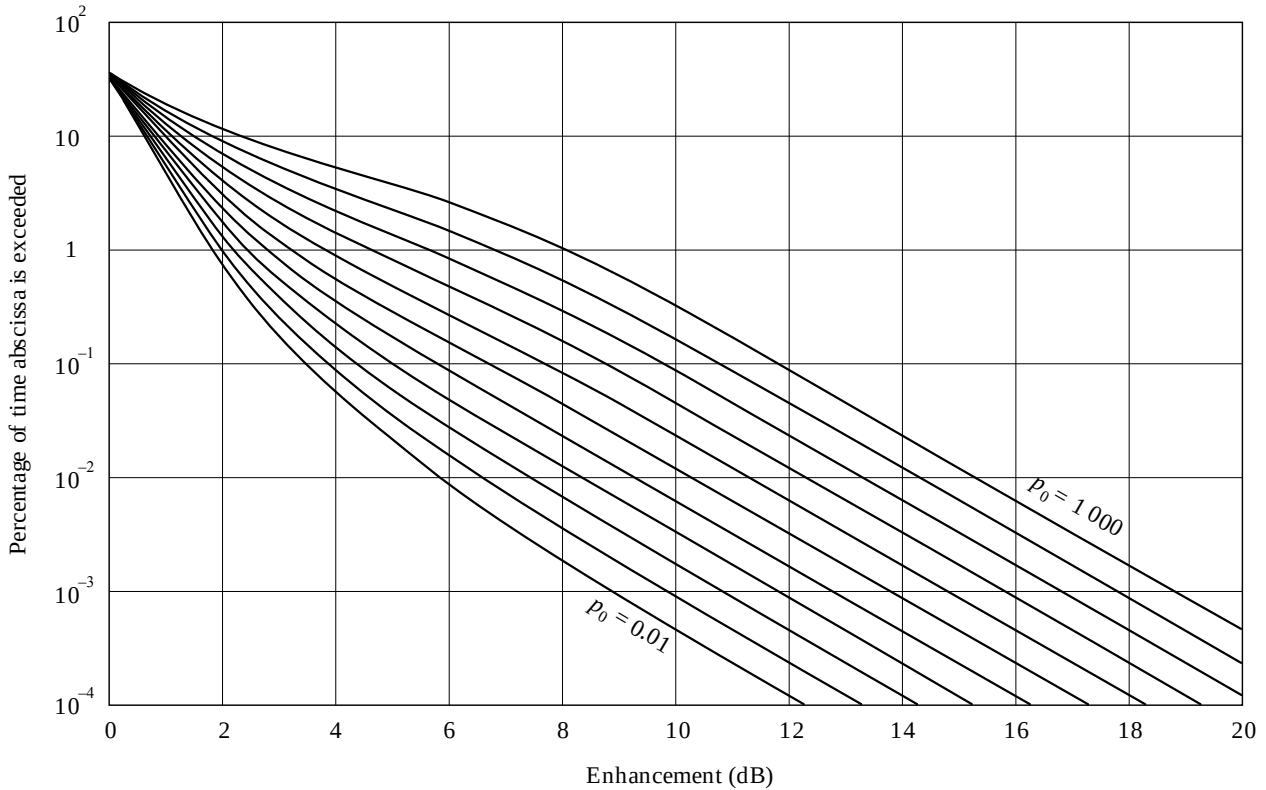
$$q_e = 8 + \left[1 + 0.3 \times 10^{-E/20} \right] \left[10^{-0.7E/20} \right] \left[q_s + 12 \left(10^{-E/20} + E/800 \right) \right] \quad (22)$$

Step 5: The percentage of time that the enhancement E (dB) is not exceeded is found from:

$$p_w = 100 - 58.21 \left[1 - \exp \left(-10^{-q_e E/20} \right) \right] \quad (23)$$

The set of curves in Fig. 4 gives a graphical representation of the method with p_0 as parameter (see equation (10) or (11), as appropriate). Each curve in Fig. 4 corresponds to the curve in Fig. 3 with the same value of p_0 . It should be noted that Fig. 4 gives the percentage of time for which the enhancements are exceeded which corresponds to $(100 - p_w)$, with p_w given by equations (19) and (23).

FIGURE 4
Percentage of time, $(100 - p_w)$, enhancement, E , exceeded in the average worst month,
with p_0 (in equation (10) or (11), as appropriate)
ranging from 0.01 to 1 000



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For prediction of exceedance percentages for the average year instead of the average worst month, see § 2.3.4.

2.3.4 Conversion from average worst month to average annual distributions

The fading and enhancement distributions for the average worst month obtained from the methods of §§ 2.3.1 to 2.3.3 can be converted to distributions for the average year by employing the following procedure:

Step 1: Calculate the percentage of time p_w fade depth A is exceeded in the large tail of the distribution for the average worst month from equation (7) or (8), as appropriate.

Step 2: Calculate the logarithmic geoclimatic conversion factor ΔG from:

$$\Delta G = 10.5 - 5.6 \log \left(1.1 \pm |\cos 2\xi|^{0.7} \right) - 2.7 \log d + 1.7 \log (1 + |\varepsilon_p|) \quad \text{dB} \quad (24)$$

where $\Delta G \leq 10.8$ dB and the positive sign is employed for $\xi \leq 45$ and the negative sign for $\xi > 45$ and where:

ξ : latitude (°N or °S)

d : path length (km)

$|\varepsilon_p|$: magnitude of path inclination (obtained from equation (6)).

Step 3: Calculate the percentage of time p fade depth A is exceeded in the large fade depth tail of the distribution for the average year from:

$$p = 10^{-\Delta G / 10} p_w \quad \% \quad (25)$$

Step 4: If the shallow fading range of the distribution is required, follow the method of Step 3b of § 2.3.2, with the following changes:

- 1) Convert the value of p_t obtained in equation (14) to an annual value by using equation (25), and use this annual value instead of p_t where p_t appears in equation (15).
- 2) The value of p_w calculated by equation (18) is the required annual value p .

Step 5: If it is required to predict the distribution of enhancement for the average year, follow the method of § 2.3.3, where $A_{0.01}$ is now the fade depth exceeded for 0.01% of the time in the average year. Obtain first p_w by inverting equation (25) and using $p = 0.01\%$. Then obtain fade depth $A_{0.01}$ exceeded for 0.01% of the time in the average year by inverting equation (7) or (8), as appropriate, and using p in place of p_w .

2.3.5 Conversion from average worst month to shorter worst periods of time

The percentage of time p_w of exceeding a deep fade A in the average worst month can be converted to a percentage of time p_{sw} of exceeding the same deep fade during a shorter worst period of time T by the relations:

$$p_{sw} = p_w \cdot (89.34T^{-0.854} + 0.676) \quad \% \quad 1 \text{ h} \leq T < 720 \text{ h for relatively flat paths} \quad (26)$$

$$p_{sw} = p_w \cdot (119T^{-0.78} + 0.295) \quad \% \quad 1 \text{ h} \leq T < 720 \text{ h for hilly paths} \quad (27)$$

$$p_{sw} = p_w \cdot (199.85T^{-0.834} + 0.175) \quad \% \quad 1 \text{ h} \leq T < 720 \text{ h for hilly land paths} \quad (28)$$

NOTE 1 – Equations (26) to (28) were derived from data for 25 links in temperate regions for which p_w was estimated from data for summer months.

2.3.6 Prediction of non-selective outage (see Note 1)

In the design of a digital link, calculate the probability of outage P_{ns} due to the non-selective component of the fading (see § 7) from:

$$P_{ns} = p_w / 100 \quad (29)$$

where $p_w(\%)$ is the percentage of time that the flat fade margin $A = F$ (dB) corresponding to the specified bit error ratio (BER) is exceeded in the average worst month (obtained from § 2.3.1 or § 2.3.2, as appropriate). The flat fade margin, F , is obtained from the link calculation and the information supplied with the particular equipment, also taking into account possible reductions due to interference in the actual link design.

NOTE 1 – For convenience, the outage is here defined as the probability that the BER is larger than a given threshold, whatever the threshold (see § 7 for further information).

2.3.7 Occurrence of simultaneous fading on multi-hop links

Experimental evidence indicates that, in clear-air conditions, deep fades on adjacent hops in a multi-hop link are almost completely uncorrelated. This applies whether frequency selective fading, flat fading or a combination occurs.

For a multi-hop link, an upper bound to the total outage probability for clear-air effects can be obtained by summing the outage probabilities of the individual hops. A closer upper bound to the probability of exceeding a fade depth A (dB) on the link of n hops can be estimated from (see Note 1):

$$P_T = \sum_{i=1}^n P_i - \sum_{i=1}^{n-1} (P_i P_{i+1})^C \quad (30a)$$

$$C = 0.5 + 0.0052A + 0.0025(d_A + d_B) \quad (30b)$$

where P_i is the outage probability predicted for the i -th of the total n hops and d_i the path length (km) of the i -th hop. Equation (30b) should be used for $A \leq 40$ dB and $(d_i + d_{i+1}) \leq 120$ km. Above these limits, $C = 1$.

NOTE 1 – Equation (30b) was derived based on the results of measurements on 19 pairs of adjacent line-of-sight hops operating in the 4 and 6 GHz bands, with path lengths in the range of 33 to 64 km.

2.3.8 Statistical data on the number of attenuation events lasting for 10 s or longer due to multipath propagation

Based on experimental studies obtained in Russia, Brazil, and Japan in the frequency range 3.7-29.3 GHz and on paths from 12.5 to 166 km length, average number of N_{10s} versus probability of attenuation exceedance due to multipath, $p(A)$, during a year period is calculated as follows:

$$N_{10s} = 3650 \cdot p(A)^{0.95} \quad (31)$$

where $p(A)$ is in percent.

2.4 Attenuation due to hydrometeors

Attenuation can also occur as a result of absorption and scattering by such hydrometeors as rain, snow, hail and fog. Although rain attenuation can be ignored at frequencies below about 5 GHz, it must be included in design calculations at higher frequencies, where its importance increases rapidly. A technique for estimating long-term statistics of rain attenuation is given in § 2.4.1. On paths at high latitudes or high altitude paths at lower latitudes, wet snow can cause significant attenuation over an even larger range of frequencies. More detailed information on attenuation due to hydrometeors other than rain is given in Recommendation ITU-R P.840.

At frequencies where both rain attenuation and multipath fading must be taken into account, the exceedance percentages for a given fade depth corresponding to each of these mechanisms can be added.

2.4.1 Long-term statistics of rain attenuation

The following simple technique may be used for estimating the long-term statistics of rain attenuation:

Step 1: Obtain the rain rate $R_{0.01}$ exceeded for 0.01% of the time (with an integration time of 1 min). If this information is not available from local sources of long-term measurements, an estimate can be obtained from the information given in Recommendation ITU-R P.837.

Step 2: Compute the specific attenuation, γ_R (dB/km) for the frequency, polarization and rain rate of interest using Recommendation ITU-R P.838.

Step 3: Compute the effective path length, d_{eff} , of the link by multiplying the actual path length d by a distance factor r . An estimate of this factor is given by:

$$r = \frac{1}{0.477d^{0.633}R_{0.01}^{0.073\alpha}f^{0.123} - 10.579(1 - \exp(-0.024d))} \quad (32)$$

where f (GHz) is the frequency and α is the exponent in the specific attenuation model from Step 2. Maximum recommended r is 2.5, so if the denominator of equation (32) is less than 0.4, use $r = 2.5$.

Step 4: An estimate of the path attenuation exceeded for 0.01% of the time is given by:

$$A_{0.01} = \gamma_R d_{eff} = \gamma_R dr \quad \text{dB} \quad (33)$$

Step 5: The attenuation exceeded for other percentages of time p in the range 0.001% to 1% may be deduced from the following power law:

$$\frac{A_p}{A_{0.01}} = C_1 p^{-(C_2 + C_3 \log_{10} p)} \quad (34)$$

with:

$$C_1 = (0.07^{C_0}) \left[0.12^{(1-C_0)} \right] \quad (35a)$$

$$C_2 = 0.855C_0 + 0.546(1 - C_0) \quad (35b)$$

$$C_3 = 0.139C_0 + 0.043(1 - C_0) \quad (35c)$$

where:

$$C_0 = \begin{cases} 0.12 + 0.4 \left[\log_{10}(f/10)^{0.8} \right] & f \geq 10 \text{ GHz} \\ 0.12 & f < 10 \text{ GHz} \end{cases} \quad (36)$$

Step 6: If worst-month statistics are desired, calculate the annual time percentages p corresponding to the worst-month time percentages p_w using climate information specified in Recommendation ITU-R P.841. The values of A exceeded for percentages of the time p on an annual basis will be exceeded for the corresponding percentages of time p_w on a worst-month basis.

The prediction procedure outlined above is considered to be valid in all parts of the world at least for frequencies up to 100 GHz and path lengths up to 60 km.

2.4.2 Combined method for rain and wet snow

The attenuation due to rain, A_p , exceeded for time percentage p , as given by equation (34) in § 2.4.1 above, is valid for radio paths through which only liquid rain falls.

It is possible for fading on a terrestrial path to be influenced by melting ice particles or wet snow in the melting layer. The incidence of this effect is determined by the height of the link in relation to the rain height, which varies in time and with geographic location.

Ice formation on an antenna, or on its cover or window, can cause large additional attenuations. It is not considered practicable to formulate a global model for this effect, since for reliable operation under freezing conditions antennas should be kept clear of icing. The method given here for estimating combined rain/wet-snow attenuation applies to ice-free antennas.

The following method estimates the attenuation exceeded for a given percentage time taking rain and wet snow into account. This method should be used in preference to § 2.4.1 unless it is known in advance that the path is not affected by wet snow. The method given in the following sub-sections starts by testing whether wet snow should be taken into account. If this is not the case, the method defaults to § 2.4.1.

The combined rain/wet-snow model assumes no correlation between rainfall rate and the average height of the melting layer. If statistically-reliable local data shows that a correlation exists, it is preferable to use the model with such data on a seasonal or monthly basis, according to the time periods over which the correlation can be assumed to be negligible.

2.4.2.1 Preliminary tests

Calculate the lower and higher antenna heights using:

$$h_{lo} = \min(h_1, h_2) \quad (\text{metres above sea level}) \quad (37a)$$

$$h_{hi} = \max(h_1, h_2) \quad (\text{metres above sea level}) \quad (37b)$$

where $h_{1,2}$ are the heights of the link terminals in metres above sea level.

Obtain the mean rain height, h_{rainm} , in metres above mean sea level. If this long-term statistic cannot be obtained from local data sources, an estimate can be obtained from Recommendation ITU-R P.839.

Test for two cases, neither of which requires further use of the rain/wet-snow method:

Case 1: If $h_{hi} \leq h_{rainm} - 3\,600$ the melting layer is always wholly above the path. In this case use the method given in § 2.4.1 for the attenuation due to rain only.

Case 2: If $h_{lo} \geq h_{rainm} + 2\,400$ the melting layer is always wholly below the path. In this case the attenuation due to precipitation can be taken to be zero.

If neither case 1 nor case 2 applies, continue as follows.

2.4.2.2 Preliminary calculations

Each of the following two preliminary calculations are performed once only.

i) *Rain-only attenuation exceeded for the required percentage time*

Use the method in § 2.4.1 to obtain the rain-only attenuation A_{rainp} dB exceeded for the required percentage time, p , as given by equation (34).

ii) *Vectors of rain-only attenuation and corresponding percentage time*

The combined rain/wet-snow model requires multiple values of the percentage time for which given values of rain-only attenuation are exceeded. Thus if the rain-attenuation model is function $A(p)$, the rain/wet-snow model needs the complementary function $p(A)$. As an efficient means to obtain this for any rain model, two vectors (one-dimensional arrays) are evaluated:

Vector T containing values of percentage time decreasing logarithmically at 10 values per decade;

Vector A containing the corresponding rain-only attenuations exceeded for each percentage time.

In this description of the rain/wet-snow model, individual members of vectors are designated by subscripted indices enclosed in square brackets. For vectors T and A the lowest index is zero.

Set the first value of each vector according to:

$$T_{[0]} = P_0 \quad (\% \text{ time}) \quad (38)$$

$$A_{[0]} = 0 \quad (\text{dB}) \quad (39)$$

where P_0 is the percentage probability of rain in an average year given by Recommendation ITU-R P.837-6 equation (1) which will have been calculated during preliminary calculation i) above.

For indices $t = 1, 2, 3 \dots$ etc. set successive pairs of values according to:

$$T_{[t]} = P_0 10^{-0.1t} \quad (\% \text{ time}) \quad (40)$$

$$A_{[t]} = A(T_{[t]}) \quad (\text{dB}) \quad (41)$$

where $A(T_{[t]})$ is the rain-only attenuation exceeded for $T_{[t]}$ percentage time given by equation (33).

Continue to use equations (40) and (41) for successive values of index t while either $T_{[t]} \geq 0.001 \%$ or $A_{[t]} - A_{[t-1]} \geq 0.1$ dB. Stop the process when neither condition is true.

Assign the following which are used later in the calculation:

$$N_{last} = N_t - 1 \quad (42)$$

$$A_{last} = A_{[N_{last}]} \quad (\text{dB}) \quad (42a)$$

$$T_{last} = T_{[N_{last}]} \quad (\% \text{ time}) \quad (42b)$$

where N_t is the number of members in each of A and T .

Purely as a matter of efficiency in calculation, while repeatedly running the rain model for equation (41), in Recommendation ITU-R P.837-6 only equations (2b), (2c) and thus (2) need to be implemented each time, since all other values remain constant for the latitude and longitude of the radio path. Moreover, in equation (33) of § 2.4.1 above, the values of k and α remain constant.