RECOMMENDATION ITU-R P.370-7*

VHF AND UHF PROPAGATION CURVES FOR THE FREQUENCY RANGE FROM 30 MHz TO 1 000 MHz

Broadcasting services

(Question ITU-R 203/3)

(1951-1953-1956-1959-1963-1966-1974-1978-1982-1986-1994-1995)

The ITU Radiocommunication Assembly,

considering

a)   that there is a need to give guidance to engineers in the planning of broadcast services in the VHF and UHF bands for all climatic conditions;

b)   that, for stations working in the same or adjacent frequency channels, the determination of the minimum geographical distance of separation required to avoid intolerable interference due to long-distance tropospheric transmission is a matter of great importance;

c)   that the curves that appear in Annex 1 are based on the statistical analysis of a considerable amount of experimental data,

noting

a)   that Recommendation ITU-R P.528 provides guidance on the prediction of point-to-area path loss for the aeronautical mobile service for the frequency range 125 MHz to 30 GHz and the distance range up to 1 800 km;

b)   that Recommendation ITU-R P.529 provides guidance on the prediction of point-to-area field strength for the land mobile service in the VHF and UHF bands;

c)   that Recommendation ITU-R P.452 provides guidance on the detailed evaluation of microwave interference between stations on the surface of the Earth at frequencies above about 0.7 GHz;

d)   that Recommendation ITU-R P.617 provides guidance on the prediction of point-to-point path loss for trans-horizon radio-relay systems for the frequency range above 30 MHz and for the distance range 100 to 1 000 km,

recommends

1   that the curves and procedures given in Annexes 1 and 2 be adopted for the prediction of field strength for the broadcasting service for the frequency range 30 to 1 000 MHz and for the distance range up to 1 000 km, subject to the following conditions:

1.1   the field strengths have been adjusted to correspond to a power of 1 kW radiated from a half-wave dipole;

1.2   the curves are based upon measurement data mainly relating to temperate climates containing "cold" and "warm" seas, e.g. the North Sea and the Mediterranean Sea. Extensive studies reveal that propagation conditions in certain areas of super-refractivity bounded by "hot" seas are substantially different;

1.3   the effective height of the transmitting antenna is defined as its height over the average level of the ground between distances of 3 and 15 km from the transmitter in the direction of the receiver;

1.4   the height of the receiving antenna is defined as the height above local terrain;

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*   This Recommendation should be brought to the attention of Radiocommunication Study Groups 10 and 11.

1.5   the parameter Δh (see Recommendation ITU-R P.310) is used to define the degree of terrain irregularity; for broadcasting services it is applied in the range 10 km to 50 km from the transmitter (see Fig. 6);

1.6   methods for determining field strengths over mixed land and sea paths are given in Annex 2;

1.7   the field strength depends upon the height of the receiving antenna as well as the nature of its immediate surroundings. Data describing antenna height gain are given in § 1.10;

1.8   account should be taken of the attenuation through forest and vegetation (see Recommendation ITU-R P.833);

1.9   improved accuracy of predicted field strengths can be obtained by taking into account terrain local to the receiving location by means of a terrain clearance angle. The method is described in § 1.4 below. In hilly and mountainous regions the effect of scattering from the terrain should also be taken into account.

ANNEX 1

1   Introduction

1.1   The propagation curves represent field-strength values in VHF and UHF bands as a function of various parameters; some curves refer to land paths, others refer to sea paths. The land path curves were prepared from data obtained mainly from temperate climates as encountered in Europe and North America. The sea path curves were prepared from data obtained mainly from the Mediterranean and the North Sea regions.

1.2   The propagation curves represent the field-strength values exceeded at 50% of the locations (within any area of approximately 200 m by 200 m) for different percentages of time. They correspond to different transmitting antenna heights and a receiving antenna height of 10 m. The land path curves refer to a value of $\Delta h = 50$ m which generally applies to rolling terrain commonly found in Europe and North America.

1.3   The curves in Figs. 1a to 4c, 9 to 11 and 13 to 16b are given for effective transmitting antenna heights between 37.5 m and 1 200 m, each value given of the "effective height" being twice that of the previous one. For different values of effective height, a linear interpolation between the two curves corresponding to effective heights immediately above and below the true value shall be used.

1.3.1   For an effective transmitting antenna height, h_1, in the range 0 to 37.5 m, the field strength at a distance x from the transmitter is taken as the same as that given on the curve for 37.5 m at a distance of $\left(x + 25 - 4.1 \sqrt{h_1}\right)$ km. This procedure is valid for distances beyond the radio horizon given by $\left(4.1 \sqrt{h_1}\right)$ km. Field strength values for shorter distances are obtained by:

–   calculating the difference between the field strength value at the radio horizon for height h_1 (using the procedure given above) and the value on the 37.5 m curve for the same distance;

–   subtracting the absolute value of the difference thus obtained from the field strength value on the 37.5 m curve for the actual distance involved.

This may be expressed as in the following formulae where $E(x, h_1)$ is the field strength (dB(μV/m)) for a distance x (km) and an effective transmitting antenna height h_1 (m):

$$E(x, h_1) = E\left[\left(x + 25 - 4.1 \sqrt{h_1}\right), 37.5\right] \qquad\qquad \text{for } x \geq 4.1 \sqrt{h_1} \qquad (1a)$$

$$E(x, h_1) = E(x, 37.5) - E\left(4.1 \sqrt{h_1}, 37.5\right) + E(25, 37.5) \qquad \text{for } x < 4.1 \sqrt{h_1} \qquad (1b)$$

1.3.2 For an effective transmitting antenna height, h_1, greater than 1 200 m, the field strength at a distance x from the transmitter is taken as the same as that given on the curve for 1 200 m at a distance of $\left(x + 142 - 4.1\sqrt{h_1}\right)$ km. This procedure is valid for distances beyond the radio horizon, given by $\left(4.1\sqrt{h_1}\right)$ km. Field strength values for shorter distances are obtained by:

– calculating the difference between the field strength value at the radio horizon for height h_1 (using the procedure given above) and the value on the 1 200 m curve for the same distance;

– adding the absolute value of the difference thus obtained to the field strength value on the 1 200 m curve for the actual distance involved.

This may be expressed as follows:

$$E(x, h_1) = E\left[\left(x + 142 - 4.1\sqrt{h_1}\right),\ 1\,200\right] \qquad \text{for } x \geq 4.1\sqrt{h_1} \qquad (2a)$$

$$E(x, h_1) = E(x,\ 1\,200) - E\left(4.1\sqrt{h_1},\ 1\,200\right) + E(142,\ 1\,200) \quad \text{for } x < 4.1\sqrt{h_1} \qquad (2b)$$

This procedure is subject to the limitation that the value obtained does not exceed the free-space value.

1.3.3 In order to take account of cases where the effective transmitting antenna height, as defined in "*recommends* 1.3" is negative, a correction term based upon the concept of terrain clearance angle (see § 1.4) may be used.

In the case that a terrain database is available, the terrain clearance angle from the transmitter should be calculated for any case where the effective transmitting antenna height is negative. The relevant correction factor may then be derived from Fig. 17.

In the case where a terrain database is not available, an approximate correction factor may be derived by using the quoted negative effective antenna height to derive an effective clearance angle as indicated below.

The effective clearance angle associated with a transmitter whose effective height is h m (where h is negative) may be calculated as arctan (h/9 000). That is, the ground is regarded as approximating an irregular wedge over the range 3 to 15 km (the specified range for calculating the effective antenna height) from the transmitter, with its mean value occurring at 9 km, as indicated in Fig. 18. This is approximately the minimum loss condition.

The definition of clearance angle in the previous paragraph gives a negative value which can be applied to the curves of Fig. 17 to obtain a correction term. Where the latter is negative it is used to reduce the field strength value for any distance given by Figs. 1a to 4c, 9 to 11 and 13 to 16b for an effective transmitting height of zero metres obtained using the extrapolation procedure given in § 1.3.1. It should be noted that Fig. 17 inherently takes account of a receiving antenna height of +10 m and thus a positive value for the correction term is found to correspond with a zero value of clearance angle.

1.4 If more precision is required for predicting the field strength for reception conditions in specific areas, e.g. in a small receiving area, a correction may be made based on a "terrain clearance angle". This angle, θ, should be representative of those angles in the reception area, which are measured between the horizontal at the receiving antenna and the line which just clears all obstacles within 16 km in the direction of the transmitter. The example in Fig. 19 also indicates the sign convention which is negative if the line to the obstacles is above the horizontal.

From the terrain clearance angles, appropriate correction factors are given in Fig. 17.

They should be applied to the results from Figs. 1a to 4c, 9 to 11 or 13 to 16b for 50% of the locations.

Where the relevant terrain clearance angle information is available, Fig. 17 (or the equivalent equations) should be used in place of the Δh correction (see § 2.1 and 3.1).

Corrections for terrain clearance angles outside the range −20° to 0.8°, are not given in Fig. 17, because of the small number of paths outside this range. However, if required, they may be obtained by linear extrapolation from the curves of Fig. 17 and limiting values of 30 dB for VHF and 40 dB for UHF at 1.5° and −32 dB for VHF and −34 dB for UHF at − 40°, subject to the condition that the free-space field strength is not exceeded.

The terrain clearance angle correction curves of Fig. 17 can be expressed as follows:

For VHF, the equation (see Note 1) is:

$$\text{Correction} = 8.1 - \left[6.9 + 20 \log \left(\sqrt{(\nu - 0.1)^2 + 1} + \nu - 0.1 \right) \right] \qquad (3)$$

where:

$$\nu = -\theta \sqrt{(4\,000 \times 95)/300} \qquad \theta \text{ rad}$$

For UHF, the equation (see Note 1) is:

$$\text{Correction} = 14.9 - \left[6.9 + 20 \log \left(\sqrt{(\nu - 0.1)^2 + 1} + \nu - 0.1 \right) \right] \qquad (4)$$

where:

$$\nu = -\theta \sqrt{(4\,000 \times 650)/300} \qquad \theta \text{ rad}$$

NOTE 1 – These equations have not been simplified in order to make the terms used in their derivation more obvious (see Recommendation ITU-R P.526).

1.5   For locations other than 50%, probability distribution curves are presented in Figs. 5 and 12. For more information on location variability, see Appendix 1.

1.6   Estimates of mixed-path field strengths should be made in accordance with the methods described in Annex 2.

1.7   Since most of the measurements relate to distances less than 500 km, the results given by these curves are less reliable above this distance. The sections of the curves in dashed lines, obtained by extrapolation, are only intended as a general guide to likely values of field strength.

1.8   All these curves are based on long-term values (several years) and may be regarded as representative of the mean climatic conditions prevailing in all the temperate regions. It should be noted, however, that for brief periods of time (e.g. for some hours or even days), field strengths may be obtained which are much higher than those shown by these curves, particularly over relatively flat terrain.

1.9   It is known that the median field strength varies in different climatic regions, and data for a wide range of such conditions in North America and Western Europe show that it is possible to correlate the observed values of median field strength with the refractive index gradient in the first kilometre of the atmosphere above ground level. If n_s and n_1 are the refractive indices at the surface and at a height of 1 km respectively, and if ΔN is defined as $(n_s - n_1) \times 10^6$, then in a standard atmosphere, $\Delta N \approx 40$, the 50% curves of Figs. 1a and 1b refer to this case. If the mean value of ΔN, in a given region, differs appreciably from 40, the appropriate median field strengths for all distances beyond the horizon are obtained by applying a correction factor of $0.5\,(\Delta N - 40)$ dB to the curves. If ΔN is not known, but information concerning the mean value of N_s is available, where $N_s = (n_s - 1) \times 10^6$, an alternative correction factor of $0.2\,(N_s - 310)$ dB may be used, at least for temperate climates. Whilst those corrections have so far only been established for the geographical areas referred to above, they may serve as a guide to the corrections which may be necessary in other geographical areas. The extent to which it is reliable to apply similar corrections to the curves for field strengths exceeded 1% and 10% of the time is not known. It is expected, however, that a large correction will be required for the 1% and 10% values, in regions where super-refraction is prevalent for an appreciable part of the time.

1.10   A change in the receiving antenna height (h_2) in the range 1.5 to 40 m can cause a field strength change, relative to the value at 10 m, which is given by:

$$\text{Height gain (dB)} = \frac{c}{6} \cdot 20 \log_{10} (h_2 / 10) \qquad (5)$$

where c is given in Table 1.

TABLE 1

Typical height gain factors, *c*

Zone	VHF (dB)	UHF (dB)
Rural	4	4
Suburban	5	6
Urban	6	8

Somewhat lower values may be experienced for non-directional antennas in non-rural areas.

2 VHF bands

2.1 The curves in Figs. 1a, 2a, 3a and 4a represent field-strength values exceeded at 50% of the locations within any area of approximately 200 m by 200 m and for 50%, 10%, 5% and 1% of the time for land paths where Δh of 50 m is considered representative. For a different value of Δh, a correction should be applied to the curves as shown in Fig. 7. For locations other than 50%, corrections may be obtained from the distribution curve in Fig. 5.

In the case of broadband digital systems having bandwidths of at least 1.5 MHz the dashed line of Fig. 5 should be used. This is to take account of the fact that such systems are less subject to frequency dependent location variation than the analogue systems for which the solid line in Fig. 5 is intended.

2.2 The curves in Figs. 1b, 2b, 2c, 3b, 3c, 4b and 4c represent field-strength values exceeded at 50% of the locations for 50%, 10%, 5% and 1% of the time for sea paths in cold seas and warm seas, the climatic characteristics of those areas being likened to those observed in the North Sea and the Mediterranean, respectively.

2.3 In areas subject to pronounced super-refraction phenomena, account should be taken of the information contained in § 1.9.

2.4 The ionosphere, primarily through the effects of sporadic-E ionization, can influence propagation in the lower part of the VHF band, particularly at frequencies below about 90 MHz. In some circumstances this mode of propagation may influence the field strength exceeded for small percentages of the time at distances beyond some 500 km, and near the magnetic equator and in the auroral zone higher percentages of the time may be involved. However, these ionospheric effects can usually be ignored in most applications covered by this Recommendation and the propagation curves of this Annex have been prepared on this assumption. Recommendation ITU-R P.534 should be consulted to determine whether the assumption is reasonable.

3 UHF bands

3.1 The curves in Figs. 9, 10 and 11 represent field-strength values exceeded at 50% of the locations within any area of approximately 200 m by 200 m and for 50%, 10% and 1% of the time for land paths where Δh of 50 m is considered representative. For different values of Δh, a correction should be applied to the curves as shown in Fig. 8. Correction factors for locations other than 50% may be obtained from the distribution curves in Fig. 12.

In the case of broadband digital systems having bandwidths of at least 1.5 MHz the dashed line of Fig. 12 should be used. This is to take account of the fact that such systems are less subject to frequency dependent location variation than the analogue systems for which the solid line in Fig. 12 is intended.

NOTE 1 – This result has been deduced from studies below 250 MHz and at 1 500 MHz which have given similar results.

3.2   The curves in Figs. 13, 14a, 14b, 15a, 15b, 16a and 16b represent field-strength values exceeded at 50% of the locations and for 50%, 10%, 5% and 1% of the time for sea paths in cold seas and warm seas, the climatic characteristics of those areas being likened to those observed in the North Sea and the Mediterranean, respectively.

3.3   In areas subject to pronounced super-refraction phenomena, account should be taken of the information contained in § 1.9.

FIGURE 1a

Field strength (dB(μV/m)) for 1 kW e.r.p.
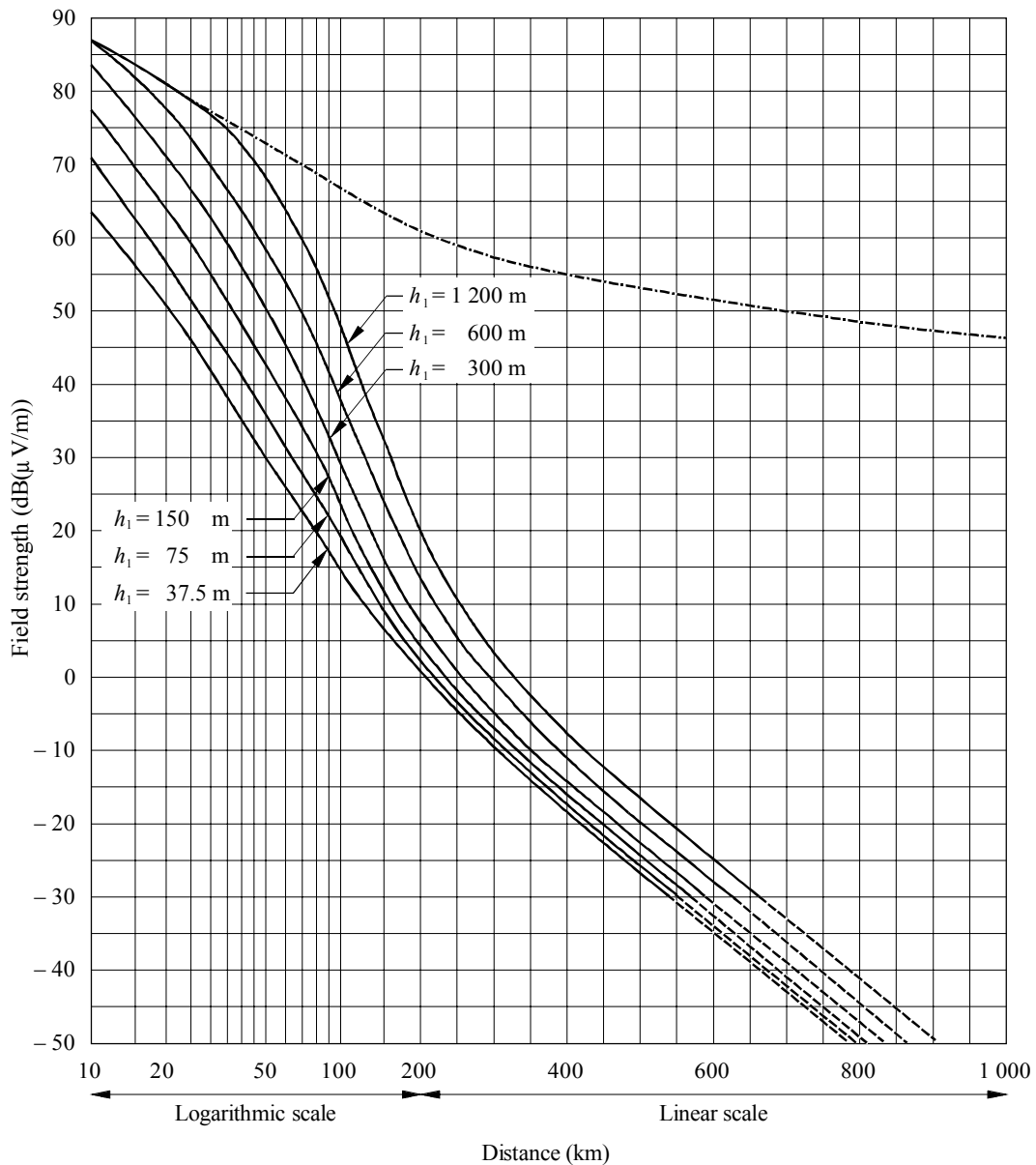
Frequency: 30-250 MHz (Bands I, II and III); land; 50% of the time;
50% of the locations; h_2 = 10 m; Δh = 50 m

------------- Free space

D01

FIGURE 1b

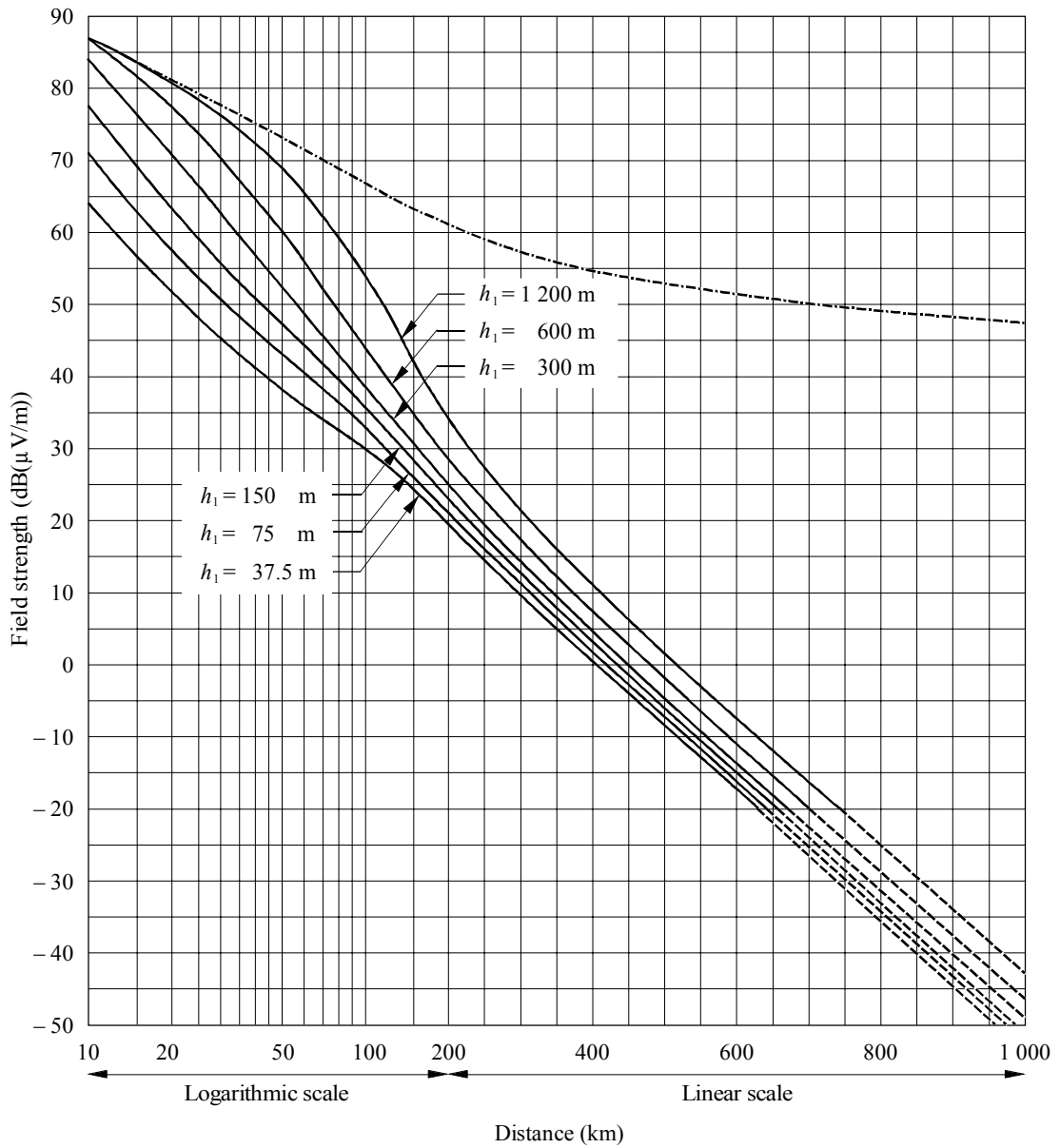**Field strength (dB(μV/m)) for 1 kW e.r.p.**
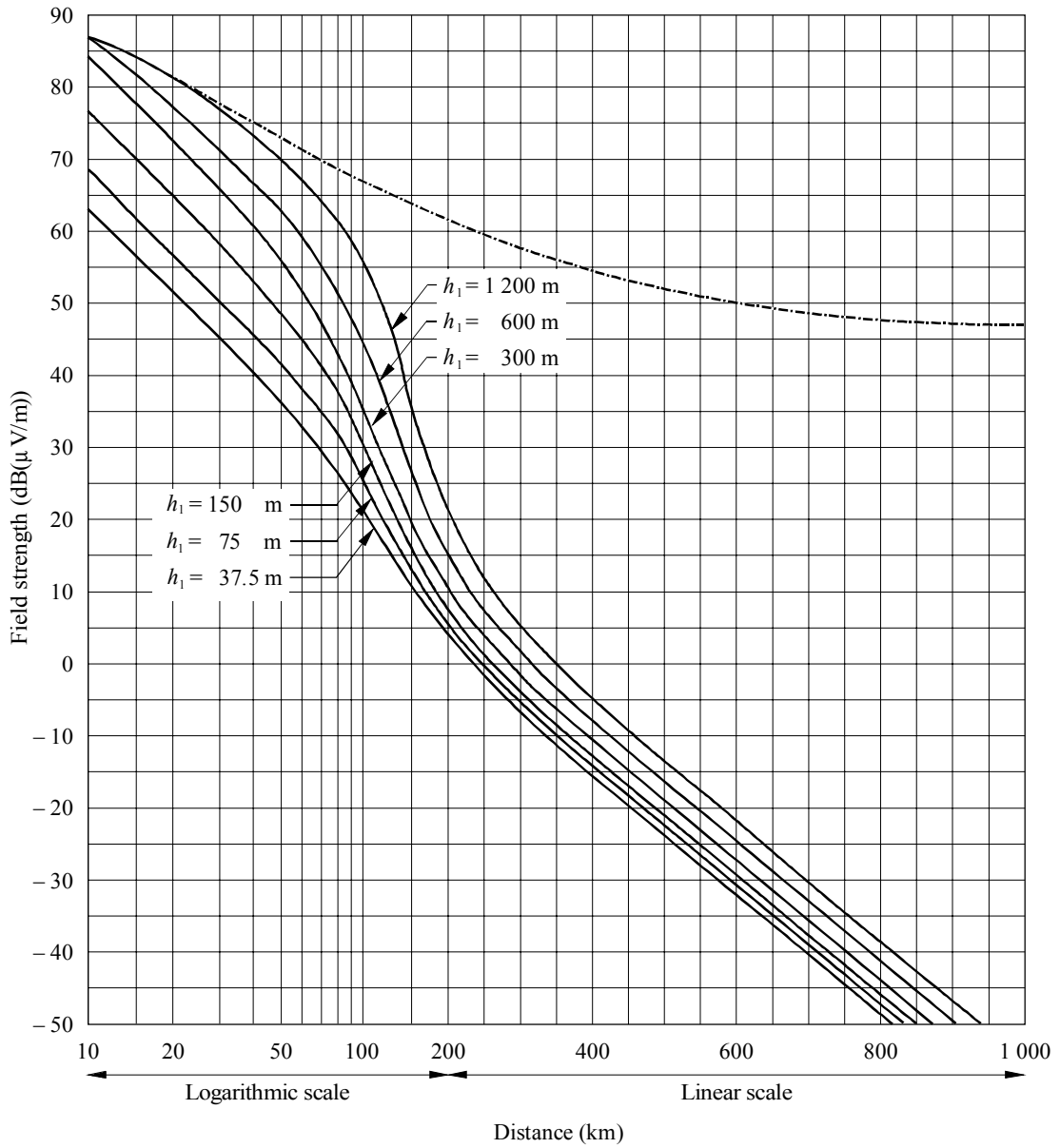
Frequency: 30-250 MHz (Bands I, II and III); sea; 50% of the time;
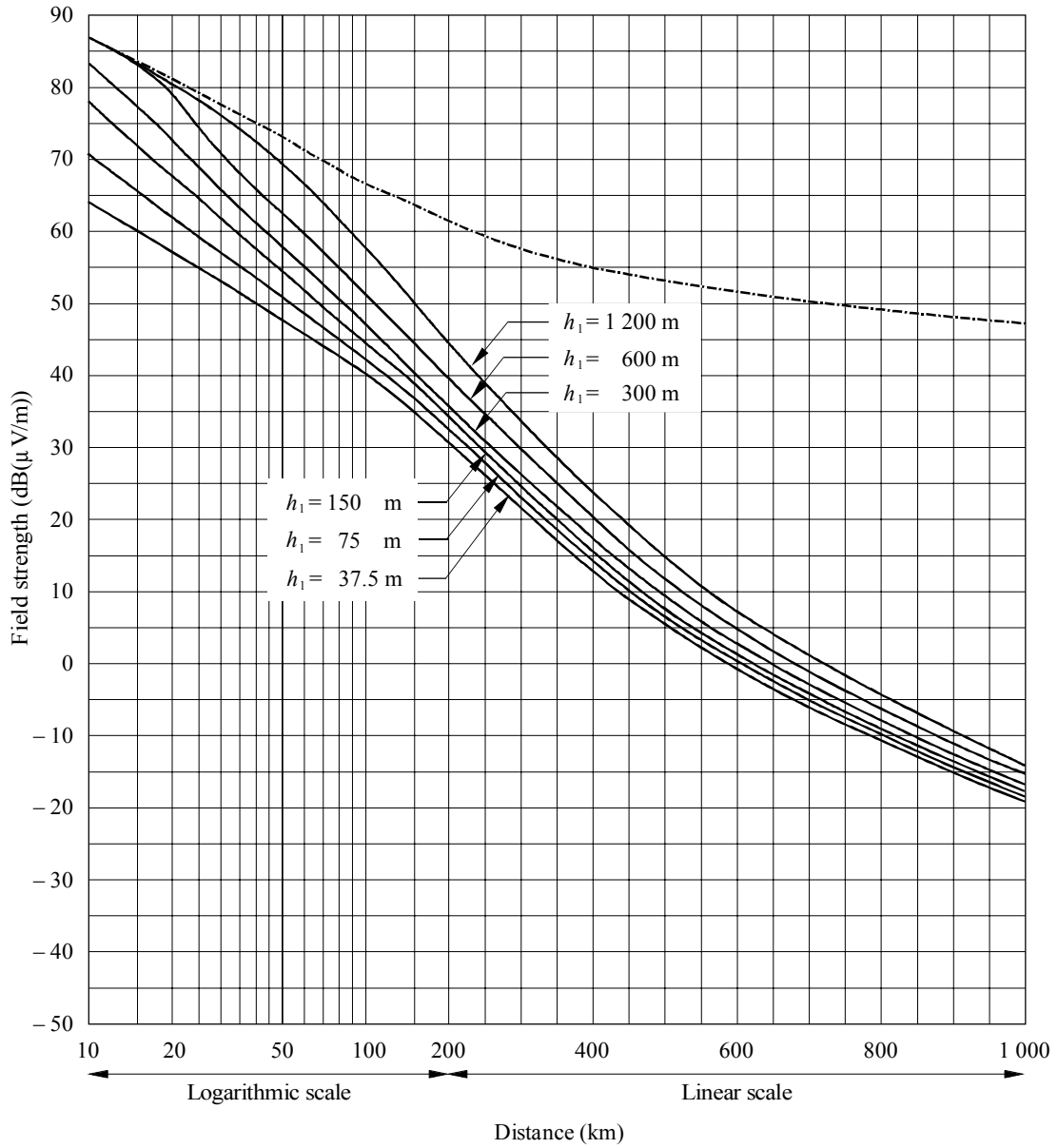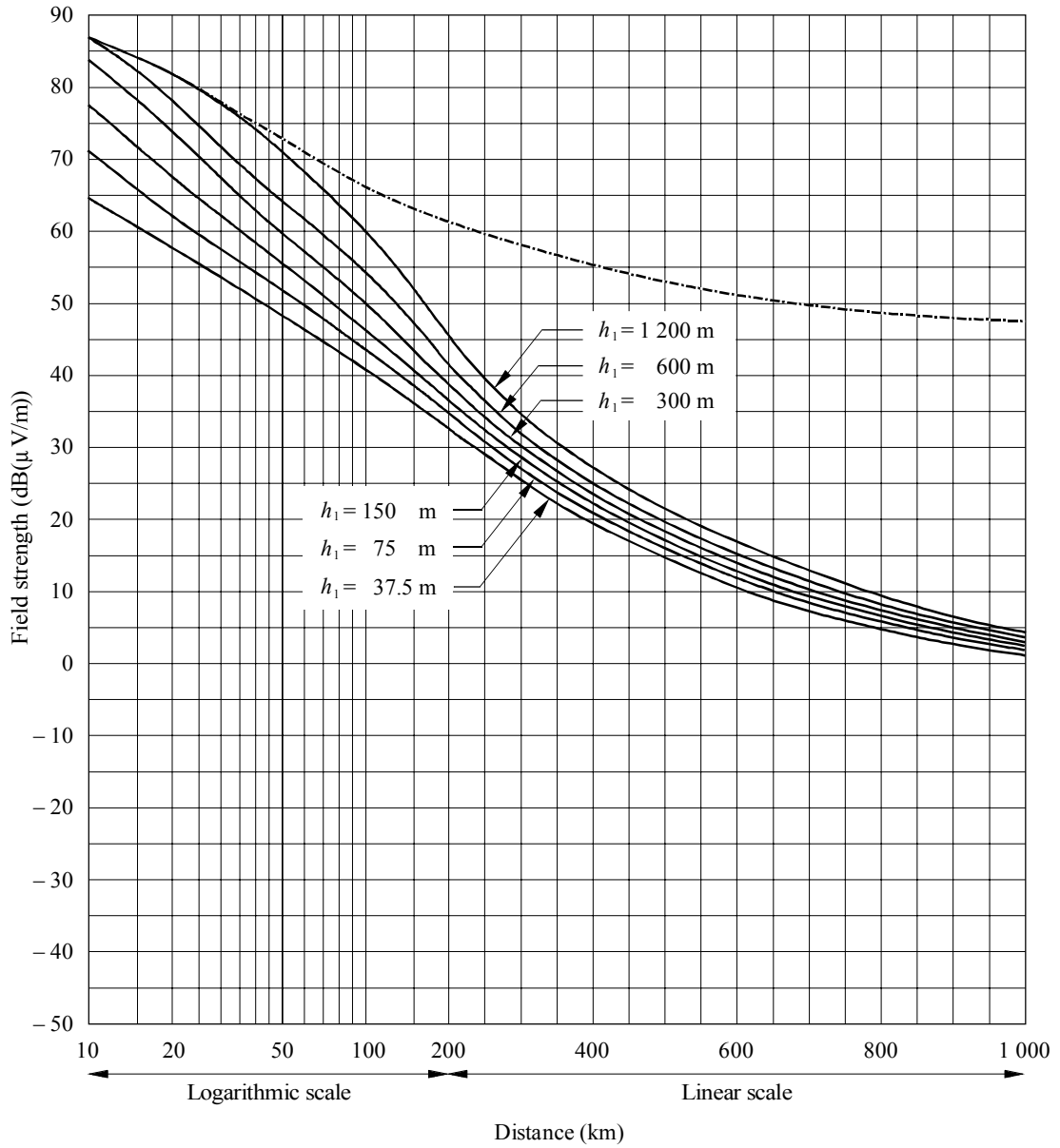50% of the locations; $h_2 = 10$ m

------- Free space

D02

FIGURE 2a

Field strength (dB(μV/m)) for 1 kW e.r.p.
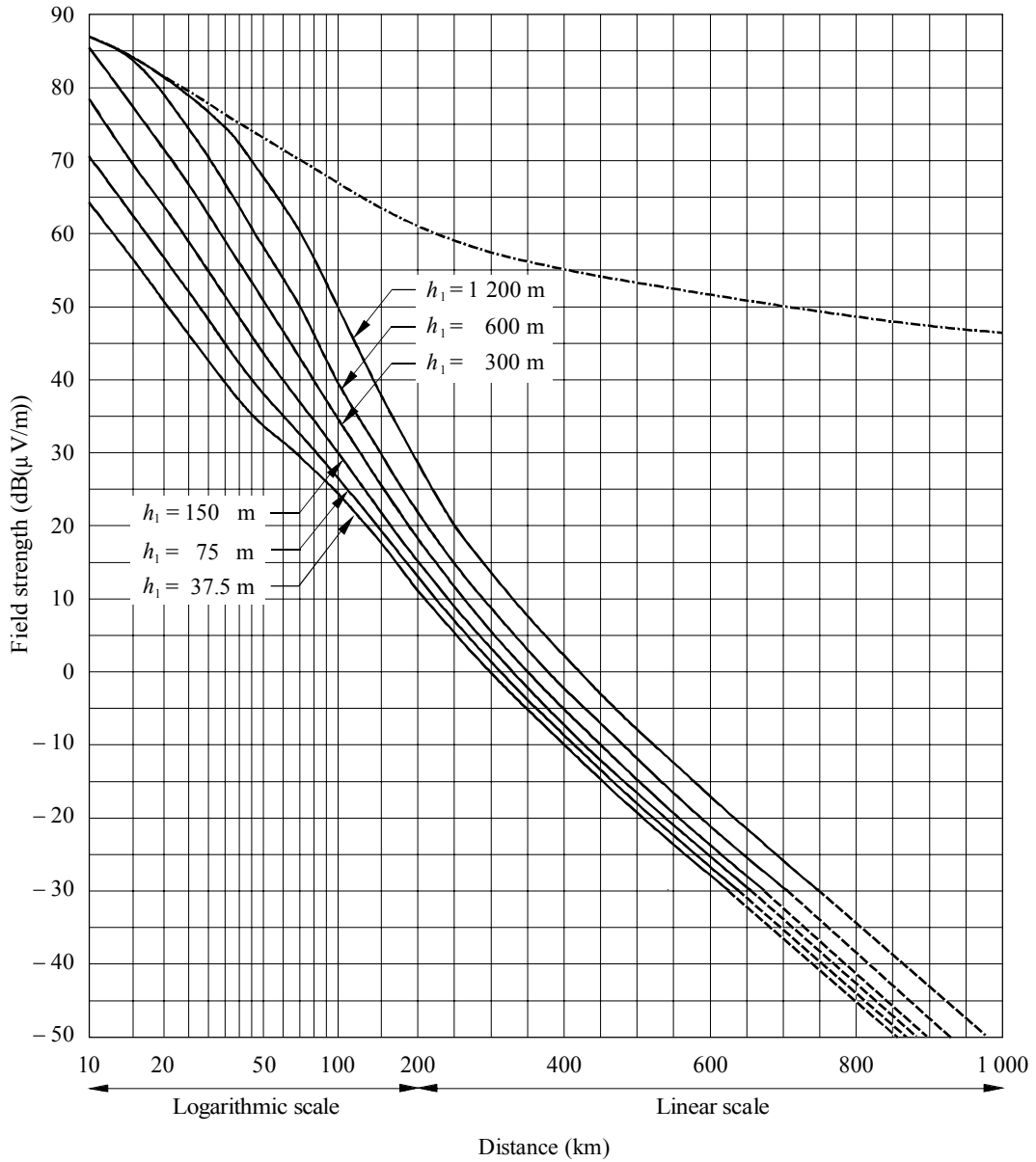
Frequency: 30-250 MHz (Bands I, II and III); land; 10% of the time;
50% of the locations; $h_2 = 10$ m; $\Delta h = 50$ m

------·-----·-----·----- Free space   D03

FIGURE 2b

Field strength (dB(μV/m)) for 1 kW e.r.p.
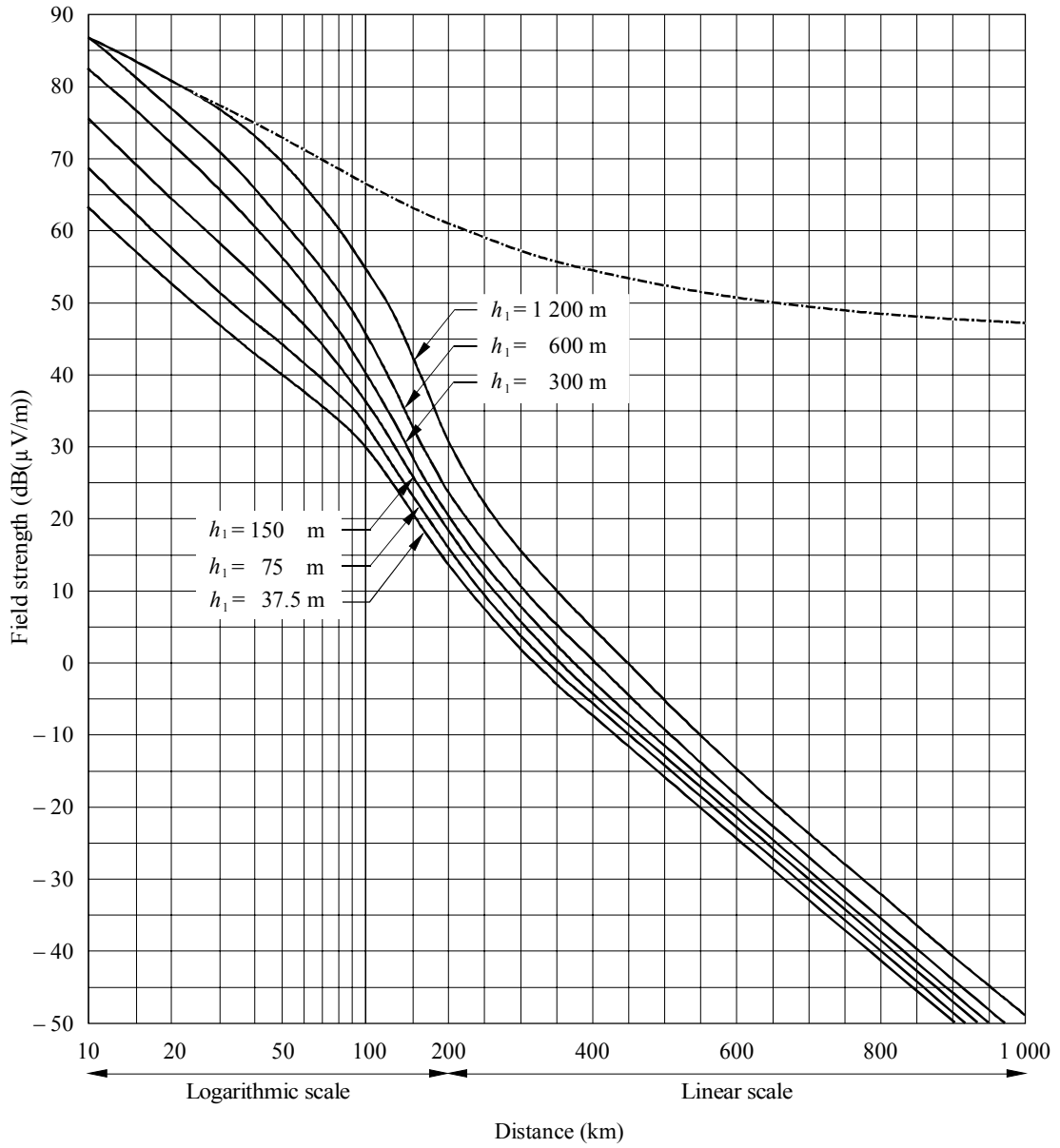
Frequency: 30-250 MHz (Bands I, II and III); cold sea; 10% of the time;
50% of the locations; $h_2 = 10$ m

- - - Free space

D04

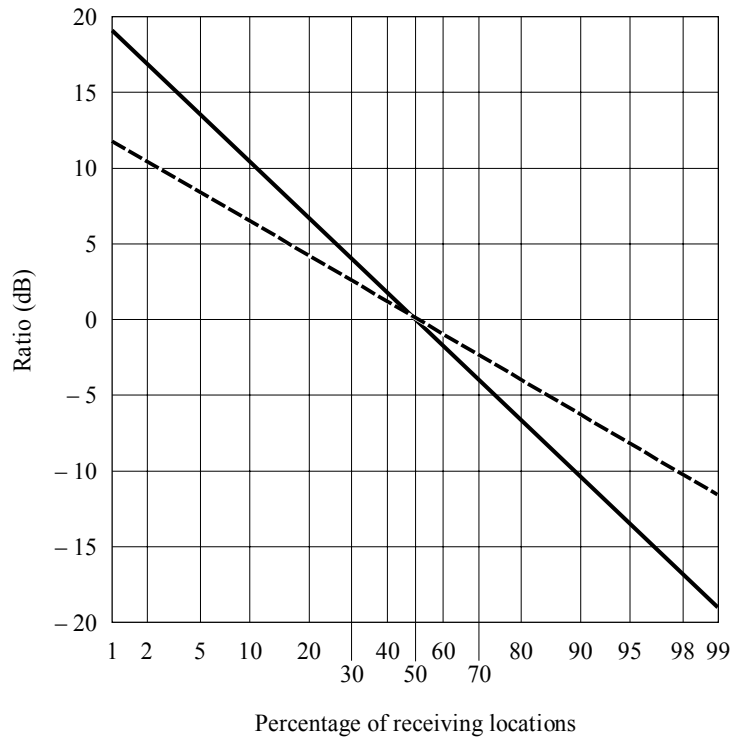FIGURE 2c

Field strength (dB(μV/m)) for 1 kW e.r.p.
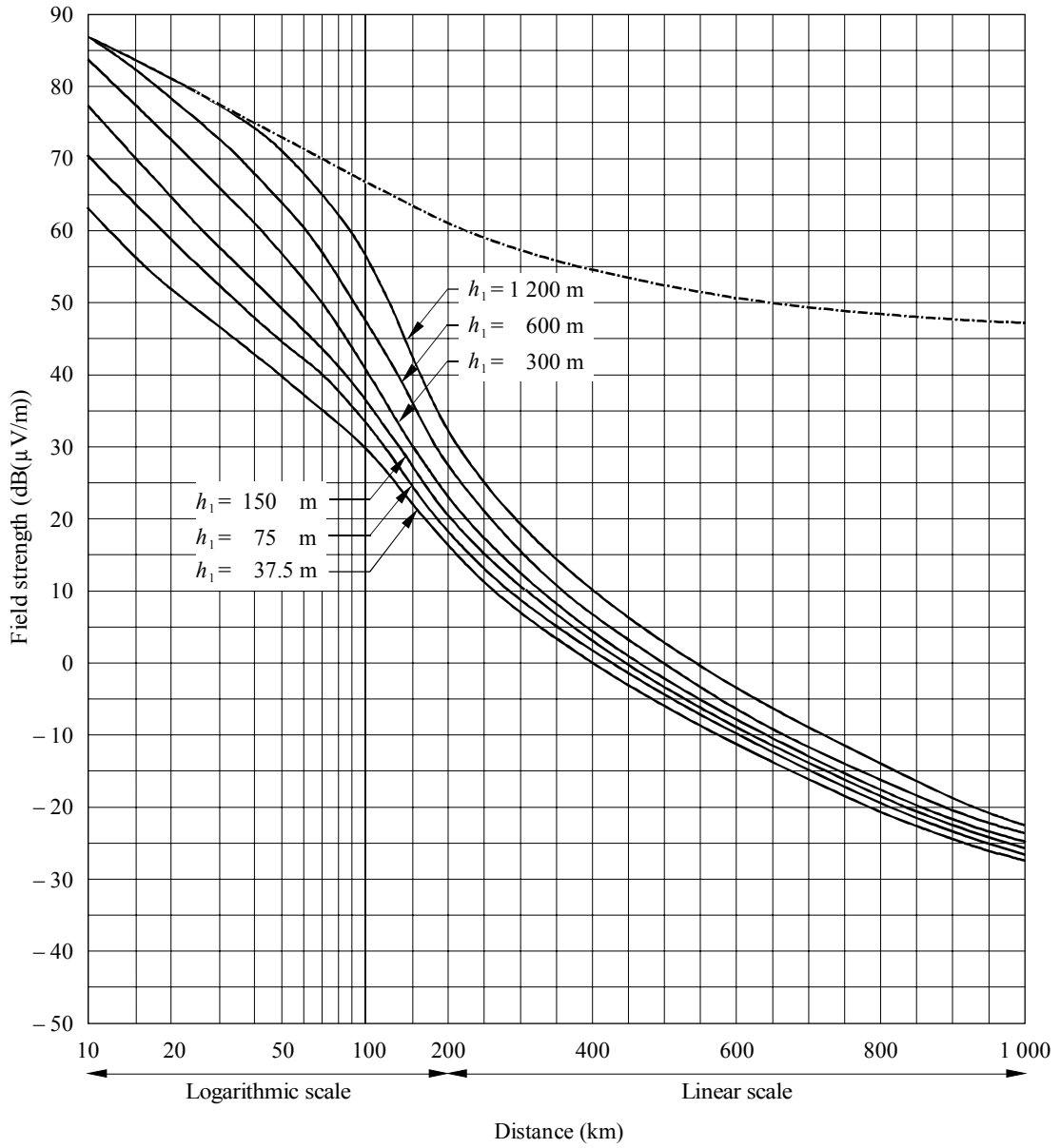
Frequency: 30-250 MHz (Bands I, II and III); warm sea; 10% of the time;
50% of the locations; $h_2 = 10$ m

---·---·--- Free space

D05

FIGURE 3a

Field strength (dB(μ V/m)) for 1 kW e.r.p.
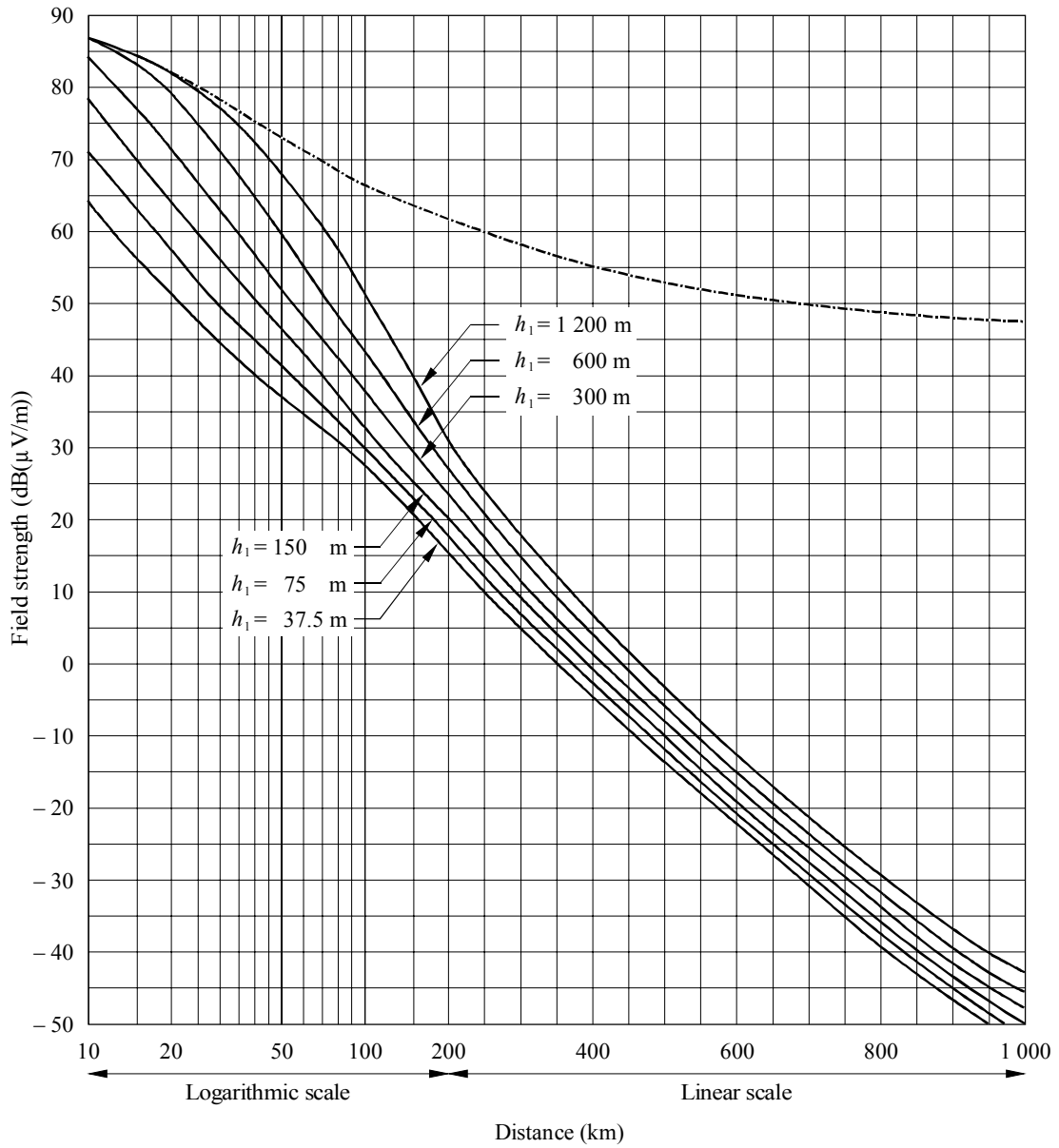
Frequency: 30-250 MHz (Bands I, II and III); land; 5% of the time;
50% of the locations; $h_2 = 10$ m; $\Delta h = 50$ m

------·------ Free space

D06

FIGURE 3b

Field strength (dB(µV/m)) for 1 kW e.r.p.
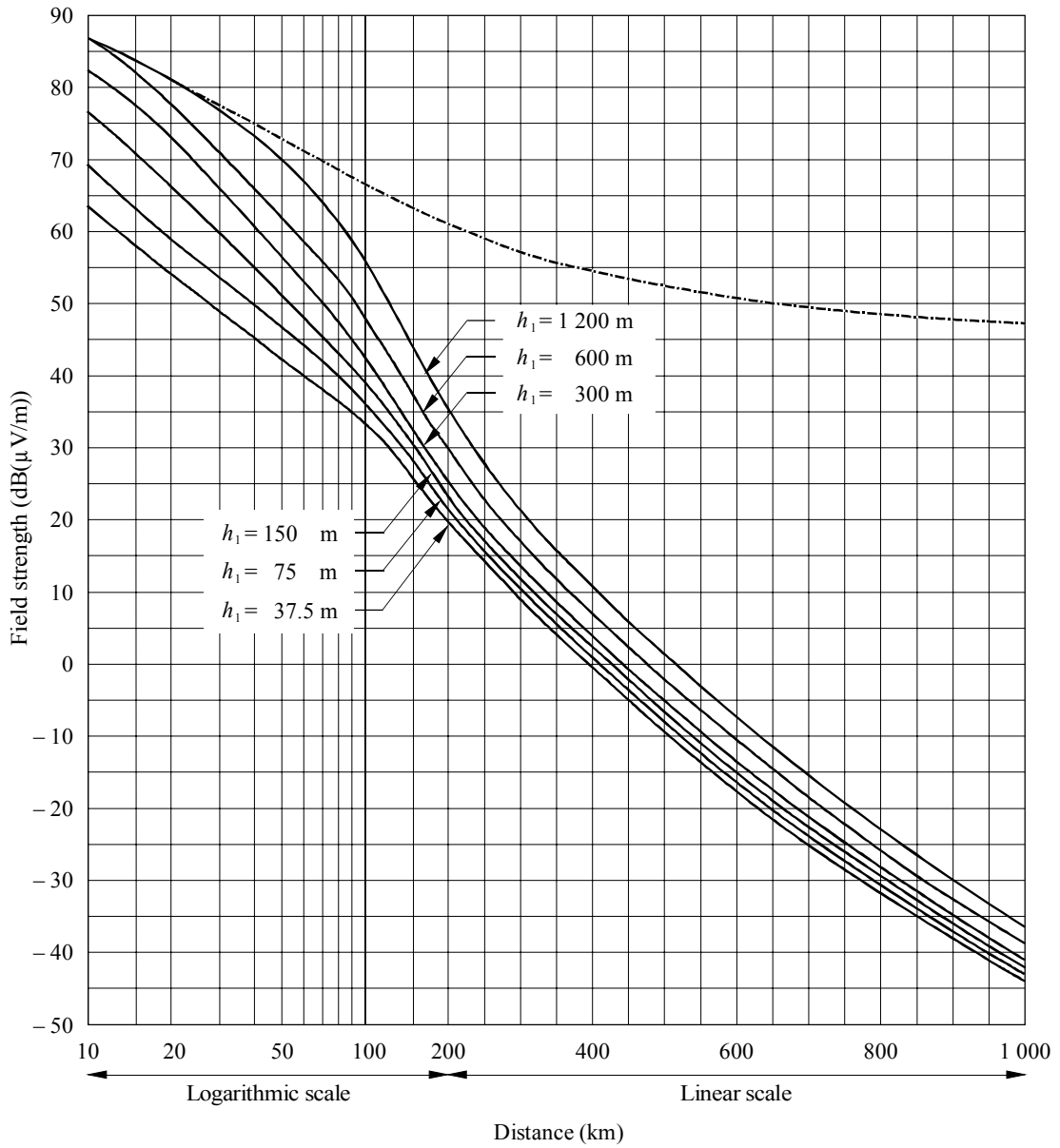
Frequency: 30-250 MHz (Bands I, II and III); cold sea; 5% of the time;
50% of the locations; $h_2 = 10$ m

---·---·--- Free space

D07

FIGURE 3c

Field strength (dB(μV/m)) for 1 kW e.r.p.
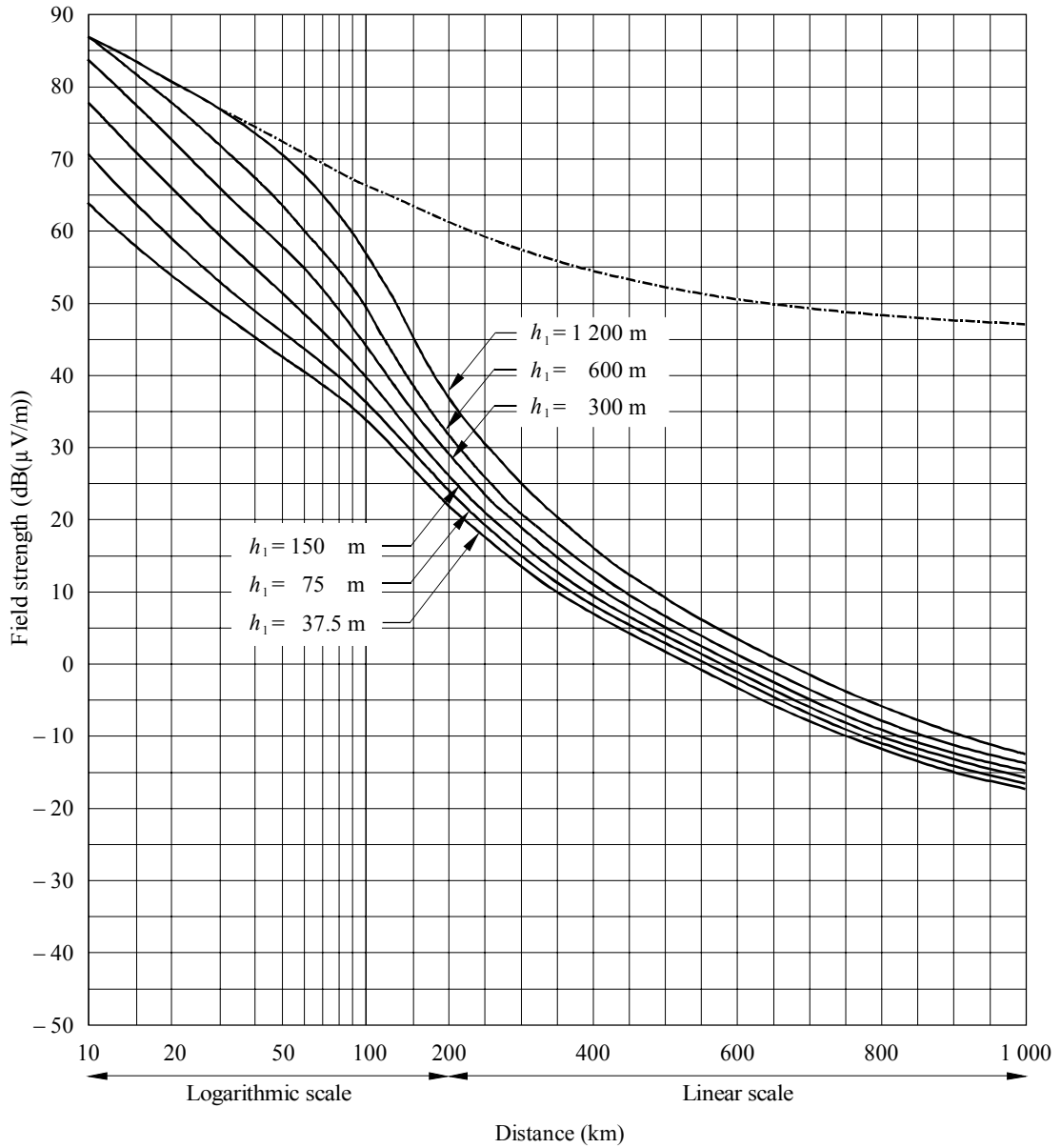
Frequency: 30-250 MHz (Bands I, II and III); warm sea; 5% of the time;
50% of the locations; $h_2 = 10$ m

- · · · Free space

D08

FIGURE 4a

Field strength (dB(μV/m)) for 1 kW e.r.p.

Frequency: 30-250 MHz (Bands I, II and III); land; 1% of the time;
50% of the locations; $h_2 = 10$ m; $\Delta h = 50$ m
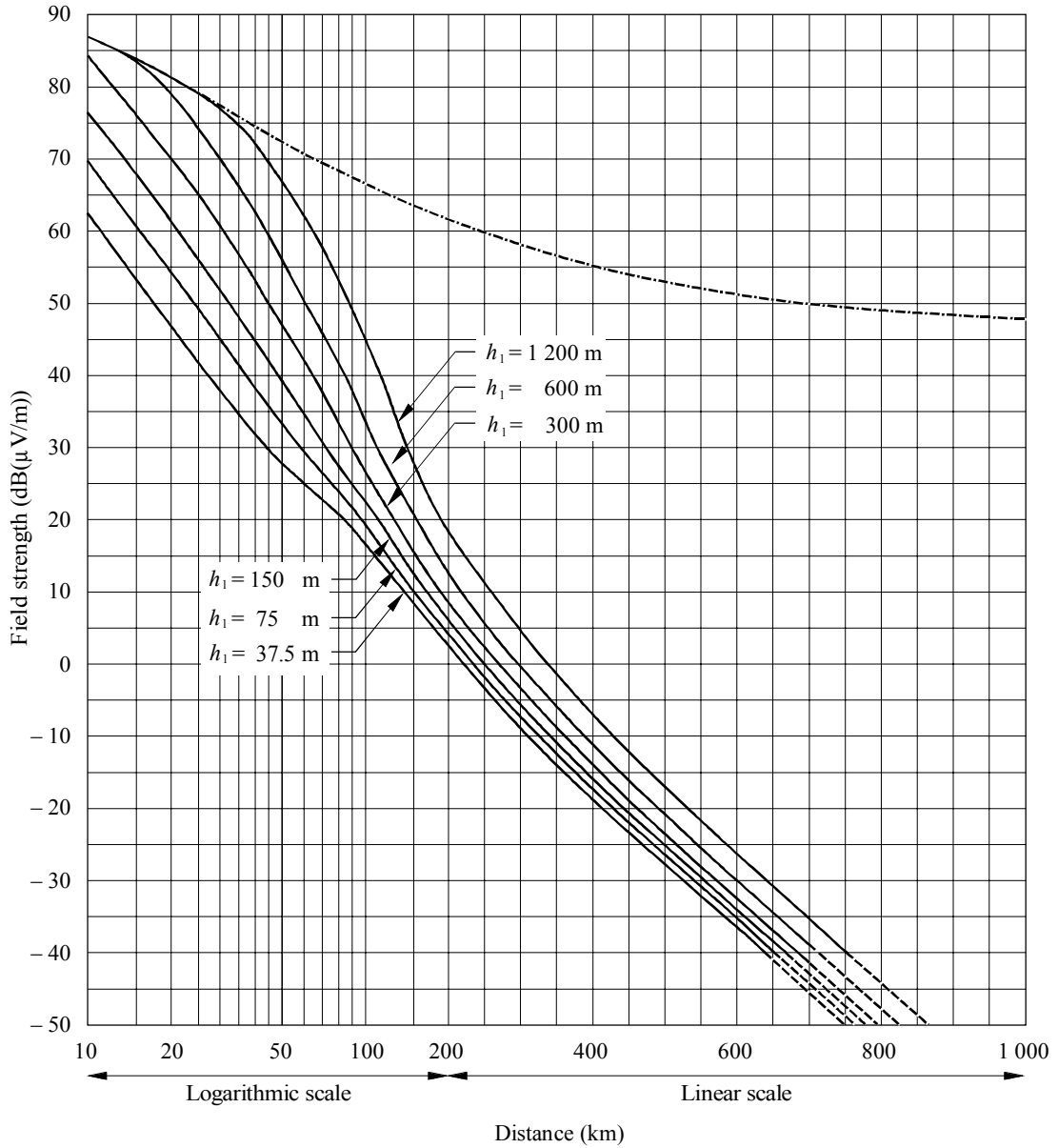
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D09

FIGURE 4b

Field strength (dB(μV/m)) for 1 kW e.r.p.

Frequency: 30-250 MHz (Bands I, II and III); cold sea; 1% of the time;
50% of the locations; $h_2 = 10$ m

–·–·–·–·– Free space

D10

FIGURE 4c

Field strength (dB(μV/m)) for 1 kW e.r.p.

Frequency: 30-250 MHz (Bands I, II and III); warm sea (excluding areas subject to
extreme super-refraction); 1% of the time; 50% of the locations; $h_2 = 10$ m

— · · — · · — Free space

D11

FIGURE 5

**Ratio (dB) of the field strength for a given percentage of the receiving
locations to the field strength for 50% of the receiving locations**

Percentage of receiving locations

Frequency: 30-250 MHz (Bands I, II and III)

————————— Analogue systems

– – – – – – – Digital systems
(>1.5 MHz bandwidth)

D12

FIGURE 6

Application of the parameter Δ*h* for broadcasting services

Distance from transmitter
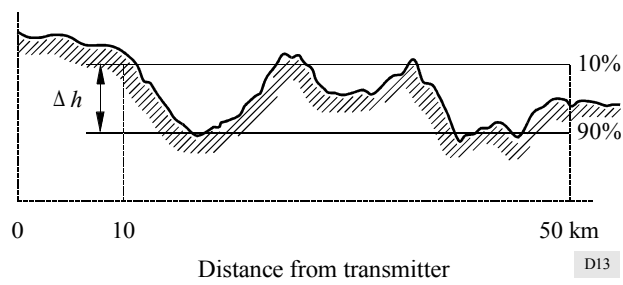
D13

FIGURE 7

Attenuation correction factor as a function of the distance d (km) and Δh
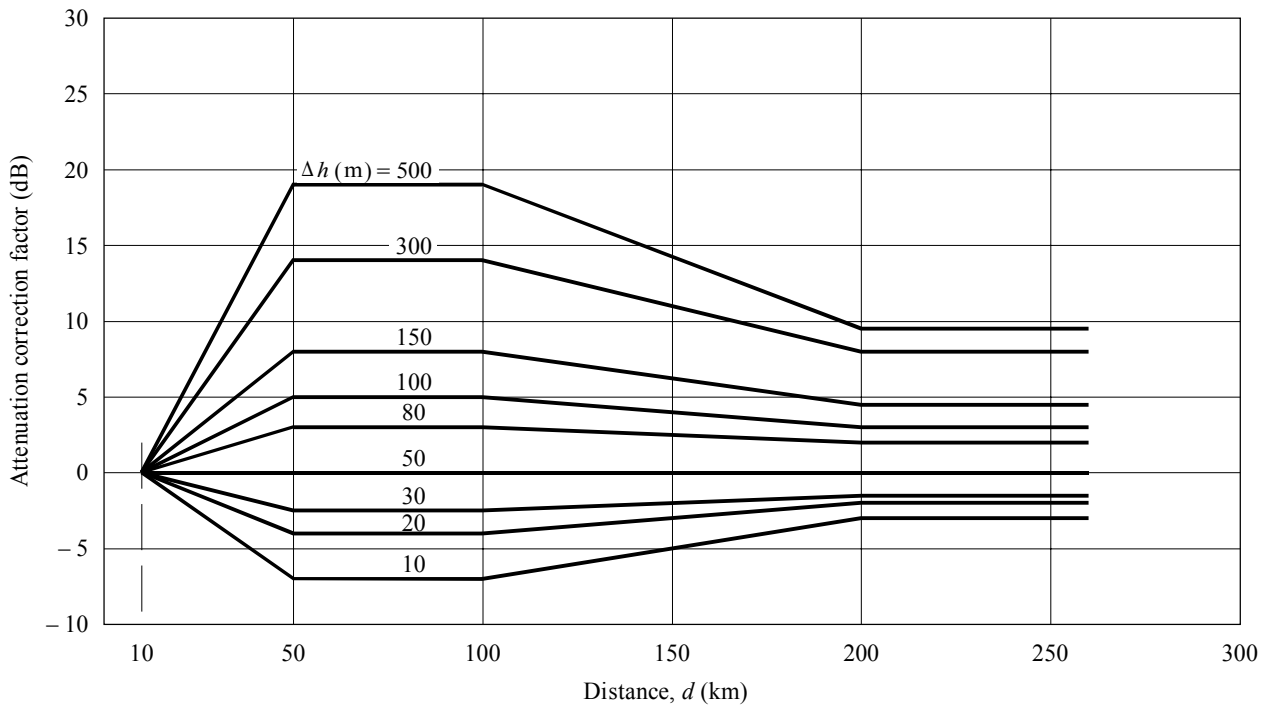
Frequency: 80-250 MHz (Bands II and III)

D14

FIGURE 8

Attenuation correction factor as a function of the distance d (km) and Δh
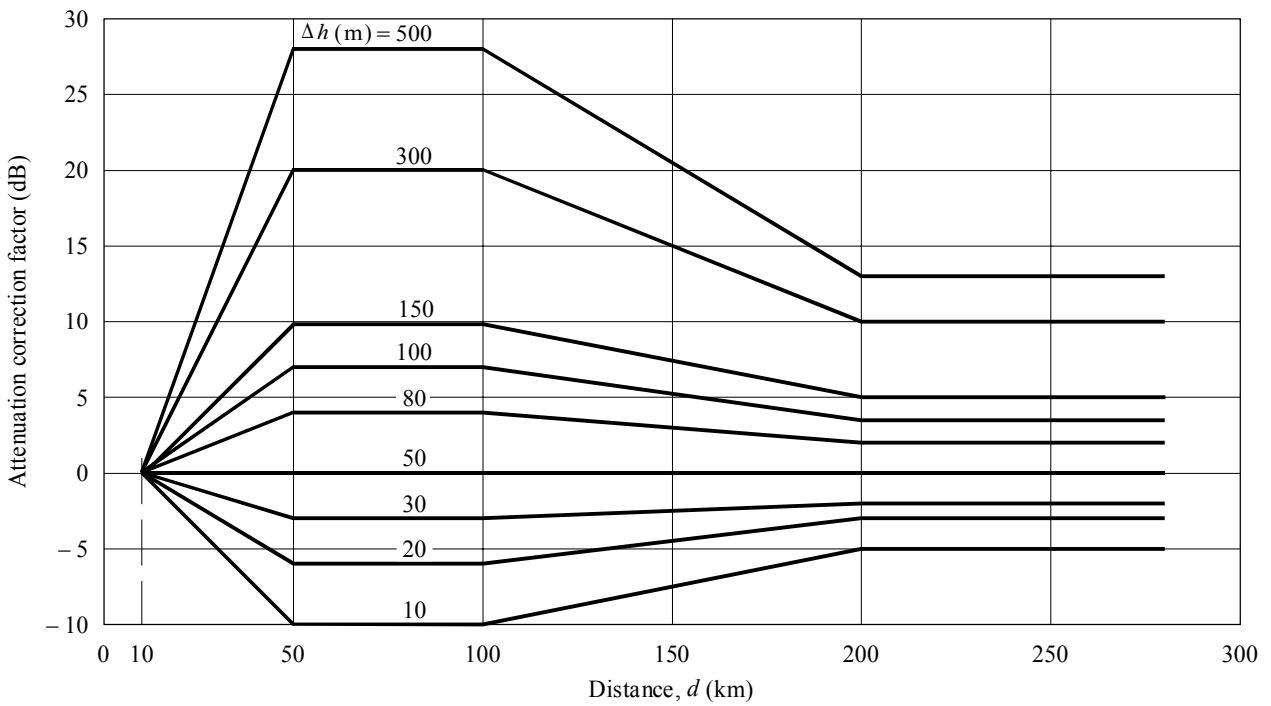
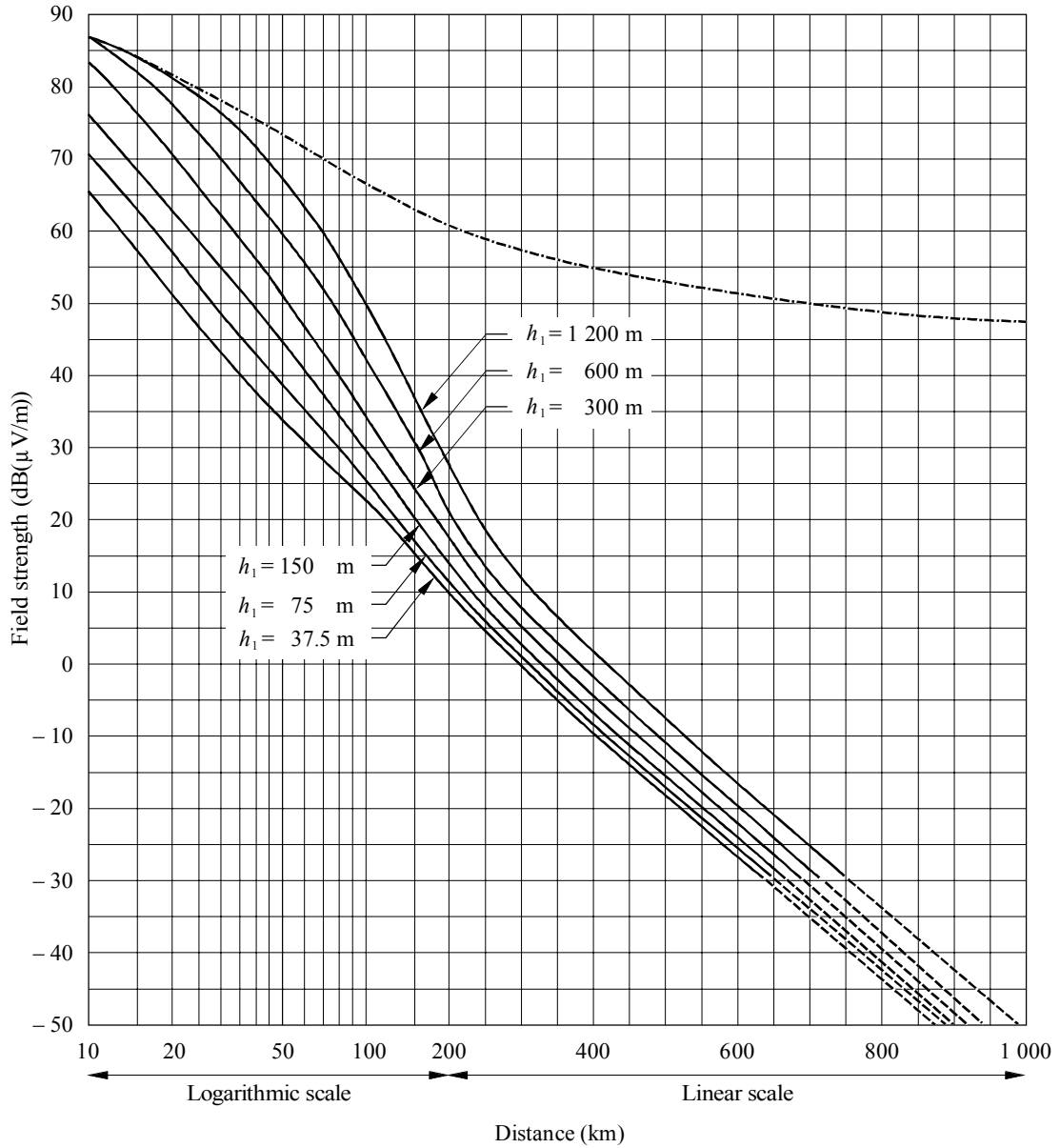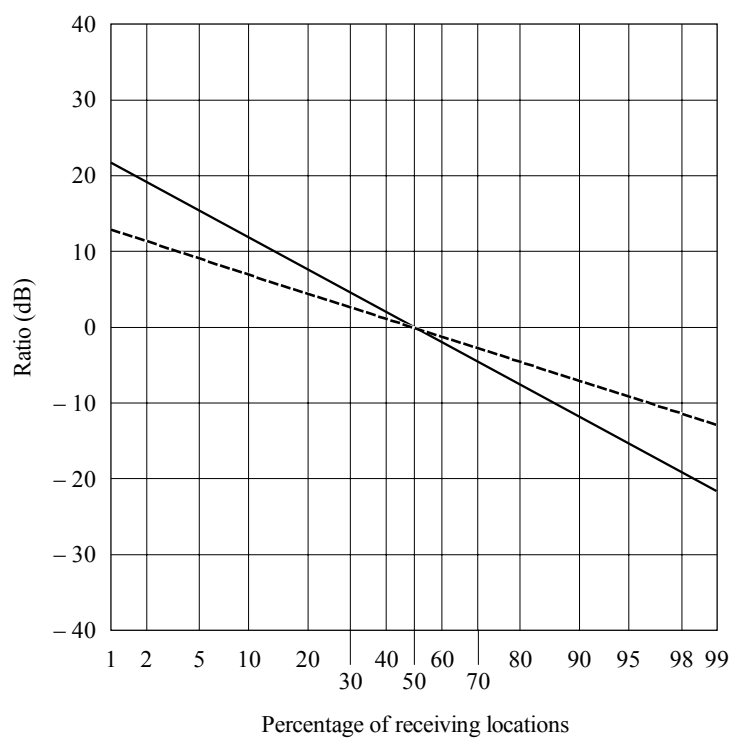Frequency: 450-1 000 MHz (Bands IV and V)

D15

FIGURE 9

Field strength (dB(μV/m)) for 1 kW e.r.p.
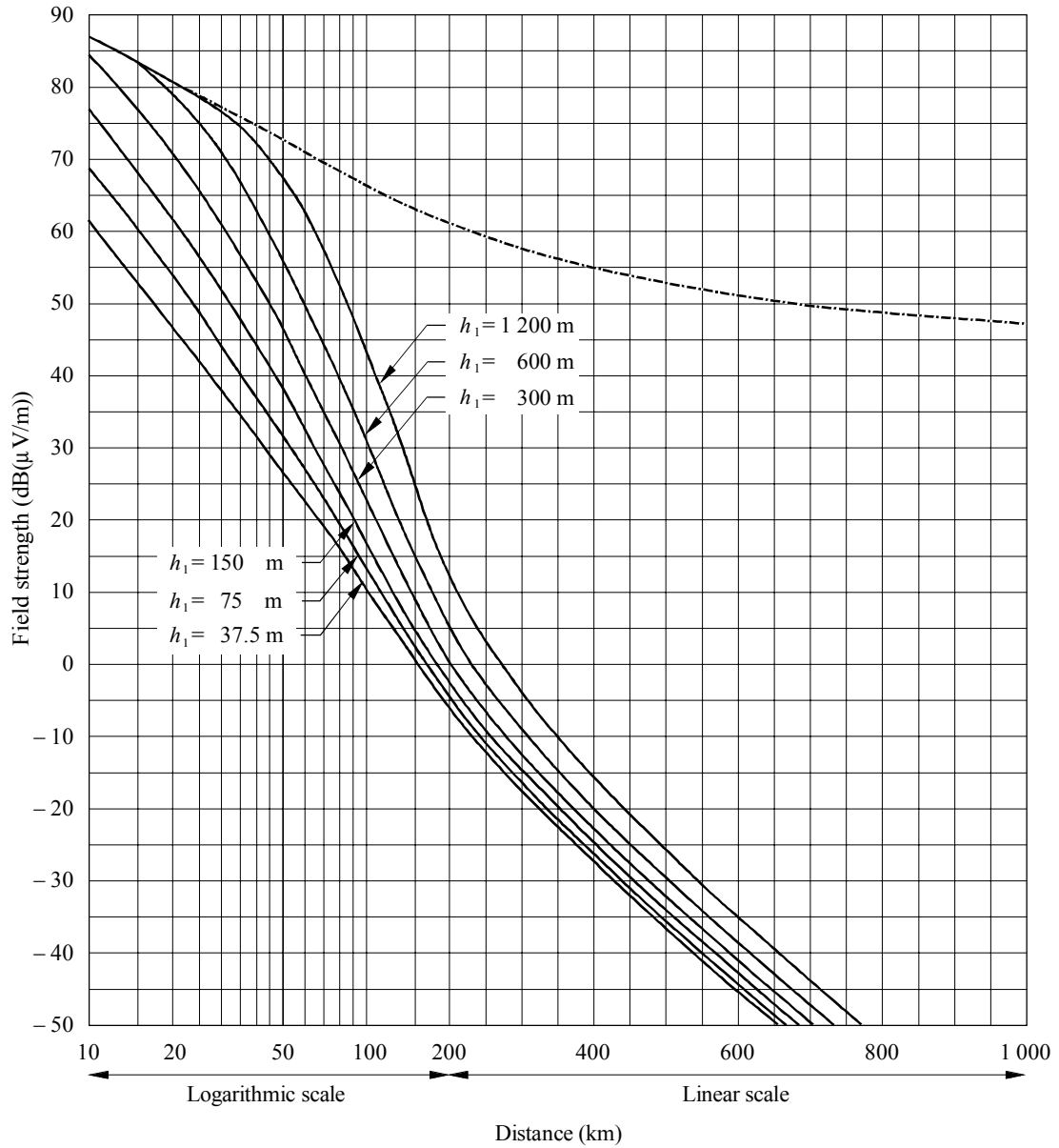
Frequency: 450-1 000 MHz (Bands IV and V); land; 50% of the time;
50% of the locations; $h_2 = 10$ m; $\Delta h = 50$ m
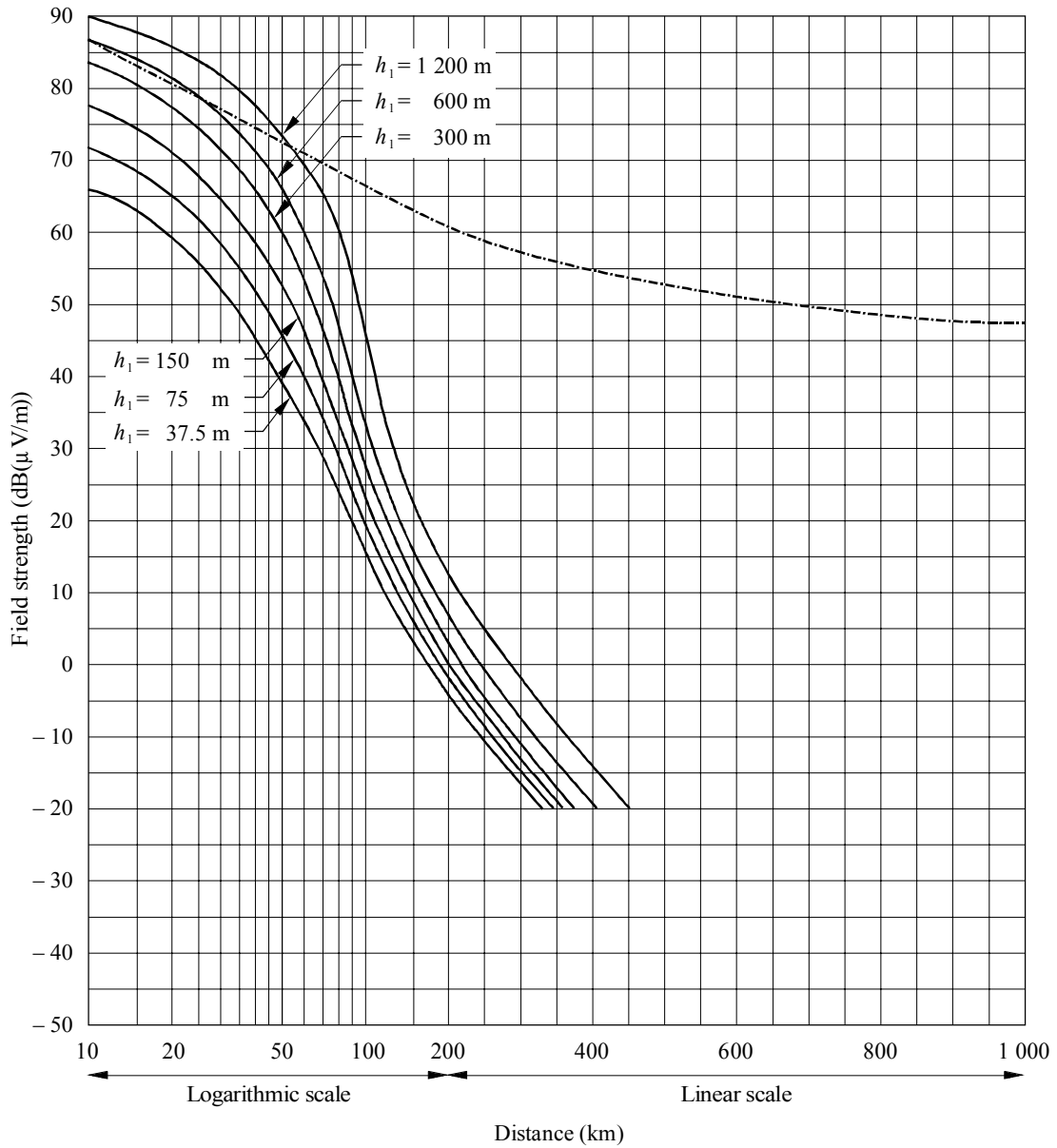
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D16

FIGURE 10

Field strength (dB(μV/m)) for 1 kW e.r.p.

Frequency: 450-1 000 MHz (Bands IV and V); land; 10% of the time;
50% of the locations; $h_2 = 10$ m; $\Delta h = 50$ m
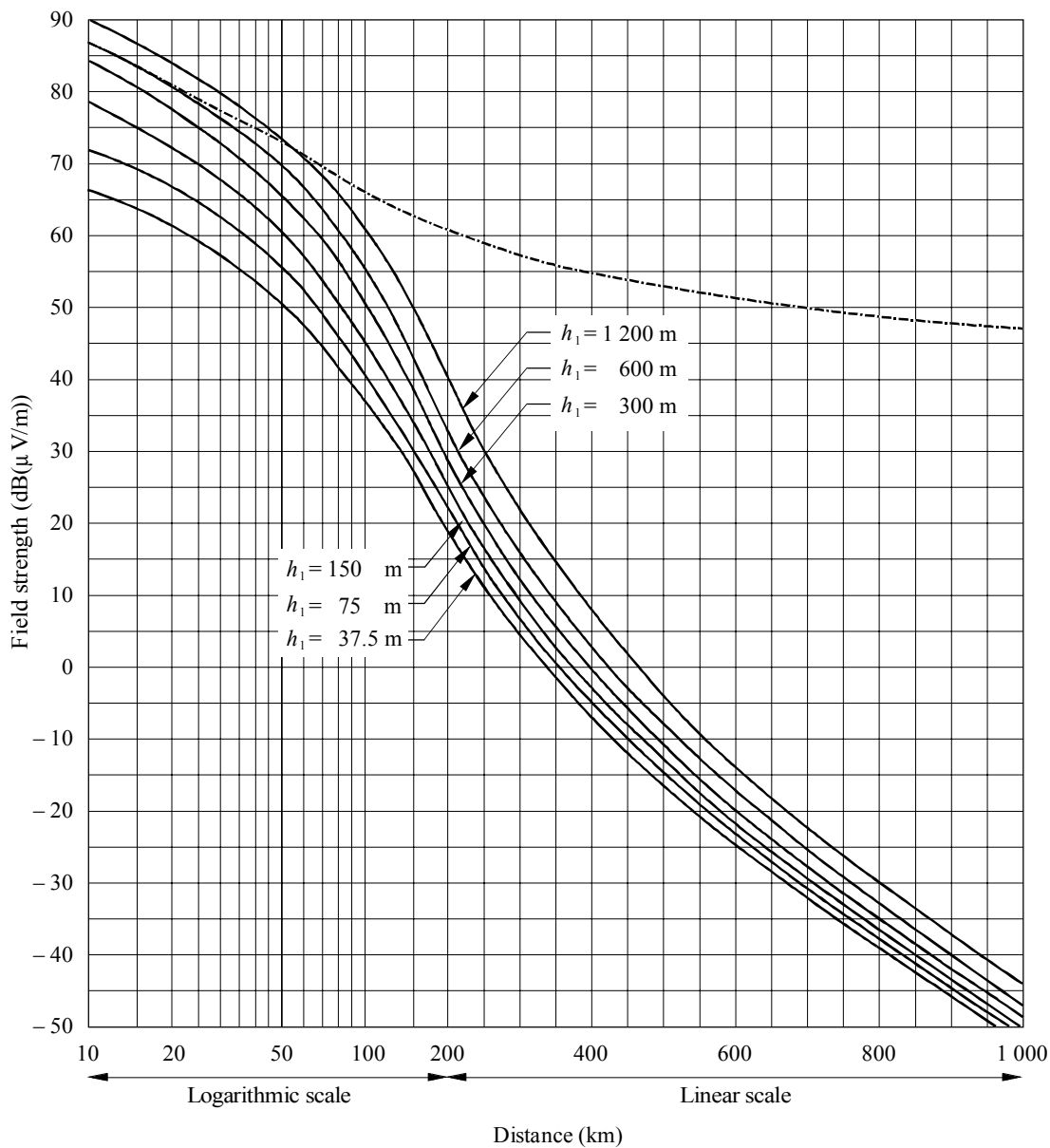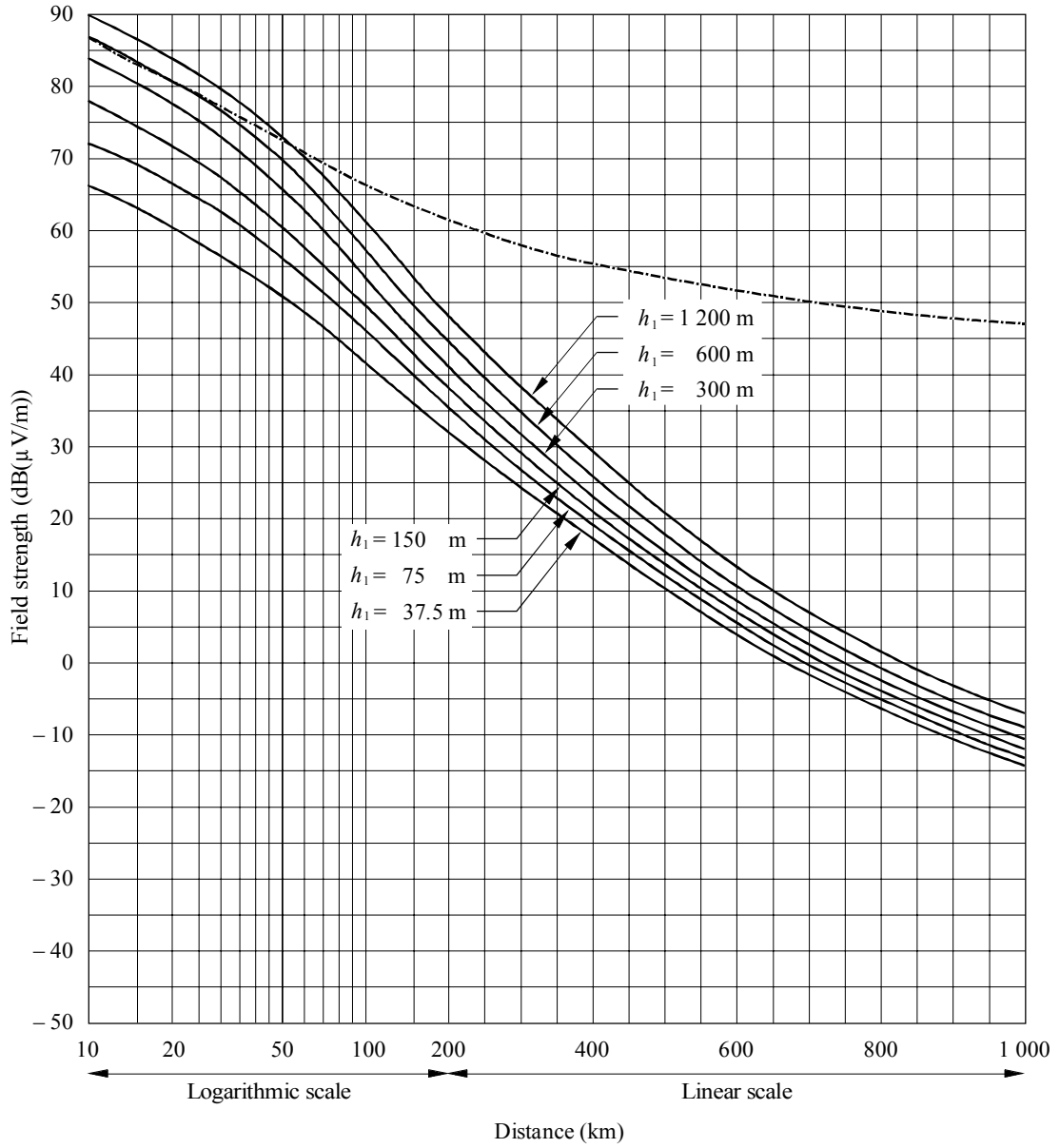
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D17

FIGURE 11

Field strength (dB(μV/m)) for 1 kW e.r.p.

Frequency: 450-1 000 MHz (Bands IV and V); land; 1% of the time;
50% of the locations; $h_2 = 10$ m; $\Delta h = 50$ m

— · — · — · — Free space

D18

FIGURE 12

**Ratio (dB) of the field strength for a given percentage of the receiving
locations to the field strength for 50% of the receiving locations**

Frequency: 450-1 000 MHz (Bands IV and V)

———————— Analogue systems

- - - - - - - - Digital systems
(>1.5 MHz bandwidth)

D19

FIGURE 13

Field strength (dB(μV/m)) for 1 kW e.r.p.

Frequency: 450-1 000 MHz (Bands IV and V); sea; 50% of the time;
50% of the locations; $h_2 = 10$ m

— · —· — Free space

D20

FIGURE 14a

Field strength (dB(μV/m)) for 1 kW e.r.p.

Frequency: 450-1 000 MHz (Bands IV and V); cold sea; 10% of the time;
50% of the locations; $h_2 = 10$ m
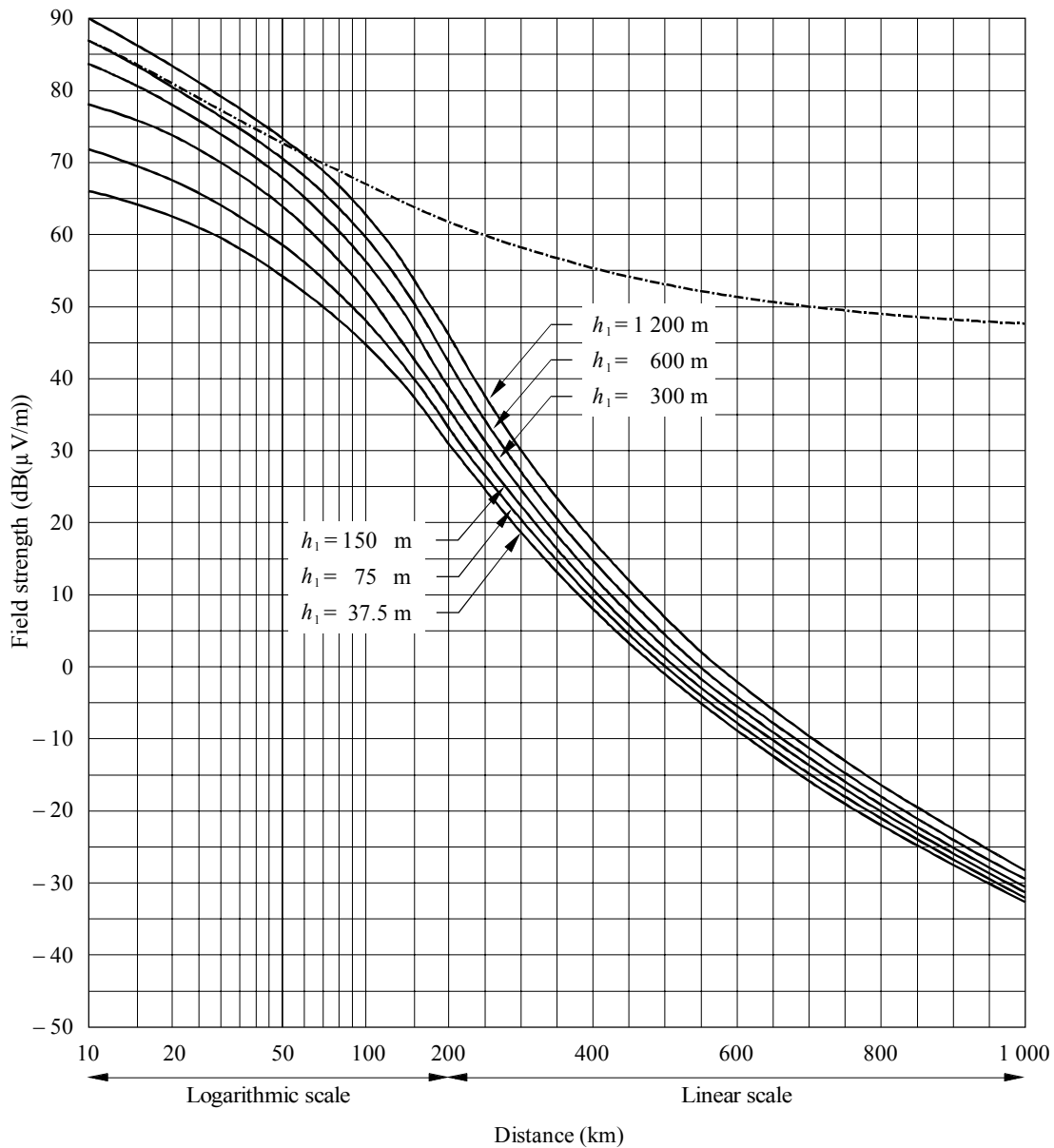
–·–·–·–·–·– Free space

D21

FIGURE 14b

Field strength (dB(μV/m)) for 1 kW e.r.p.

Frequency: 450-1 000 MHz (Bands IV and V); warm sea; 10% of the time;
50% of the locations; $h_2 = 10$ m

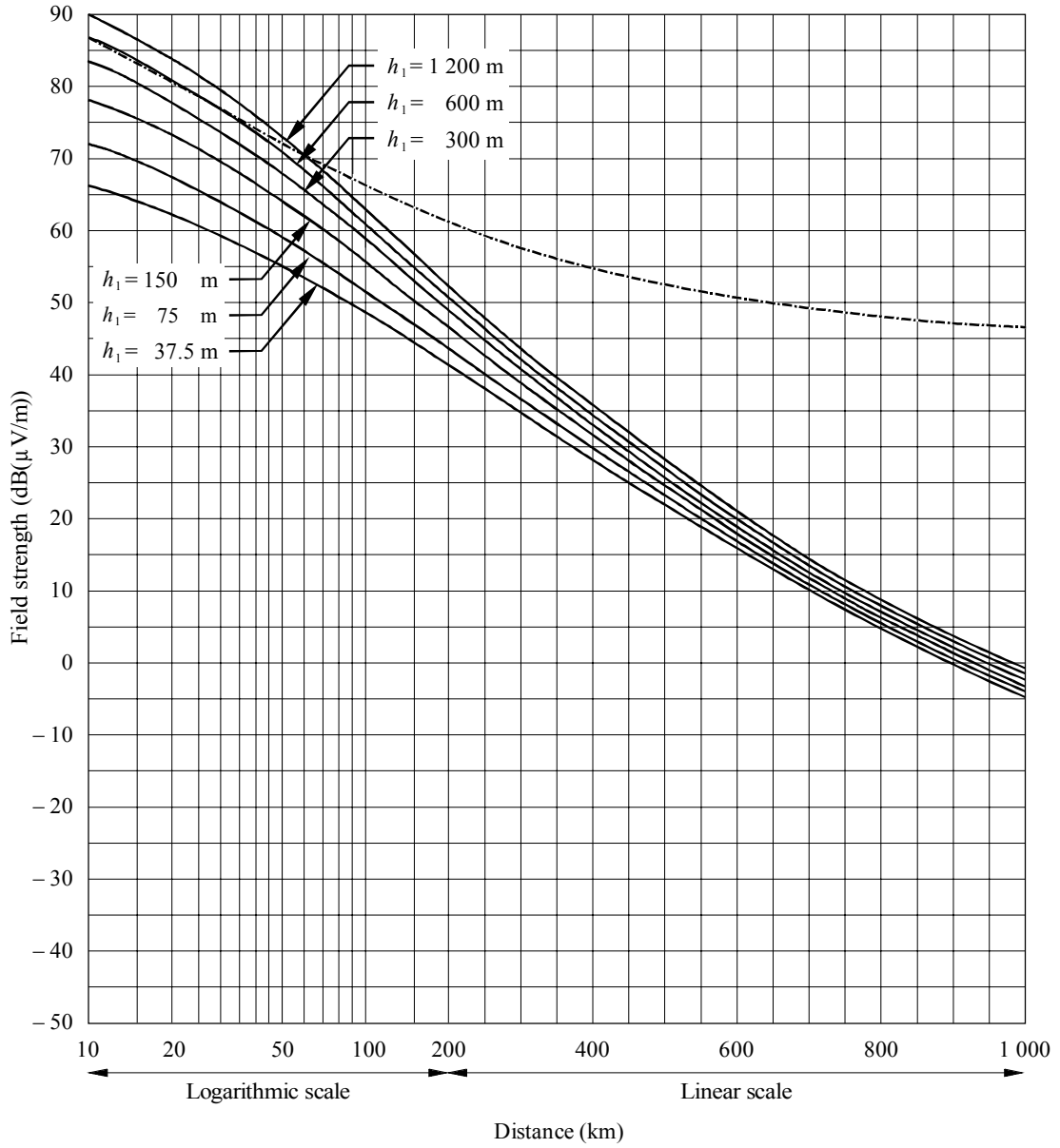— · · — · · — · · — Free space

D22

FIGURE 15a

Field strength (dB(μV/m)) for 1 kW e.r.p.

Frequency: 450-1 000 MHz (Bands IV and V); cold sea; 5% of the time;
50% of the locations; $h_2 = 10$ m

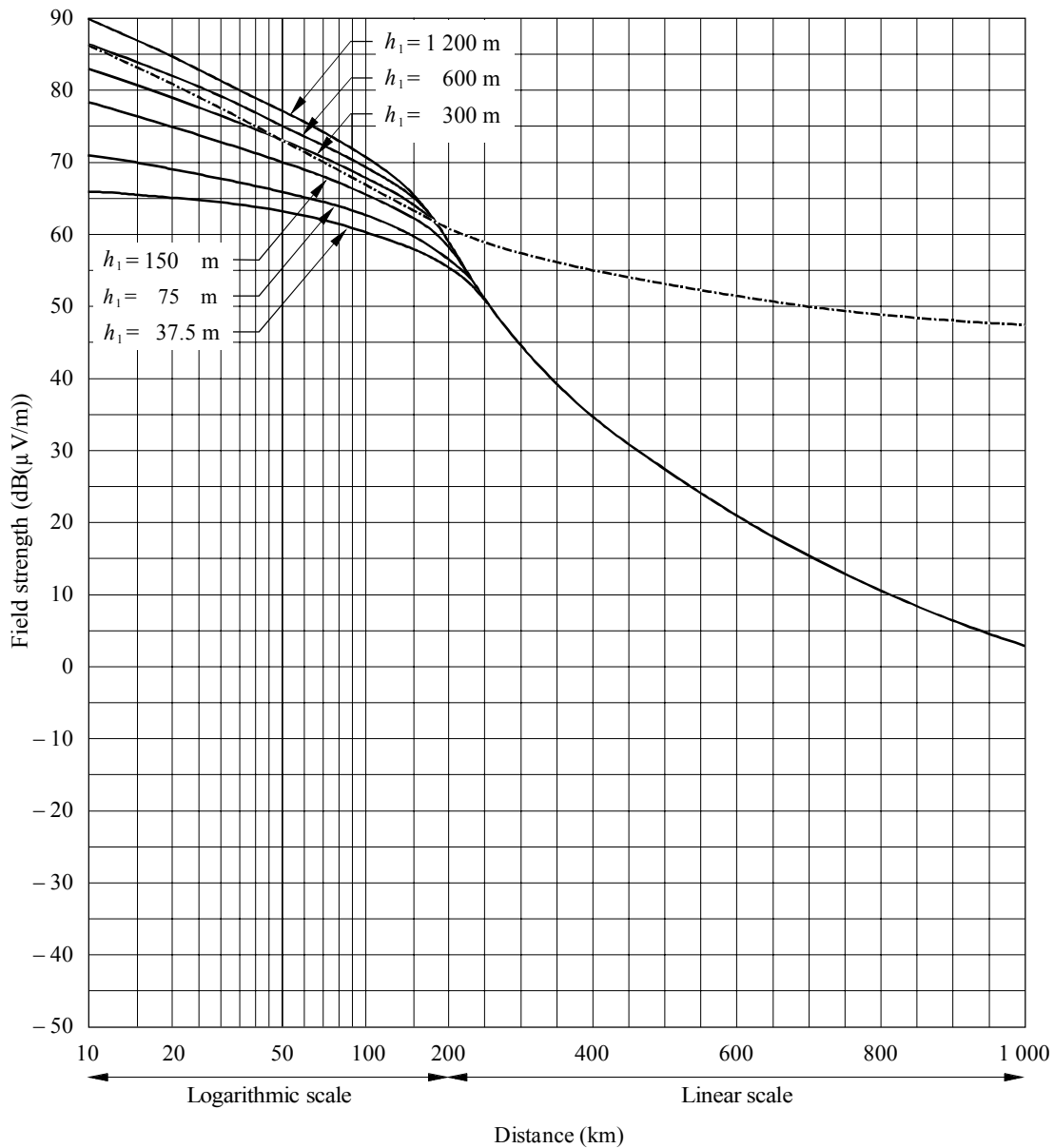— · · — · · — Free space

D23

FIGURE 15b

Field strength (dB(μV/m)) for 1 kW e.r.p.

Frequency: 450-1 000 MHz (Bands IV and V); warm sea; 5% of the time;
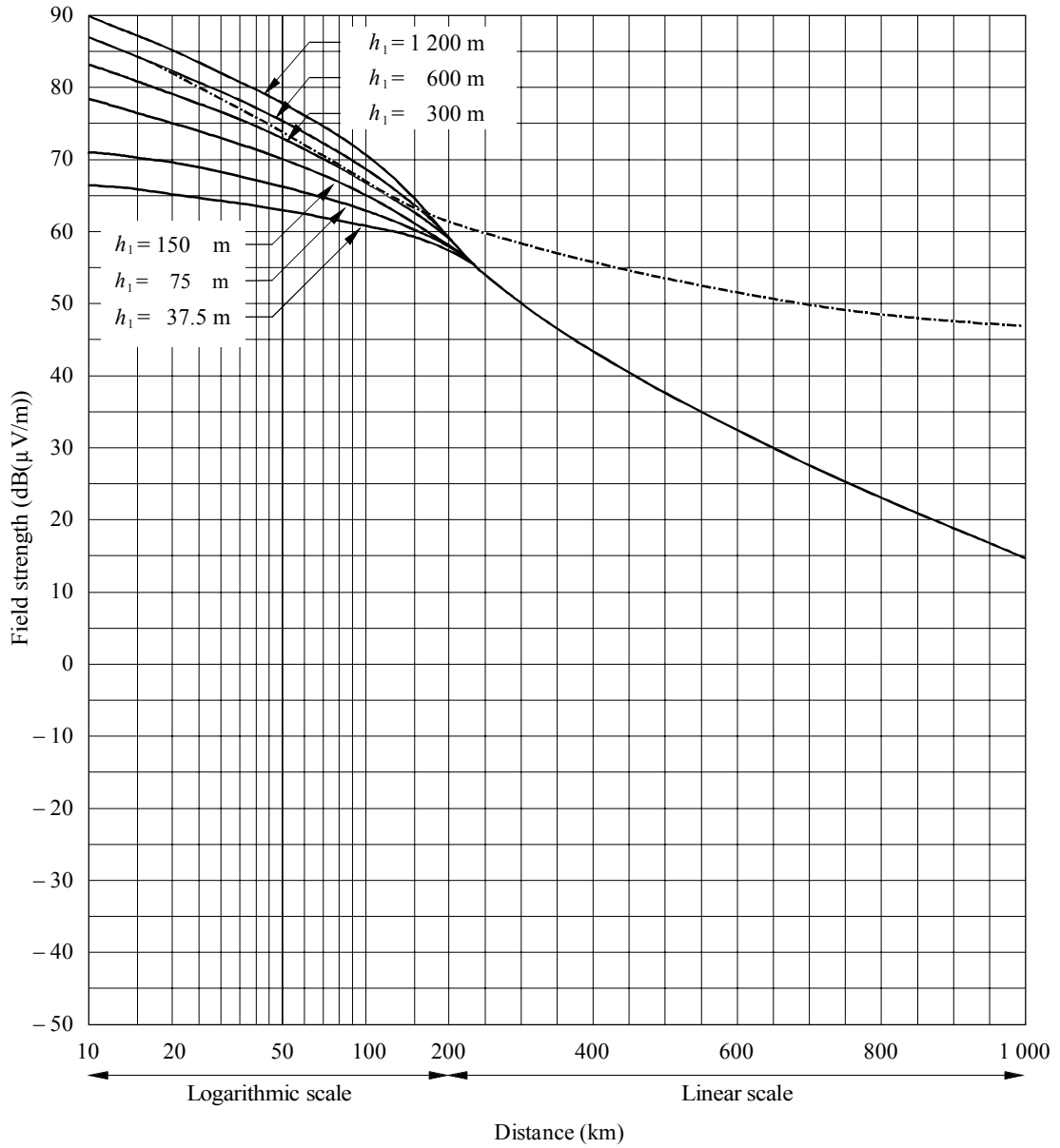50% of the locations; $h_2 = 10$ m

– – – – – – Free space

D24

FIGURE 16a

Field strength (dB(μV/m)) for 1 kW e.r.p.

Frequency: 450-1 000 MHz (Bands IV and V); cold sea; 1% of the time;
50% of the locations; $h_2 = 10$ m
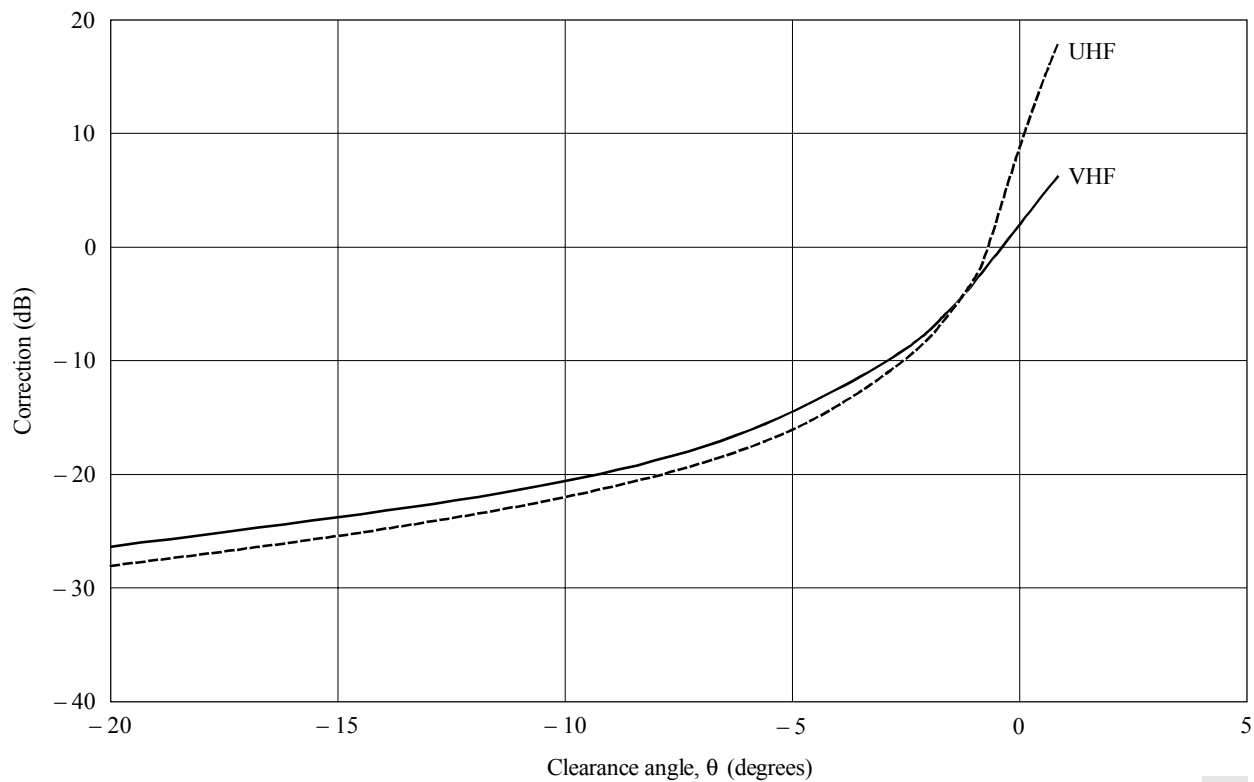
–·–·–·–·–·– Free space

D25

FIGURE 16b

Field strength (dB(µV/m)) for 1 kW e.r.p.

Frequency: 450-1 000 MHz (Bands IV and V); warm sea (excluding areas subject to
extreme super-refraction); 1% of the time; 50% of the locations; $h_2 = 10$ m
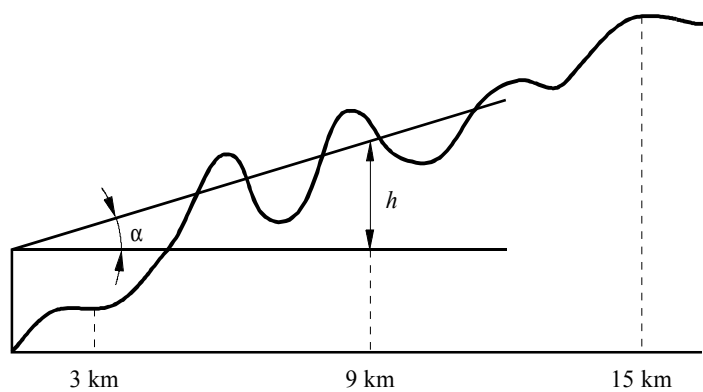
— · · — · · — Free space

D26

FIGURE 17

Terrain clearance angle correction factor

D27

FIGURE 18

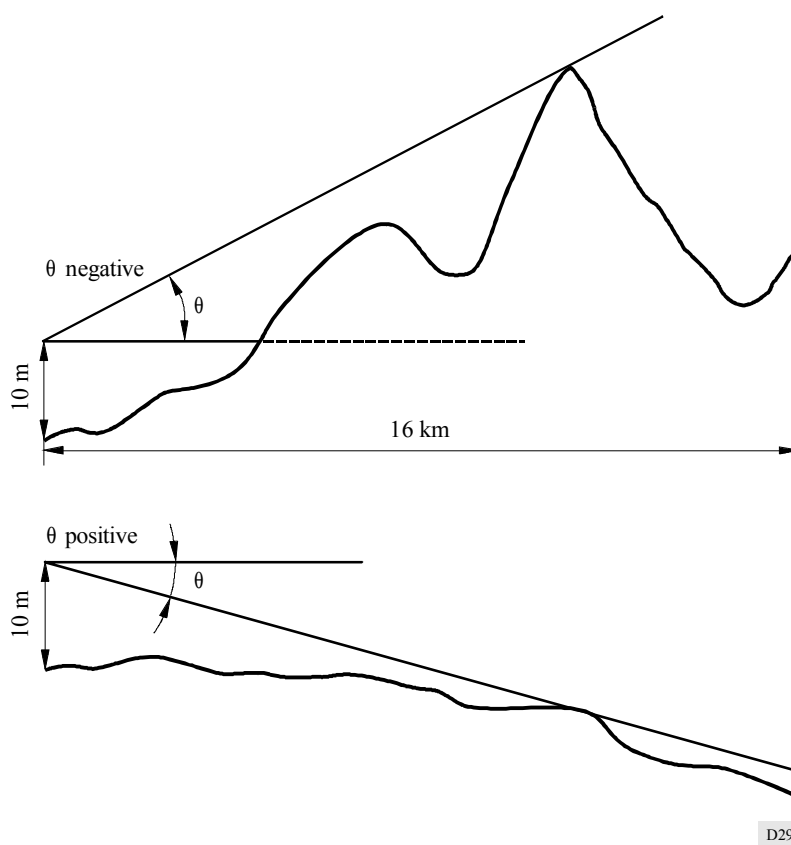**Effective clearance angle**

α: effective terrain clearance angle

h: effective antenna height (negative) as defined in § 1.3 of *recommends*

D28

FIGURE 19

Terrain clearance angle

θ negative

θ

10 m

16 km

θ positive

θ

10 m

D29

APPENDIX 1

TO ANNEX 1

Location variability in area-coverage prediction

Area-coverage prediction methods are intended to provide the statistics of reception conditions over a given area, rather than at any particular point. The interpretation of such statistics will depend on the size of the area considered.

When one terminal of a radio path is stationary, and the other terminal is moved, path loss will vary continuously with location, according to the totality of influences affecting it. It is convenient to classify these influences into three main categories:

–   *Multipath variations*

   Signal variations will occur over scales of the order of a wavelength due to phasor addition of multipath effects, e.g. reflections from the ground, buildings, etc.

–   *Local ground cover variations*

   Signal variations will occur due to obstruction by ground cover in the local vicinity, e.g. buildings, trees, etc., over scales of the order of the sizes of such objects. The scale of these variations will normally be significantly larger than multipath variations.

–   *Path variations*

   Signal variations will also occur due to changes in the geometry of the entire propagation path e.g. the presence of hills, etc. For all except very short paths, the scale of these variations will be significantly larger than those of local ground cover variations.

In area-coverage planning, location variability normally refers to the spatial statistics of local ground cover variations, with multipath variations averaged. This is a useful result over scales substantially larger than the ground cover variations, and over which path variations are insignificant. This may be an impracticable condition for an area over which path geometry is changing rapidly, such as sloping ground.

At VHF and UHF, location variability is typically quoted for an area of the order of a square of 100-200 m side, sometimes with the additional requirement that the area is flat. The important issue is whether path geometry significantly affects variations over the area concerned.

ANNEX 2

When paths occur over zones of different propagation characteristics, the following method is used which takes account of the different characteristics of the various parts of the path:

a)   At UHF, for percentages of time < 10%, the following procedure for calculating the field strength for paths crossing a land/sea boundary is used:

$$E_{m,t} = E_{l,t} + A\left(E_{s,t} - E_{l,t}\right) \tag{6}$$
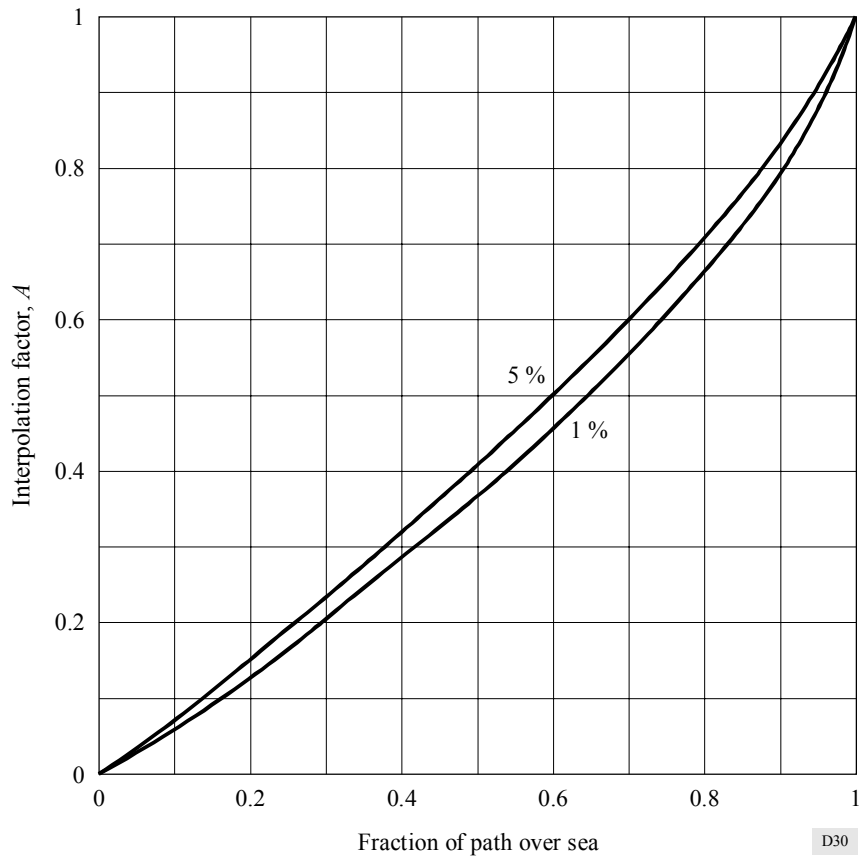
where:

   $E_{m,t}$:   field strength for mixed path for $t\%$ of the time

   $E_{l,t}$:   field strength for land path equal in length to the mixed path for $t\%$ of the time

   $E_{s,t}$:   field strength for sea path equal in length to the mixed path for $t\%$ of the time

   A :   interpolation factor as given in Fig. 20.

FIGURE 20

Interpolation for mixed land/sea paths

In cases where the path crosses more than two zones (of which at least one is sea), the linear procedure given in b) is applied, first, to those sections of the path crossing sea zones and, secondly, to those sections crossing land zones. The two resulting values of field strength are then combined using the non-linear procedure given above. For all other cases, the procedure given in b) is applied.

b)   At VHF and at UHF for percentages of time ≥ 10%, the following procedure is to be used:

$$\textbf{Error!} \tag{7}$$

where:

   $E_{m,t}$:   field strength for mixed path for t% of time

   $E_{i,t}$:   field strength for path in zone i equal in length to the mixed path for t% of time

   d_i :   length of path in zone i and

   d_T :   length of total path.