

[Final] Draft Report on

Propagation model and interference range calculation for Inductive Systems 10 kHz - 30 MHz

August, 11, 1998.

[Unofficial copy of ERC Report 069
for purpose of background information
to CILIR.exe interference range
calculation program]

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Source: PT SE24.

0. Executive summary.

Inductive short range radio systems are increasingly being introduced into the frequency bands below 30 MHz. These systems are normally allowed to operate on a non-interference basis to existing services, after appropriate compatibility studies have been made. The ERC could not identify a suitable propagation model for inductive systems which is necessary for the compatibility studies. There is no suitable model available in ITU-R, although there is some relevant information. With the assistance of manufacturers of inductive systems, the ERC has produced the following report on a propagation model and interference range calculation for use in compatibility studies concerning inductive systems in the frequency range 10 kHz - 30 MHz.

To assess the interference potential of an inductive system the field strength at a given distance is calculated, this may be compared to the protection requirements of a specific service, or to predicted noise levels, to determine the interference range.

The Biot-Savart law can be used to calculate the magnetic dipole moment, however this is only valid when calculating the field strength very close to the antenna within the near field range. For this study longer distances are considered and so Maxwells equations are used to determine the magnetic dipole moment from the expected field strength at 10 m. The magnetic dipole moment is the product of the total current in the inductive loop, multiplied by the surface area; from this figure an effective radiated power level can be calculated; once this is known ITU-R Recommendation P.368-7 can be used to determine the function of field strength with distance.

The interfering range is the distance at which field strength decays to either the specified protection level or, where this is not available, to the noise level. **Figure B1** contains a summary of ITU-R Recommendation P.372 for both atmospheric and manmade noise. The methodology to determine the interference range can be found in **Section 8**.

Section 8 contains a complete algorithm for the interference range calculation which can be implemented as a computer program. A sample program has been made to complement this report, a copy is available from the ERO.

1. Introduction.

The propagation model for inductive systems is split up in four parts:

1. The near field model.
2. The far field model.
3. The ITU-R groundwave propagation model.
4. The free space model.

The near field model starts from the real antenna structure. The magnetic field strength is calculated using the Biot-Savart law. It is used to calculate the (effective) magnetic dipole moment from the measured magnetic field strength at the specified measuring distance.

There is a need to use this model when the dimensions of the inductive loop is in the same order of that of the measuring range. When the dimensions of the loop are smaller (most often the case), a simplified formula can be used to calculate the magnetic dipole moment, or the far field model can be used.

As the near field model is in principle a magneto static model it cannot be used for cases wherein the measuring distance is equal or larger than the radian wavelength ($\lambda/2\pi$).

Only magnetic dipoles are considered, not the far field cancelling antennas as quadropole (e.g. figure eight) antennas. For purpose of estimating the far field radiation far field cancelling antennas can be considered as a magnetic dipole wherein the magnetic dipole moment is the netto result of the cancelling of separate magnetic dipoles in counterphase.

In the compatibility studies the radiation and field strength is of interest at large distances only, and its relation to the field strength measurements at the specified measurement ranges.

Studies have shown that for antenna dimensions up to 2 m, the specific quadropole effects can be ignored at measuring distances of 10 m or more. For larger antenna dimensions the measuring distance of 30 m may be useful.

The dipole moment is considered as the source of a radiated power P_{rad} from where, according the data from the recommendation ITU-R P.368-7, the field strength at 1 km or larger distances can be calculated. This data is accurate within 1 dB.

For distances smaller than 1 km an estimated 40 dB/decade or 20 dB/decade roll-off relative to the 1 km field strength value is applied, depending on frequency and type of ground.

For cases where victim receivers maybe elevated or airborne a free space propagation model has to be used. Here the asymptotic field strength decay of ITU-R P.368-7 is used starting from the same radiated power P_{rad} .

2. The near field model.

The near field model uses the actual antenna structure. It calculates the magnetic field-strength using the Biot-Savart law. This model is valid in the near field region, $r \ll \lambda/2\pi$. Figure 1 defines a rectangle loop antenna and figure 2 a circular type.

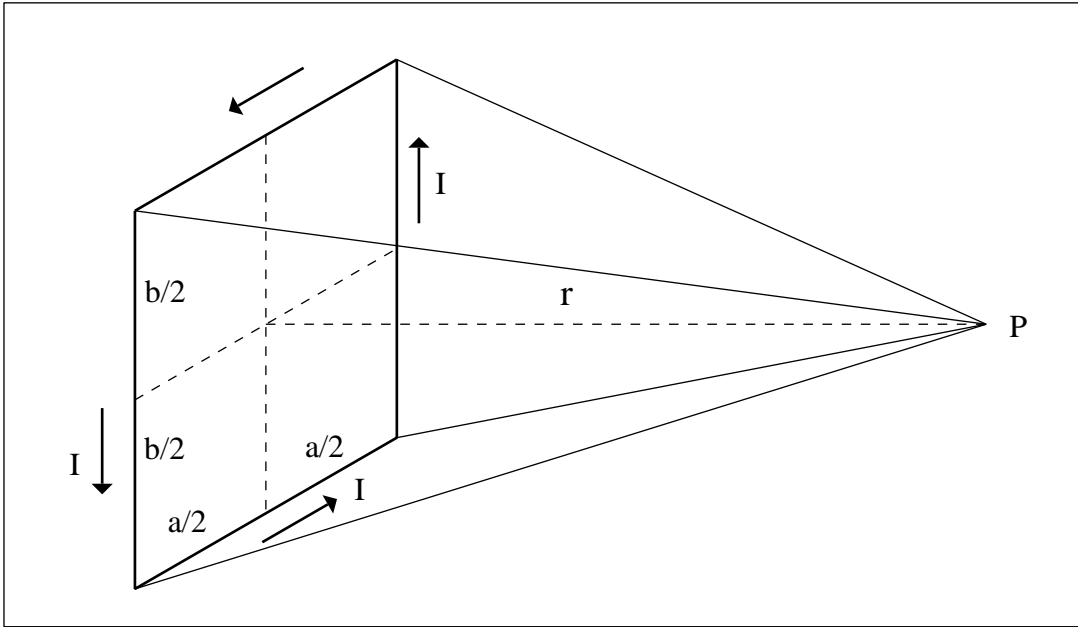


Figure 1. Field strength calculation at point P for a rectangle loop using the Biot-Savart law.

The magnetic field strength at a measuring point P on the axis of the loop is given by formula (1):

$$H = \frac{I \cdot a \cdot b}{4\pi\sqrt{r^2 + (a/2)^2 + (b/2)^2}} \cdot \left\{ \frac{1}{r^2 + (a/2)^2} + \frac{1}{r^2 + (b/2)^2} \right\} \quad (1)$$

In case P is far away from the loop this formula simplifies to formula (2):

$$H = \frac{I \cdot a \cdot b}{2\pi r^3} = \frac{I \cdot A}{2\pi r^3} \quad a, b \ll r \quad (2)$$

Wherein A = the surface of the loop.

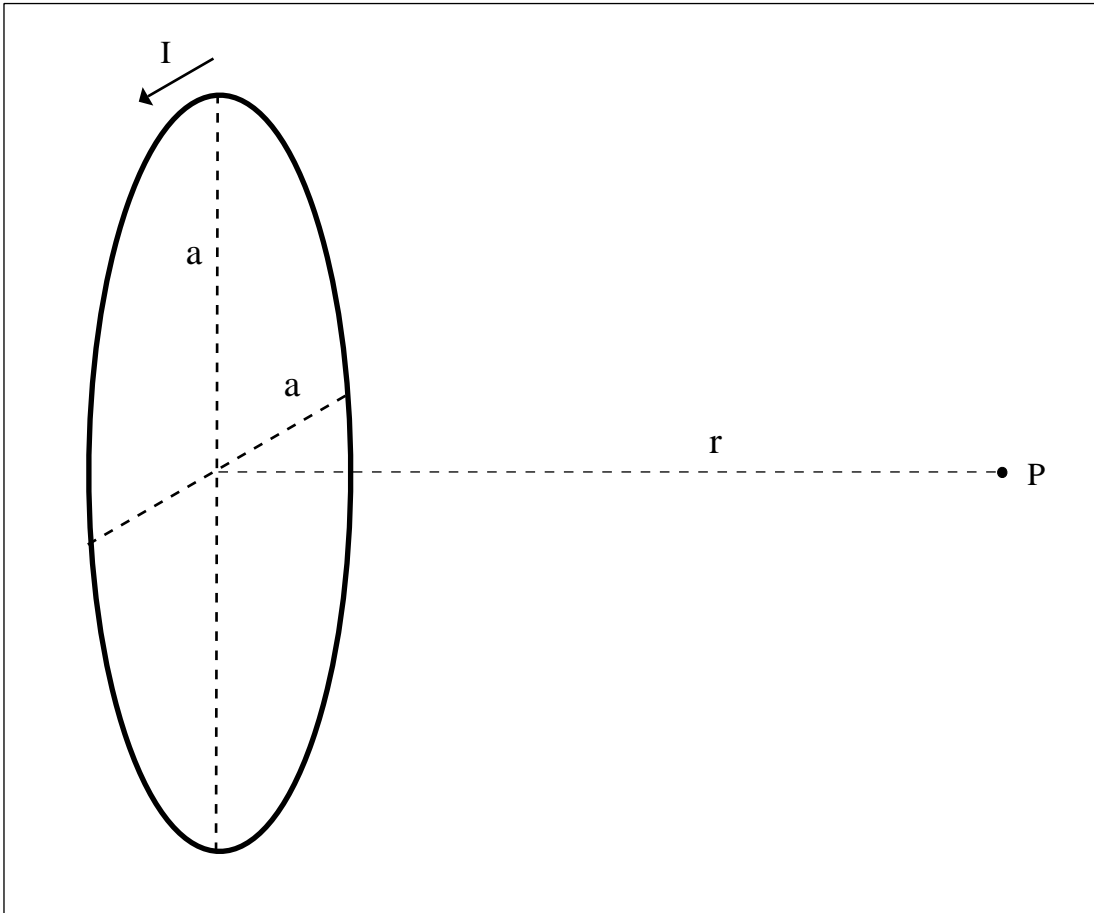


Figure 2. Field strength calculation at point P for a circular loop using the Biot-Savart law.

For the circular loop the field strength is given by formula (3):

$$H = \frac{I \cdot a^2}{2(r^2 + a^2)^{3/2}} \quad (3)$$

and this simplifies to (4) for longer distances:

$$H = \frac{I \cdot a^2}{2r^3} = \frac{I \cdot A}{2\pi \cdot r^3} \quad a \ll r \quad (4)$$

3. The far field model.

The far field model of radiation of loop antennas is based upon that of a magnetic dipole radiator. Figure 3 defines the magnetic dipole.

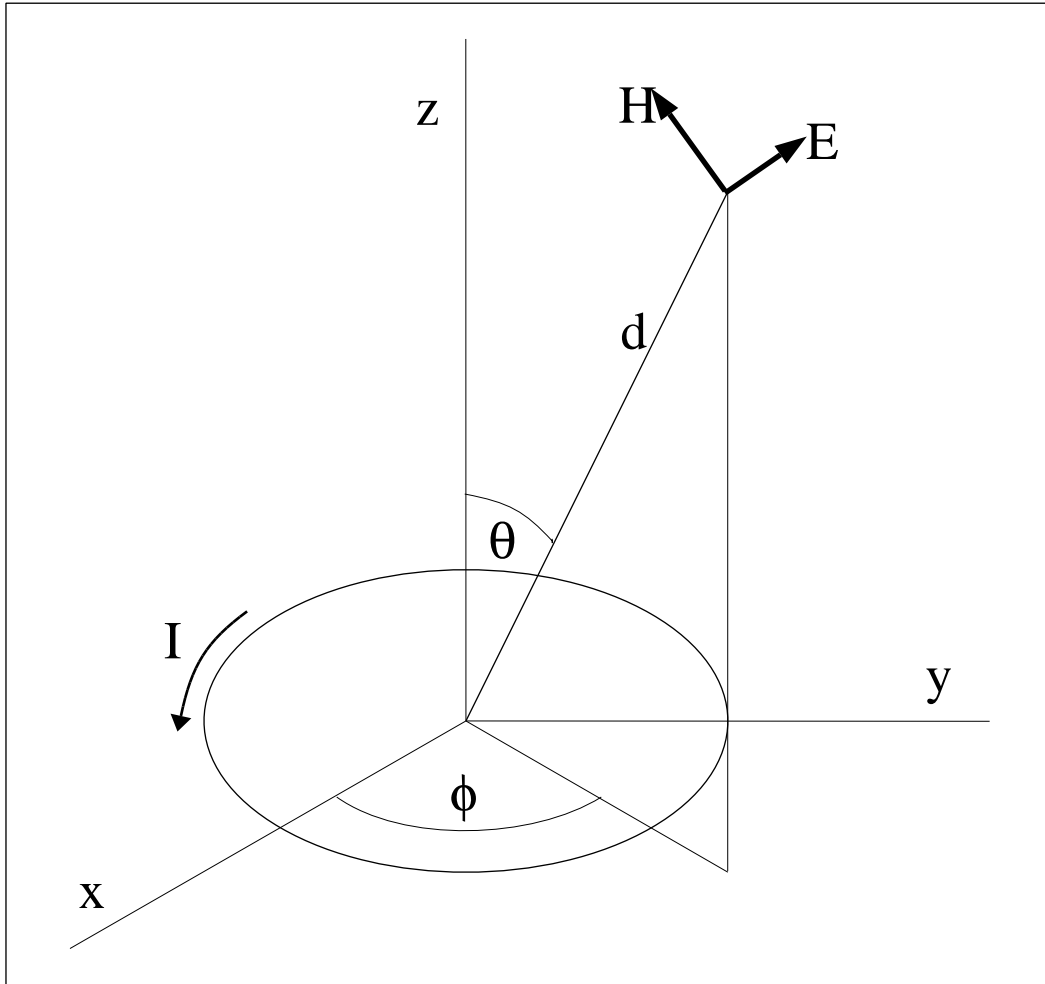


Figure 3. Definition of a magnetic dipole.

$$H = \frac{[m]}{4\pi\lambda^2 r} \left\{ 2\left(\frac{\lambda^2}{r^2} + j\frac{\lambda}{r}\right)\cos\theta \cdot \hat{r} + \left(-1 + \frac{\lambda^2}{r^2} + j\frac{\lambda}{r}\right)\sin\theta \cdot \hat{\theta} \right\} \quad (5)$$

H = magnetic field strength [A/m]

m = magnetic dipole moment [A.m²]

λ = radian wavelength = $\lambda/2\pi$

r = distance to antenna loop

θ = angle between the axis of the magnetic dipole and measuring position

.... \hat{r} : Field strength component in the direction of propagation.

.... $\hat{\theta}$: Field strength component perpendicular to the direction of propagation.

Two main direction are defined, see figure 4:

1. **Coaxial:** on the axis of the loop. $\theta = 0^\circ$.
2. **Coplanar:** in the plane of the loop. $\theta = 90^\circ$.

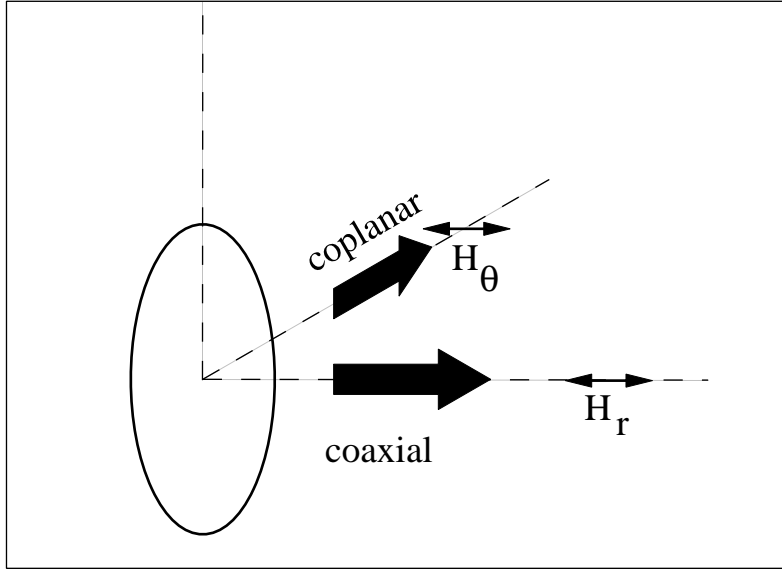


Figure 4. Definition of radiation directions.

In the coaxial case is $\theta = 0^\circ$:

$$H = \frac{[m]}{4\pi\lambda^2 r} 2 \left(\frac{\lambda^2}{r^2} + j \frac{\lambda}{r} \right) \hat{r} \quad (6)$$

$$|H| = \frac{m}{2\pi} \sqrt{\left(\frac{1}{r^3} \right)^2 + \left(\frac{1}{\lambda r^2} \right)^2} = \frac{m}{2\pi} \frac{\sqrt{\lambda^2 + r^2}}{\lambda r^3} \quad (7)$$

$$m = |H| \cdot \frac{2\pi \cdot \lambda r^3}{\sqrt{\lambda^2 + r^2}} \quad (8)$$

In the coplanar case is $\theta = 90^\circ$:

$$H = \frac{[m]}{4\pi\lambda^2 r} \left(-1 + \frac{\lambda^2}{r^2} + j \frac{\lambda}{r} \right) \hat{\theta} \quad (9)$$

$$|H| = \frac{m}{4\pi} \sqrt{\left(\frac{1}{r^3} - \frac{1}{\lambda^2 r} \right)^2 + \left(\frac{1}{\lambda r^2} \right)^2} = \frac{m}{4\pi} \frac{\sqrt{\lambda^4 - \lambda^2 r^2 + r^4}}{\lambda^2 r^3} \quad (10)$$

$$m = |H| \cdot 4\pi \cdot \frac{\lambda^2 r^3}{\sqrt{\lambda^4 - \lambda^2 r^2 + r^4}} \quad (11)$$

The formulas (8) and (11) give the ability to calculate the magnetic dipole moment from the field strength limit at the defined measuring distance.

Knowing the effective magnetic dipole the field strength at every position in space can be calculated according formula (5). However for purpose of the compatibility study the field strength in the

worse case direction needs to be calculated only. Thereby a different approach is needed for both the interfering source and victim receiver at ground level, and the interfering source and/or victim receiver elevated or airborne.

In the first case the propagation between interference source, the inductive loop, and the victim receiver is dominated by the ground propagation effects. The data in the recommendation ITU-R P.368-7, considering groundwave propagation, will be used for calculating interference distances.

In the second case the propagation between the inductive loop and the victim receiver is given by free space roll-off of the field strength, thus 20 dB/decade.

Determining the worse case direction of radiation a closer look is needed concerning the roll-off of the magnetic field strength in the immediate vicinity of a magnetic loop. Therefore the roll-off is plotted for the coaxial direction according formula (7) and for the coplanar direction according formula (10). The distance range is chosen in such a way that the distance according the radian wavelength ($\lambda/2\pi$) is in the middle of (logarithmic) plot.

For some example frequencies the usual measuring distances (3, 10 and 30 m) has been positioned in this plot, what results in the figures 4, 5 and 6 for respectively 2.0, 6.78 and 13.56 MHz.

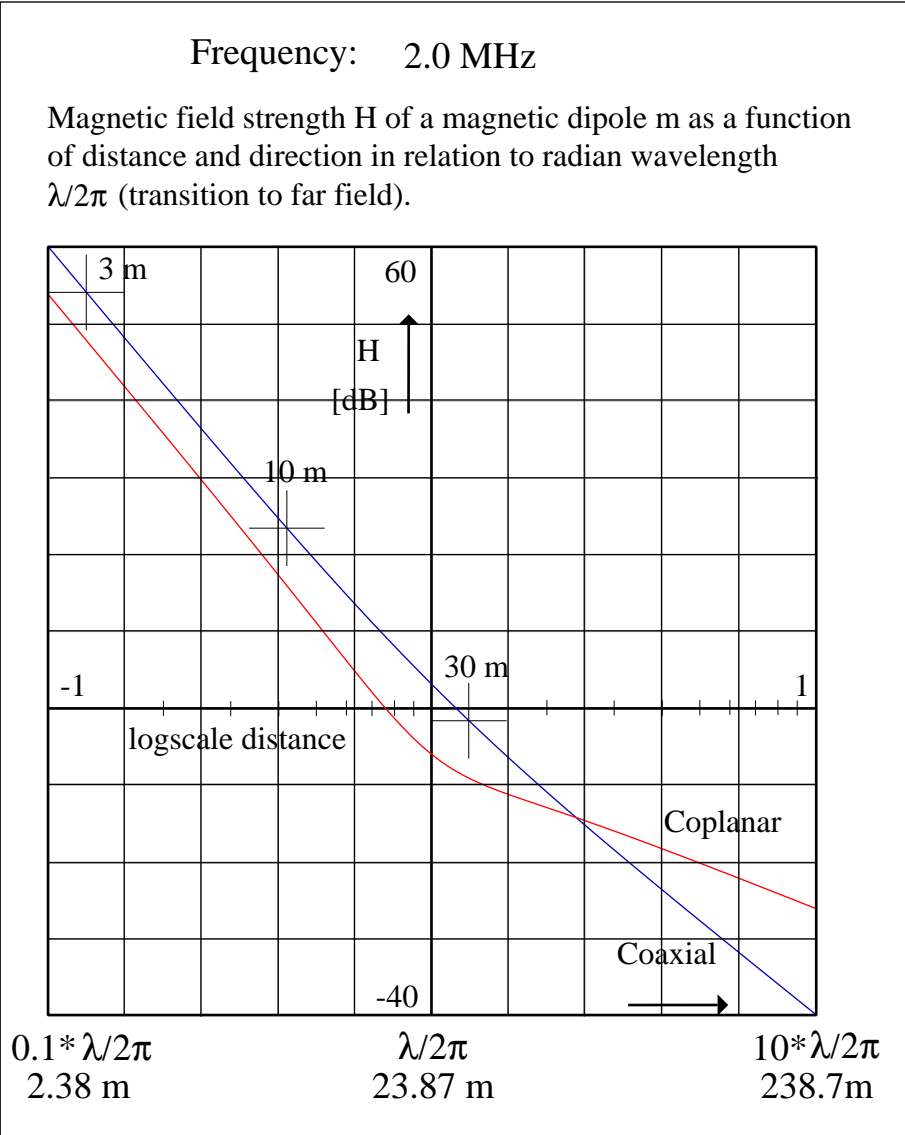


Figure 5. Magnetic field strength H of a magnetic dipole m as a function of distance and direction in relation to radian wavelength $\lambda/2\pi$ (transition to far field) for the frequency of 2.0 MHz.

Of practical importance is the cross-over point of the coaxial curve and the coplanar curve. This cross-over point is positioned at $2.354 \cdot \lambda / 2\pi$ m from the magnetic dipole. At shorter distances the strongest magnetic field strength will be found on the coaxial direction, so that for calculating the magnetic dipole moment from the field strength limit, formula (8) has to be used.

At longer distances than the cross-over point the strongest magnetic field strength will be found in the coplanar direction, so that for calculating the magnetic dipole moment from the field strength limit, formula (11) has to be used.

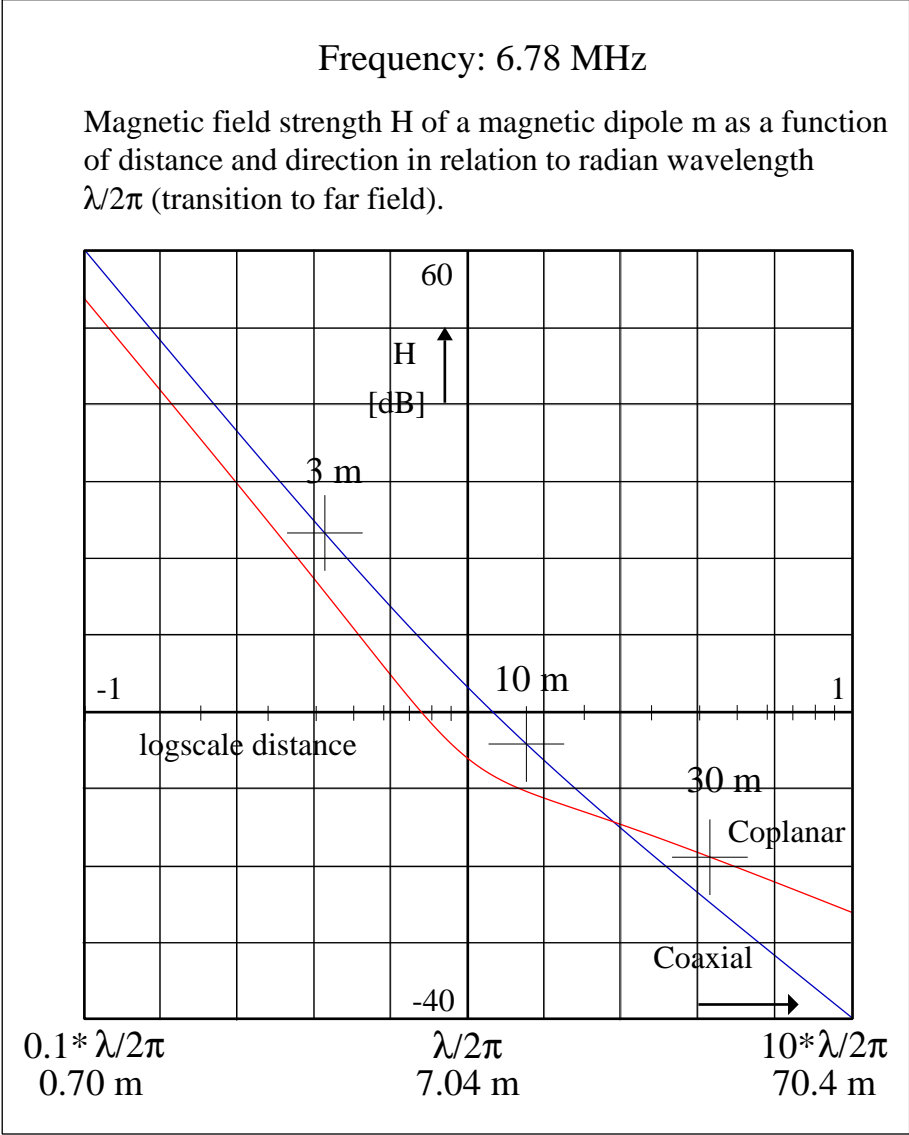


Figure 6. Magnetic field strength H of a magnetic dipole m as a function of distance and direction in relation to radian wavelength $\lambda/2\pi$ (transition to far field) for the frequency of 6.78 MHz.

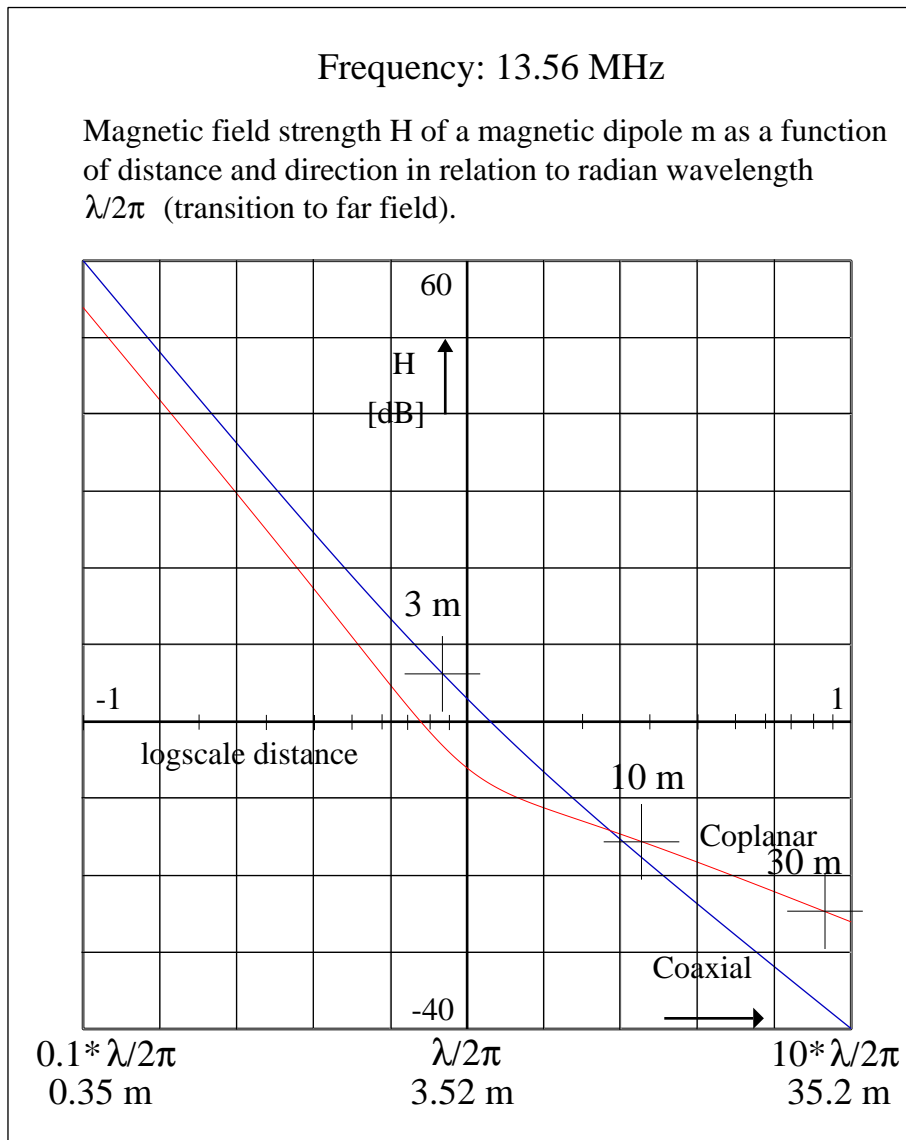


Figure 7. Magnetic field strength H of a magnetic dipole m as a function of distance and direction in relation to radian wavelength $\lambda/2\pi$ (transition to far field) for the frequency of 13.56 MHz.

Now the magnetic dipole is calculated, the radiated power can be calculated by the formulas (12) and (13).

$$P_{rad} = \frac{8\mu_0\pi^3 f^4}{3c^3} \cdot (m)^2 = 3.848 \cdot 10^{-30} \cdot f^4 \cdot (m)^2 \quad (12)$$

$$= \frac{\mu_0 c}{6\pi\lambda^4} \cdot (m)^2 = \frac{20}{\lambda^4} \cdot (m)^2 \quad (13)$$

The radiation pattern is in the shape of a figure of eight.

This level of radiated power links the far field model to the ITU-R groundwave propagation model.

4. The ITU-R groundwave propagation model.

In the far field model the loop antenna is assumed to be positioned in free space. In reality the antenna is mounted on a floor not far above ground level. This means that for propagation over larger distances the wave travels over ground. The recommendation ITU-R P.368-7 and the associated ITU-R computer program, GRWAVE, offers a model for vertically polarized groundwave propagation. The data is given in the format of sets of curves. A set of curves is related to a type of ground, each curve representing a frequency in the range 10 kHz to 30 MHz. The curves show the field strength as a function of the distance in the range 1 km to 10 000 km, assuming a radiated power of 1 kW from a short vertical monopole. ITU-R P. 368-7 indicates an accuracy of 1 dB, but the data is only given for distances of 1 km or more. For distances less than 1 km an estimate can be made by extrapolating the curves downwards from 1 km.

The propagation of a groundwave can be divided into three regions: the nearby region, the middle region, and the far region.

The nearby region.

The roll-off is 20 dB/decade. ITU-R P. 368-7 shows an asymptote here, which curve represents the roll-off for ideal conducting ground, and to which the curves approach for short distances. This asymptote has a roll-off of 20 dB/decade. The asymptotic value of the field strength at 1 km distance, $E_{asymptote,20}$, is 109.5 dB μ V/m.

Note that this asymptote is 3 dB greater than the corresponding free space value, since radiation is confined to the halfspace above the conducting ground.

The curve of the asymptote is described by formula (14), see the recommendations ITU-R P.341-3 and P.525-2:

$$E = 300 \frac{\sqrt{P}}{r} \quad (E \text{ in } mV/m, P \text{ in } kW, r \text{ in } km) \quad (14)$$

The middle region.

The roll-off is 40 dB/decade. The middle region is determined for the field strength at 1 km distance for frequencies of 2 MHz and higher for the most types of ground. For each type of ground a second asymptote can be drawn along the curve, with a roll-off of 40 dB/decade. This second asymptote will intersect the first one. At the distance of intersection the transition distance, $d_{transition}$, is defined, as can be seen in figure 8. The lower part of figure 8 shows the situation where the transition distance is below 1 km. This means that the value of the second asymptote at 1 km distance, $E_{asymptote,40}$, is below the value of the first asymptote at 1 km, so $E_{asymptote,40} < 109.5$ dB μ V/m.

The upper part shows the situation for $d_{transition} > 1$ km, so $E_{asymptote,40} > 109.5$ dB μ V/m. This value of $E_{asymptote,40}$ only has a meaning of the extrapolation of the asymptote.

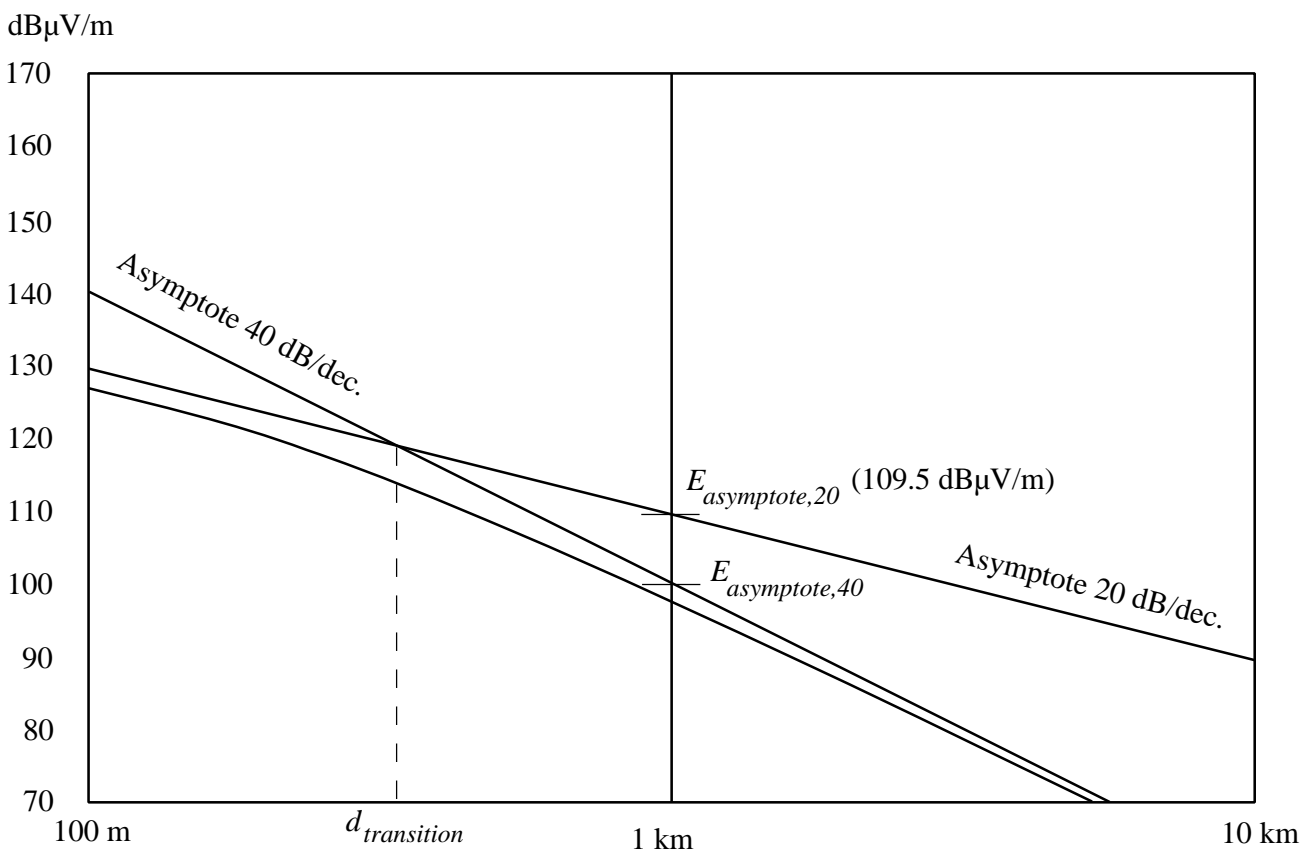
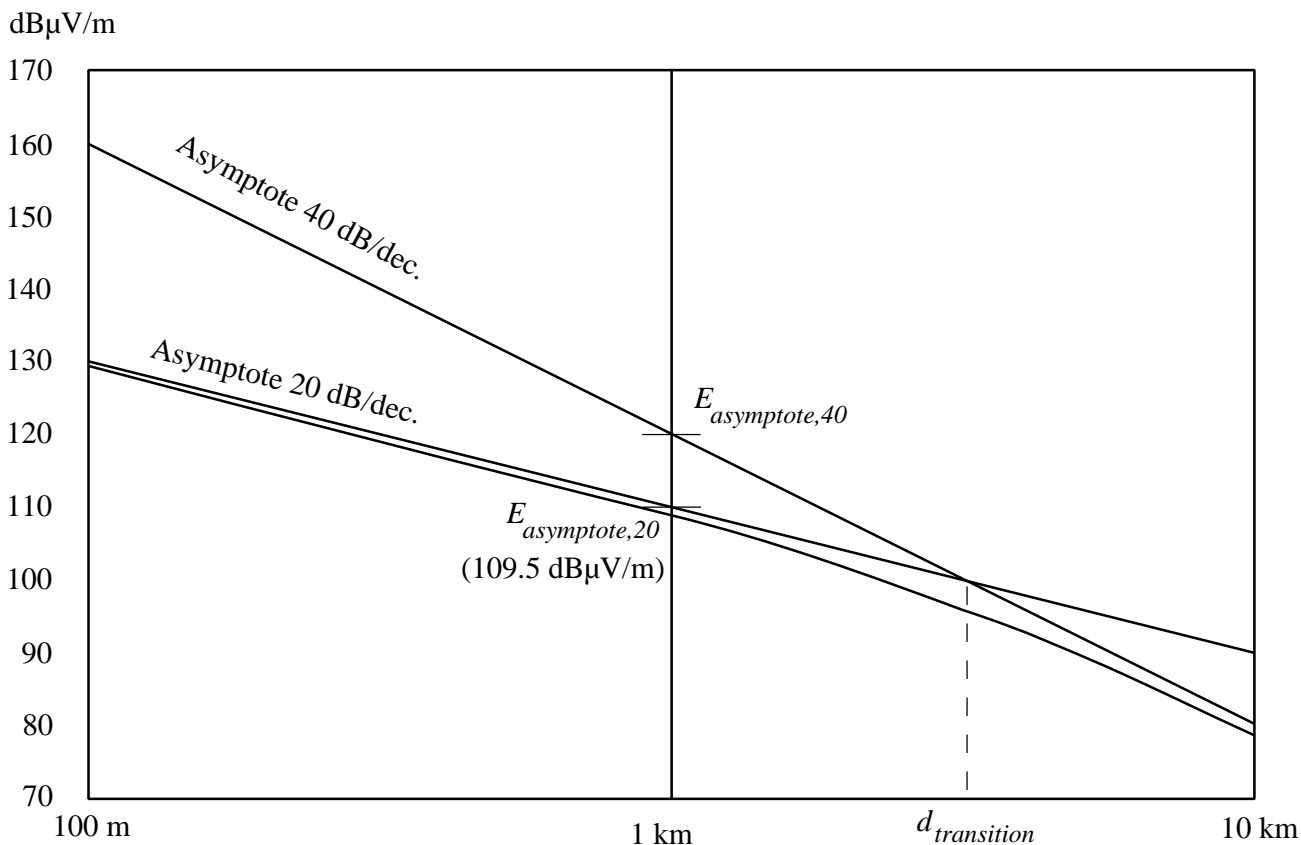


Figure 8. The upper diagram shows an example of the asymptotic curves when the transition distance lies beyond 1km; the lower diagram shows the situation when the transition distance lies within 1km.

The value of the second asymptote at 1 km distance, $E_{asymptote,40}$, is shown in table A1 and in figure A1 of annex A for frequencies between 10 kHz and 30 MHz, for the given types of ground. The transition point between the three regions depends completely on the frequency and on the conductivity and the permittivity of the ground.

The transition range, $d_{transition}$, can be calculated now from both asymptotic field strength values at 1 km distance, namely the field strength on the frequency under consideration at 1 km distance, according to the 40 dB/decade asymptote, $E_{asymptote,40}$, and the value of the field strength according to the 20 dB/decade asymptote at 1 km distance, $E_{asymptote,20}$ (= 109.5 dB μ V/m), both for a radiated power of 1 kW.

$$E_2 = E_{asymptote,40} - 40\log(d/1000) \quad (E_2 \text{ on } 2^{nd} \text{ asymptote}) \quad (15)$$

$$E_1 = E_{asymptote,20} - 20\log(d/1000) \quad (E_1 \text{ on } 1^{st} \text{ asymptote}) \quad (16)$$

$$E_2 = E_1 \quad \text{for } d = d_{transition} \quad (17)$$

$$E_{asymptote,40} - 40\log(d/1000) = E_{asymptote,20} - 20\log(d/1000) \quad (18)$$

$$d_{transition} = 1000 * 10^{-\frac{(E_{asymptote,20} - E_{asymptote,40})}{20}} \quad (\text{d in meter}) \quad (19)$$

The far region.

The roll-off increases to 150 dB/decade at distances greater than 100 - 3000 km.

With the low radiated powers of the SRD/inductive systems the distances of concern are much less than 100 km. This means that the far region is not of interest when considering SRD/inductive systems.

Note.

Carefully inspecting the curves for frequencies < 4 MHz reveals that the transition from the 40 dB/decade roll-off to the asymptotic 20 dB/decade roll-off is very gradual. This means that the actual value for the field strength at the transition point is a few dBs lower than what the asymptotic roll-off curves indicate. Measurements have shown that at a few hundred meter distance multi-path interference can occur between the groundwave and the free space wave, which can enhance the field strength several dBs locally. The netto result is that these asymptotic curves can be taken as a worse case scenario.

5. Free space propagation.

In case the victim receiver is not at groundlevel the free space propagation model has to be used. Still the source is assumed to be placed on the ground or only slightly elevated, so the fraction of free space radiation that radiates downwards will be reflected and will add to the power radiated upwards in the worse case situation. This means an antenna gain of 3 dB over the magnetic dipole free space radiation. As a consequence the free space radiation over ground can be described by formula (14), which gives the same outcome as the asymptote in ITU-R P.368-7.

6. Interference range.

To determine the interference distance, *the range outside which no harmful interference will occur*, a maximum field strength level has to be determined. This level depends on the minimum signal level that an affected radio service expects.

This minimum signal level depends on the kind of radio service. For example the broadcasting services guarantee minimum field strength levels at their target areas. Table 1 gives an overview of these field strength levels:

Minimum field strength level in the broadcasting service.		
Frequency band (MHz)	Minimum field strength E_{min} (dB μ V/m)	Required Signal/Noise Ratio SNR (dB)
0.1485 - 0.2835	77	30
0.5265 - 1.6065	60	30

Table 1. Example of minimum field strength levels as required for the broadcasting service.

For other radio services the receiver characteristics and the noise level at the receiving site determine the minimum signal level. The source of the noise can be of atmospheric, galactic or manmade nature.

Annex B presents a study into noise field strength levels, based on the ITU-R Recommendation P.372. Figure B1 of annex B shows the results of this study as noise field strength levels, depending on the frequency. The noise field strength levels are dependent on the receiver bandwidth. The shown curves correspond with a bandwidth of 2.7 kHz.

This bandwidth is the usual value for SSB telephony. For most telegraphy and data communication modes smaller bandwidths are used, while for shortwave broadcasting a maximum bandwidth of 9 kHz is appropriate.

The manmade noise field strength levels are given for four different environments: business, residential, rural and quiet rural, and, like the galactic noise level, are time and season independent.

Atmospheric noise is the result of natural electrical activity (thunderstorms) in the earth atmosphere. Propagated over long distances thousands of lightning discharges per minute results in a low level EM field with a nature of noise.

As well as the location of the electrical activity, as the propagation over the path from the location of the electrical activity to the receiver location, is strongly dependent on the season of the year and on the time of the day.

The atmospheric noise field strength levels given in figure B1 are derived as mean values for the European area. As there are large differences in the noise field strength levels between seasons and between time of day a statistical distribution is made. This results in three curves:

- the 20% curve: a chance of 20% that the actual noise level is below the given field strength level;
- the 50% curve: a chance of 50% that the actual noise level is below the given field strength level;
- the 80% curve: a chance of 80% that the actual noise level is below the given field strength level.

The nature of the radio service and the environment at the receiving site determine which curve should be used. The curve determines the reference noise field strength level which is used in the interference range calculation.

For example many radio services are well engineered. That means that the transmitting power, antenna characteristics, and coverage, are alligned with propagation characteristics, noise levels and operational conditions, so that a predictable and reliable service is obtained.

It is reasonable to assume that for these calculations the highest occurring noise field strength level is used, thus the relevant manmade level or the 80% atmospheric level.

Alternatively some services make use of the lowest noise field strength levels like the Radio Astronomy Service, the Space Research service and the Amateur (-Satellite) Service. In this case the noise field strength levels according the quiet rural environment manmade noise, the galactic noise and the 20% curve of the atmospheric noise, are relevant.

7. The bandwidth ratio.

The characteristics of the interfering inductive loop signal, especially the bandwidth, can be an important factor. The field strength level at the measuring distance is determined using a measuring receiver with quasi-peak weighting and a bandwidth of 9 kHz (200 Hz in the range 9 - 150 kHz). In a victim receiver, with a smaller bandwidth than that of the measuring receiver, less interfering signal power is received when the interfering signal has a bandwidth wider than the actual receiver bandwidth. Also the detector in the victim receiver can have a response which is depending on the characteristics of the interfering signal. These effects can be compensated for by adding the bandwidth ratio, BWR , to the reference noise field strength level.

In the generic case, or when the bandwidth of the interfering signal is not wider than the victim receiver bandwidth, or in case of an unmodulated carrier, $BWR = 0$ dB should be assumed.

In the case where the interfering signal frequency is swept over a bandwidth at least as large as the bandwidth of the measuring receiver, or otherwise the signal power is homogeneous spread over the bandwidth of the measuring receiver, such as the sidebands of the datalink in an ID system, the ratio of the bandwidth of the measuring receiver to the bandwidth of the victim receiver should be used as bandwidth ratio:

$$BWR = 10 \log (b_{measuring-rx}/b_{victim-rx}). \quad (20)$$

8. The interference range calculation.

The interference range can be calculated now. First the reference noise field strength, $E_{noise2.7}$, is determined from annex B. This noise level is corrected for the bandwidth of the victim receiver in kHz:

$$E_{noise} = E_{noise2.7} + 10 \log(b_{victim-rx}/2.7) \quad (21)$$

Secondly for broadband interference the bandwidth ratio, BWR , is determined. Adding these values give the maximum interference level, $E_{interference}$:

$$E_{interference} = E_{noise} + BWR \quad (22)$$

$E_{interference}$ is compared with the roll-off of the interfering signal.

In case for a service the minimum field strength, E_{min} , and required Signal/Noise Ratio, SNR , is known the maximum interference level is calculated as:

$$E_{interference} = E_{min} - SNR \quad (23)$$

A complete algorithm for calculating the interference distance is shown below in quasi programming language:

INTERFERENCE RANGE CALCULATION

INPUT The frequency, f , in MHz.
 The magnetic field strength limit, H_{limit} , in dB μ A/m.
 The measuring distance, d , in meter.
 The victim receiver at ground level (*groundwave*
 propagation)
 or airborne (*free space* propagation)?

IF *groundwave* is true:

INPUT $E_{asymptote,40}$ according annex A in dB μ V/m.

CALCULATE

$$d_{transition} = 1000 * 10^{-\frac{(E_{asymptote,20} - E_{asymptote,40})}{20}} \quad (\text{d in meter}) \quad (19)$$

INPUT The noise field strength in 2.7 kHz, $E_{noise2.7}$, according Annex B, in dB μ V/m.

The bandwidth of the victim receiver, BW , in kHz.

The bandwidth ratio, BWR , in dB.

OR:

$E_{interference}$ directly from data of the radio service.

CALCULATE The radian wavelength $\lambda/2\pi = c/2\pi f$.

IF $d < \lambda/2\pi * 2.354$

$$m = |H| \cdot \frac{2\pi \cdot \lambda d^3}{\sqrt{\lambda^2 + d^2}} \quad (8)$$

The field strength at the measuring position is maximal in the coaxial direction.

IF $d \geq \lambda/2\pi * 2.354$

$$m = |H| \cdot 4\pi \cdot \frac{\lambda^2 d^3}{\sqrt{\lambda^4 - \lambda^2 d^2 + d^4}} \quad (11)$$

The field strength at the measuring position is maximal in the coplanar direction.

OUTPUT Magnetic dipole moment, m , in Am².

CALCULATE

$$P_{rad} = \frac{20}{\lambda^4} \cdot (m)^2 \quad (13)$$

$$r_{interference} = \sqrt[3]{\frac{m}{2\pi H_{interference}}} \quad (27)$$

(from formula (7))

OUTPUT The interference range is inside the near field range.
The groundwave interference range is $r_{interference}$ m.

IF free space is TRUE

$$r_{interference} = 10^{\frac{120 + 49.5 + P_{rad_dB} - E_{interference}}{20}} \quad (25)$$

(from formula (14))

IF $r_{interference} > \lambda/2\pi * 2.354$

OUTPUT The interference range is limited to the 20 dB/dec. roll-off range.

The free space interference range is $r_{interference}$ m.

ELSE

$$r_{interference} = \sqrt{\frac{m}{H_{interference} \lambda 2\pi}} \quad (26)$$

(from formula (7))

IF $r_{interference} > \lambda/2\pi$

OUTPUT The interference range is close to the near field range.

The free space interference range is $r_{interference}$ m.

ELSE

$$r_{interference} = \sqrt[3]{\frac{m}{2\pi H_{interference}}} \quad (27)$$

(from formula (7))

OUTPUT The interference range is inside the near field range.

The free space interference range is $r_{interference}$ m.

9. Example of a roll-off curve for an inductive loop system.

Figure 9 gives an example of the roll-off of an inductive loop system. In this example the radian wavelength $\lambda/2\pi$ equals 10 m, and the field strength at the measuring distance of 10 m is 9 dB μ A/m. For the type of ground "Land" is assumed with $\sigma = 3$ mS/m and $\epsilon = 22$. Figure A1 in annex A gives for $E_{asymptote,40}$ 97 dB μ V/m. Combined with an calculated radiated power $P_{rad} = -95$ dBkW the field strength at 1 km distance will be 2 dB μ V/m in the case of groundwave propagation. In the free space situation the field strength at 1 km is obtained by adding $P_{rad} = -95$ dBkW to $E_{asymptote,20} = 109.5$ dB μ V/m: 14.5 dB μ V/m.

From both field strength values at 1 km the 20 dB/dec. and the 40 dB/dec. curves are drawn.

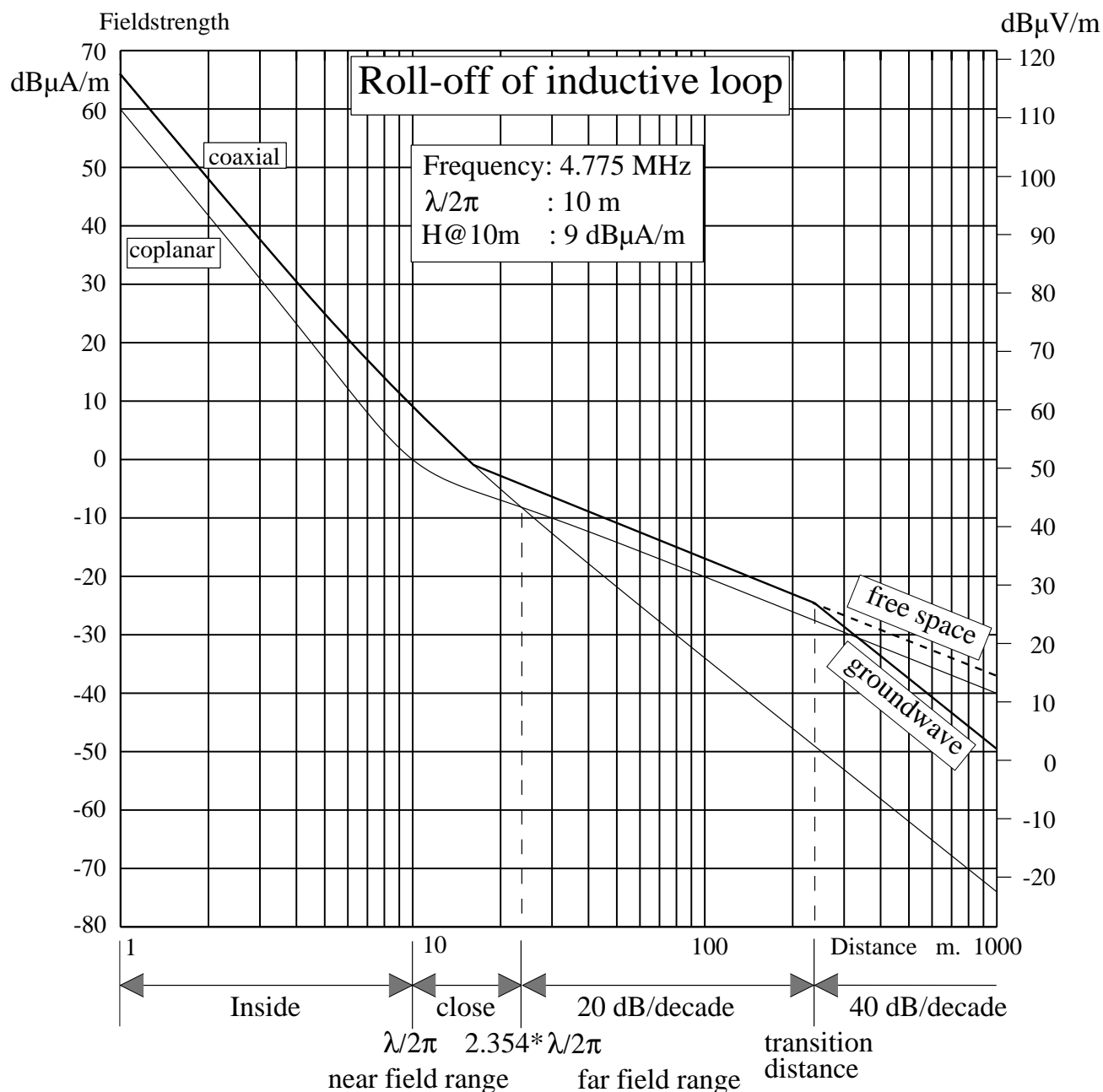


Figure 9. Roll-off of an inductive loop.

Annex A.

Data according to ITU-R P.368-7.

Table of fieldstrength of the 40 dB/dec. roll-off asymptote at the distance of 1 km by an effective radiated power of 1 kW (symbolic value for long path calculation), derived from ITU-R P.368-7. (dB μ V/m): $E_{\text{asymptote},40}$.												
Ground type:		1	2	3	4	5	6	7	8	9	10	11
σ		1	5	3e-3	30e-3	10e-3	3e-3	1e-3	3e-4	1e-4	30e-6	10e-6
ϵ		80	70	80	40	30	22	15	7	3	3	3
10	kHz	166	166	165	167	165	165	165	164	163	159	151
15		164	165	164	165	163	164	164	163	160	154	144
20		163	164	163	164	163	163	163	162	157	149	139
30		162	163	162	163	162	163	161	158	152	142	132
40		162	162	161	162	161	162	160	155	148	137	128
50		161	161	159	162	161	161	158	152	144	133	124
75		160	160	157	161	159	158	154	146	137	126	119
100		159	159	155	160	158	156	150	142	132	121	116
150		158	158	151	158	156	153	144	134	124	115	112
200		158	158	147	157	154	148	140	129	119	111	109
300		157	157	141	155	150	142	132	122	112	107	106
400		156	156	136	153	147	135	127	117	107	104	103
500		156	155	132	150	143	134	123	113	103	102	102
750		154	154	126	146	137	127	117	107	98	98	98
1.0	MHz	152	153	122	142	132	120	112	103	96	96	96
1.5		151	153	118	135	124	114	107	98	92	92	92
2.0		150	152	115	129	119	109	103	95	89	89	89
3.0		147	151	111	123	112	103	98	93	86	86	86
4.0		144	149	108	117	107	99	95	90	83	84	83
5.0		142	148	107	113	103	97	93	87	81	82	82
7.5		136	146	103	105	97	93	89	84	78	78	78
10		132	143	101	100	94	90	87	81	76	76	76
15		126	138	97	95	89	87	83	77	72	72	72
20		120	134	95	91	87	84	81	75	70	70	70
30		113	127	91	87	83	80	77	72	66	66	66

Table A1. Table of the asymptotic value of field strength of 1 kW transmitter at 1 km distance $E_{\text{asymptote},40}$.

List of ground types according ITU-R PN.368-7:

1. Sea water, low salinity. $\sigma = 1 \text{ S/m}$, $\epsilon = 80$.
2. Sea water, average salinity. $\sigma = 5 \text{ S/m}$, $\epsilon = 70$.
3. Fresh water. $\sigma = 3 \text{ mS/m}$, $\epsilon = 80$.
4. Land (very wet). $\sigma = 30 \text{ mS/m}$, $\epsilon = 40$.
5. Wet ground. $\sigma = 10 \text{ mS/m}$, $\epsilon = 30$.
6. Land. $\sigma = 3 \text{ mS/m}$, $\epsilon = 22$.
7. Medium dry ground. $\sigma = 1 \text{ mS/m}$, $\epsilon = 15$.
8. Dry ground. $\sigma = 0.3 \text{ mS/m}$, $\epsilon = 7$.
9. Very dry ground. $\sigma = 0.1 \text{ mS/m}$, $\epsilon = 3$.
10. Fresh water ice, -1 °C. $\sigma = 30 \text{ }\mu\text{S/m}$, $\epsilon = 3$.
11. Fresh water ice, -10 °C. $\sigma = 10 \text{ }\mu\text{S/m}$, $\epsilon = 3$.

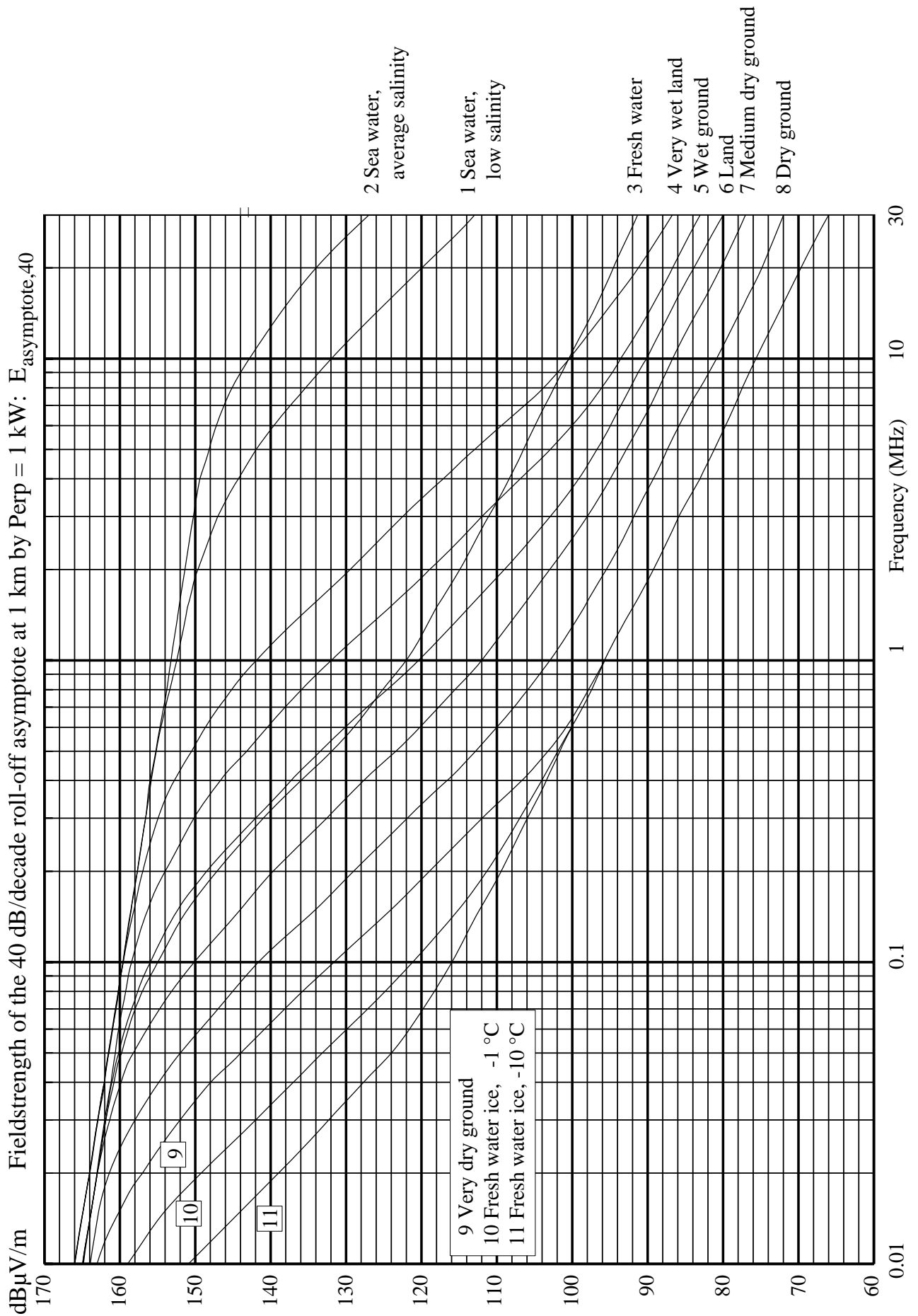


Figure A1. Field strength of the 40 dB/decade roll-off asymptote at 1 km distance from a 1 kW transmitter.

Table of 20 to 40 dB/decade roll-off transition distance, according ITU-R P.368-7 (km)												
Figure:		1	2	3	4	5	6	7	8	9	10	11
σ	S/m	1	5	3e-3	30e-3	10e-3	3e-3	1e-3	3e-4	1e-4	30e-6	10e-6
ϵ		80	70	80	40	30	22	15	7	3	3	3
Frequency												
10	kHz	650	580	600	640	630	600	600	560	510	300	120
15		550	550	525	570	570	550	540	470	370	160	53
20		500	500	490	530	520	490	480	400	260	100	30
30		460	480	420	480	460	440	400	280	140	44	13
40		440	440	380	440	410	390	320	190	90	24	8
50		400	380	330	410	380	340	270	140	55	15	5.5
75		350	325	260	360	330	270	170	70	24	6.5	3
100		310	290	190	320	290	220	110	40	14	3.6	2.2
150		290	270	120	280	230	140	55	17	5.5	1.9	1.4
200		260	260	75	240	175	90	32	9	3.1	1.2	1.0
300		230	230	36	190	110	44	14	4	1.4	0.79	0.67
400		220	210	21	150	75	24	8	2.3	0.79	0.53	0.47
500		200	190	14	110	50	16	5	1.4	0.50	0.42	0.40
750		170	170	7	65	22.5	7	2.2	0.75	0.28	0.27	0.27
1	MHz	140	150	4.8	40	13	3.3	1.3	0.47	0.21	0.21	0.20
1.5		125	140	2.7	18	6	1.6	0.71	0.27	0.13	0.14	0.13
2		110	130	1.9	10	3	1.0	0.45	0.20	0.094	0.094	0.094
3		80	115	1.25	4.6	1.3	0.50	0.27	0.13	0.067	0.067	0.067
4		55	95	0.89	2.5	0.75	0.30	0.19	0.089	0.050	0.050	0.050
5		44	85	0.75	1.5	0.45	0.24	0.15	0.075	0.038	0.040	0.042
7.5		22.5	65	0.50	0.63	0.24	0.14	0.094	0.050	0.027	0.027	0.027
10		13	48	0.38	0.32	0.17	0.11	0.071	0.038	0.021	0.021	0.021
15		6.5	28	0.25	0.18	0.10	0.067	0.047	0.025	0.013	0.013	0.013
20		3.4	17	0.19	0.12	0.071	0.053	0.035	0.019	0.011	0.011	0.011
30		1.7	7.5	0.13	0.07	0.047	0.035	0.024	0.013	0.007	0.007	0.007

Table A2. Table of 20 to 40 dB/decade roll-off transition distance.

Distance for the transition from 20 dB/decade to 40 dB/decade roll-off.

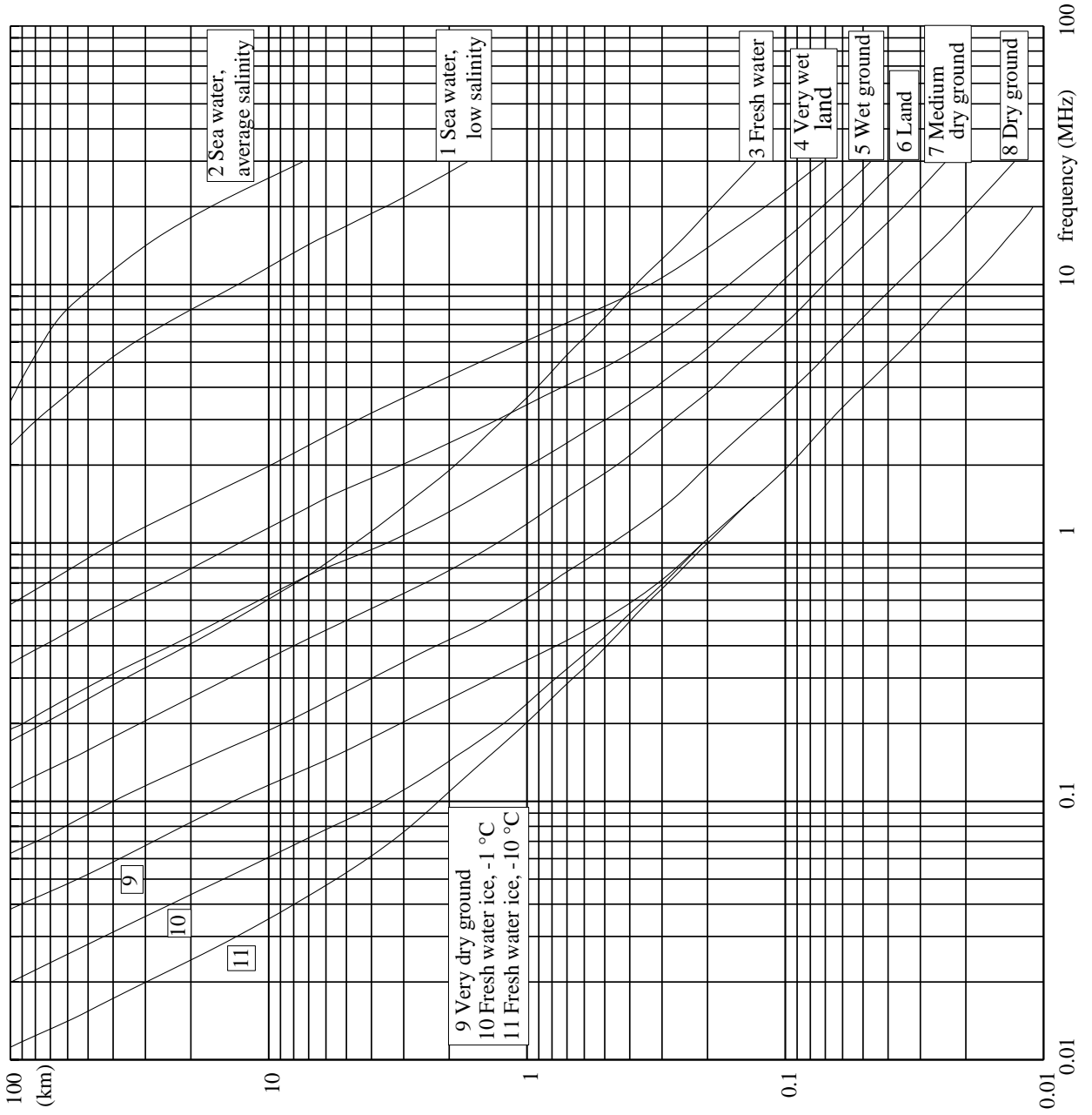


Figure A2. Transition distance as a function of frequency and type of ground.

Expected noise field strength levels

Introduction.

In this annex a study is made into the noise levels that primary radio users will encounter. Three sources of noise will be taken into account: the atmospheric noise, the galactic noise and manmade noise. Together they form the absolute lower sensitivity limit which a receiving station has to cope with.

This goal can be achieved by using the information of the *ITU-R Recommendation P.372* and converting noise powers to noise field strength levels, depending on frequency and statistical distribution.

The Recommendation gives atmospheric noise data due to lightning as a function of:

- the geographical position,
- the four seasons of the year,
- six blocks of 4 hours a day,
- and the frequency.

Three curves are derived, which gives the probabilities of 20 %, 50 %, and 80 % that the actual noise level will be lower than that indicated field strength (distribution function of the field strength). A receiver bandwidth of 2.7 kHz is assumed, field strength values for various bandwidths can be calculated from this curves.

The Recommendation also gives the relationships between the levels of manmade noise in four environments, such as:

- quiet rural,
- rural,
- residential,
- business,

and the frequency are given. Besides that a relationship for the galactic noise level is given.

Estimation of the atmospheric noiselevels.

Atmospheric noise is the result of natural electrical activity (thunderstorms) in the earth atmosphere, propagated over long distances. Thousands of lightning discharges per minute results in a EM field with a nature of noise.

As well as the location of the electrical activity as the propagation to the receiver location is strongly depending on the season of the year as on the time of the day. Also the geographical location of the receiver is relevant.

ITU-R P.372 gives the noise figure (F_n) lines mapped in the earth surface for every season and for every 4 hours block of the day. These noise figures are valid for the frequency of 1 MHz. Additional graphics show the noise figures for other frequencies, 10 kHz to 100 MHz, using the 1 MHz value as a parameter.

The noise figures are estimated for the European area and collected in table B1 for frequencies between 10 and 1000 kHz, and in table B2 for frequencies between 1 and 30 MHz.

Season	period	F (dB over kTo)										
		10	20	30	50	70	100	200	300	500	700	1000 kHz
Winter	00-04	157	145	138	128	122	114	99	92	81	75	70
	04-08	158	144	136	124	117	108	92	83	74	68	63
	08-12	153	135	124	118	99	88	68	56	44	35	28
	12-16	155	136	123	108	97	87	69	59	46	39	32
	16-20	154	140	131	118	110	102	86	77	67	61	57
	20-24	154	142	134	123	116	108	92	83	74	67	62
Spring	00-04	157	146	138	128	122	114	98	89	79	74	68
	04-08	157	142	134	121	112	103	85	74	62	55	50
	08-12	156	138	128	113	104	93	71	59	57	37	30
	12-16	158	142	132	119	111	101	83	72	59	51	42
	16-20	159	144	136	124	117	107	92	83	73	66	60
	20-24	158	146	138	128	122	115	100	91	81	76	70
Summer	00-04	159	148	141	132	125	117	101	92	82	76	70
	04-08	158	147	139	128	119	111	92	82	68	61	55
	08-12	158	144	134	121	116	101	80	68	53	44	35
	12-16	164	149	139	127	118	109	90	80	67	59	50
	16-20	164	151	142	131	123	115	99	90	79	72	65
	20-24	160	148	141	131	124	116	101	92	82	76	70
Autumn	00-04	158	148	141	132	125	117	103	94	84	78	73
	04-08	157	146	137	127	119	110	93	82	72	65	60
	08-12	151	141	131	118	109	99	78	66	52	44	35
	12-16	158	143	133	121	112	101	84	72	59	51	42
	16-20	159	146	138	128	121	113	97	88	78	71	65
	20-24	158	148	141	131	124	118	104	96	86	80	75

Table B1. Atmospheric noise figures for the frequency range 10 - 1000 kHz.

Season	period	F (dB over kTo)							
		1	2	3	5	7	10	15	20 MHz
	h LT								
Winter	00-04	70	62	58	51	45	35	18	2
	04-08	63	56	54	49	46	36	22	6
	08-12	28	19	18	22	27	32	28	15
	12-16	32	22	20	24	28	34	35	24
	16-20	57	49	46	43	41	38	30	21
	20-24	62	56	53	49	45	37	22	9
Spring	00-04	68	60	57	52	46	37	23	8
	04-08	50	43	42	42	41	37	23	9
	08-12	30	20	19	22	27	30	26	14
	12-16	42	29	26	27	29	33	32	22
	16-20	60	50	47	45	44	42	36	21
	20-24	70	62	58	53	49	41	29	17
Summer	00 - 04	70	62	59	54	48	41	27	12
	04 - 08	55	47	45	45	43	38	26	10
	08 - 12	35	24	22	24	27	29	26	13
	12 - 16	50	37	32	30	31	33	30	18
	16 - 20	65	54	50	47	46	44	36	23
	20 - 24	70	61	57	53	49	42	30	17
Autumn	00 - 04	73	65	60	53	47	38	21	5
	04 - 08	60	53	50	46	42	35	20	6
	08 - 12	35	24	23	25	29	31	27	16
	12 - 16	42	30	27	28	31	34	33	25
	16 - 20	65	55	51	48	45	42	34	24
	20 - 24	75	66	61	55	49	42	30	18

At 30 MHz the galactic noise is determining, see table B8 and figure B1.

Table B2. Atmospheric noise figures for the frequency range 1 - 20 MHz.

The electric field strength can be calculated now:

$$E_n = F_a - 95,5 + 20 \log f_{MHz} + 10 \log b \quad (B1)$$

Where:

E_n : r.m.s. noise field strength (dB μ V/m) in bandwidth b (Hz).

F_a : noise figure for the centre frequency f_{MHz} (MHz).

For the receiver bandwidth b the value of 2.7 kHz is chosen, commonly the widest bandwidth in use in communication systems on the MF and HF bands, except for AM broadcasting, where 9 kHz is the standard bandwidth.

The tables B3 and B4 give the noise field strengths.

Season	period	E_noise (in 2.7 kHz bandwidth) in dB μ V/m										
		10	20	30	50	70	100	200	300	500	700	1000 kHz
Winter	00-04	56	50	46	41	38	33	24	20	14	11	9
	04-08	57	49	44	37	33	27	17	11	7	4	2
	08-12	52	40	32	31	15	7	-7	-16	-23	-29	-33
	12-16	54	41	31	21	13	6	-6	-13	-21	-25	-29
	16-20	53	45	39	31	26	21	11	5	0	-3	-4
Spring	20-24	53	47	42	36	32	27	17	11	7	3	1
	00-04	56	51	46	41	38	33	23	17	12	10	7
	04-08	56	47	42	34	28	22	10	2	-5	-9	-11
	08-12	55	43	36	26	20	12	-4	-13	-10	-27	-31
	12-16	57	47	40	32	27	20	8	0	-8	-13	-19
Summer	16-20	58	49	44	37	33	26	17	11	6	2	-1
	20-24	57	51	46	41	38	34	25	19	14	12	9
	00-04	58	53	49	45	41	36	26	20	15	12	9
	04-08	57	52	47	41	35	30	17	10	1	-3	-6
	08-12	57	49	42	34	32	20	5	-4	-14	-20	-26
Autumn	12-16	63	54	47	40	34	28	15	8	0	-5	-11
	16-20	63	56	50	44	39	34	24	18	12	8	4
	20-24	59	53	49	44	40	35	26	20	15	12	9
	00-04	57	53	49	45	41	36	28	22	17	14	12
	04-08	56	51	45	40	35	29	18	10	5	1	-1
Autumn	08-12	50	46	39	31	25	18	3	-6	-15	-20	-26
	12-16	57	48	41	34	28	20	9	0	-8	-13	-19
	16-20	58	51	46	41	37	32	22	16	11	7	4
	20-24	57	53	49	44	40	37	29	24	19	16	14

Table B3. Atmospheric noise field strength for the frequency range 10 - 1000 kHz.

Season	period	E_noise (in 2.7 kHz bandwidth) in dB μ V/m								
		1	2	3	5	7	10	15	20 MHz	
Winter	h LT									
	00-04	9	7	6	4	1	-6	-20	-33	
	04-08	2	1	2	2	2	-5	-16	-29	
	08-12	-33	-36	-34	-25	-17	-9	-10	-20	
	12-16	-29	-33	-32	-23	-16	-7	-3	-11	
	16-20	-4	-6	-6	-4	-3	-3	-8	-14	
Spring	20-24	1	1	1	2	1	-4	-16	-26	
	00-04	7	5	5	5	2	-4	-15	-27	
	04-08	-11	-12	-10	-5	-3	-4	-15	-26	
	08-12	-31	-35	-33	-25	-17	-11	-12	-21	
	12-16	-19	-26	-26	-20	-15	-8	-6	-13	
	16-20	-1	-5	-5	-2	0	1	-2	-14	
Summer	20-24	9	7	6	6	5	0	-9	-18	
	00-04	9	7	7	7	4	0	-11	-23	
	04-08	-6	-8	-7	-2	-1	-3	-12	-25	
	08-12	-26	-31	-30	-23	-17	-12	-12	-22	
	12-16	-11	-18	-20	-17	-13	-8	-8	-17	
	16-20	4	-1	-2	0	2	3	-2	-12	
Autumn	20-24	9	6	5	6	5	1	-8	-18	
	00-04	12	10	8	6	3	-3	-17	-30	
	04-08	-1	-2	-2	-1	-2	-6	-18	-29	
	08-12	-26	-31	-29	-22	-15	-10	-11	-19	
	12-16	-19	-25	-25	-19	-13	-7	-5	-10	
	16-20	4	0	-1	1	1	1	-4	-11	
	20-24	14	11	9	8	5	1	-8	-17	

At 30 MHz the galactic noise is determining, see table B8 and figure B1.

Table B4. Atmospheric noise field strength for the frequency range 1 - 20 MHz.

For every frequency a value for the field strength is given for 24 equally distributed periods over the year and the day. Next the occurrence of each value for E_n is counted and for every frequency a value of E_n is determined for which value the number of occurrence, n , is below 20 %, about 50 %, and below 80 %. These results are collected in the tables B5 and B6.

Distribution function of Noise fieldstrength in dB μ V/m											
% of time	frequency in kHz										
	10	20	30	50	70	100	200	300	500	700	1000
20 % (n < 5)	53	45	39	31	27	18	3	-6	-14	-20	-26
50 % (n ~ 12)	57	49	45	40	35	27	17	10	5	1	-1
80 % (n > 19)	58	53	49	44	40	35	26	20	15	12	9

Table B5. Distribution function of atmospheric noise field strength levels for 10 - 1000 kHz.

Distribution function of Noise fieldstrength in dB μ V/m								
% of time	frequency in MHz							
	1	2	3	5	7	10	15	20
20 % (n < 5)	-26	-31	-30	-23	-16	-9	-16	-29
50 % (n ~ 12)	-1	-5	-6	-2	-1	-4	-11	-20
80 % (n >19)	9	7	6	6	4	1	-4	-12
At 30 MHz the galactic noise is determining, see table B8 and figure B1.								

Table B6. Distribution function of atmospheric noise field strength levels for 1 - 20 MHz.

The values of E_n are plotted in figure B1, resulting in three curves 20 %, 50 % and 80 %.

Manmade and galactic noise.

As well as manmade noise as galactic noise are not season and time dependent. The ITU-R Recommendation gives the relationship between the noise factor and the frequency in the form of formula (B2):

$$F_{am} = c - d \log f \quad (B2)$$

Wherein F_{am} = the median value of the noise figure, c and d are constants according table B7, and f is the frequency.

Constants for formula (B2)			
Environmental category	c	d	Valid frequency range
Business	76.8	27.7	0.3 - 250 MHz
Residential	72.5	27.7	0.3 - 250 MHz
Rural	67.2	27.7	0.3 - 250 MHz
Quiet rural	53.6	28.6	0.3 - 30 MHz
Galactic noise	52.0	23.0	10 - > 200 MHz

Table B7. Table of constants for formula B2.

Using formula (B2), and thereafter (B1), The noise figures and noise field strength levels are calculated for some key frequencies and shown in table B8. As the relations are linear the values for two frequencies are needed to plot these curves in figure B1.

Environmental category	Noise figure F_{am} (dB)					Noise field strength E_n (dB μ V/m)				
	Frequency (MHz)					Frequency (MHz)				
	0.01	0.3	1	10	30	0.01	0.3	1	10	30
Business	(132.2)	91.3	76.8	49.1	35.9	(31.0)	19.6	15.6	7.9	4.2
Residential	(127.9)	87.0	72.5	44.8	31.6	(26.7)	15.3	11.3	3.6	-0.1
Rural	(122.6)	81.7	67.2	39.5	26.3	(21.4)	10.0	6.0	-1.7	-5.4
Quiet rural	(110.8)	68.6	28.6	25.0*	11.4*	(9.6)	-3.1	-7.6	-16.2*	-20.3*
Galactic noise				29.0	18.0				-12.2	-13.6

* Below the level of galactic noise.

Table B8. Man made noise figures and field strength levels.

Conclusion

The curves in figure B1 show the relevant noise levels that primary radio users generally will encounter in Europe. The values of the noise levels which are shown, correspond:

1. to the atmospheric noise with a distribution likelihood of resp. 20 %, 50 % and 80 %;
2. to manmade noise levels;
3. to the galactic noise level.

The quiet rural environment manmade noise level at the lower frequencies, and the galactic noise level at the higher frequencies, should be used as a floor level to the atmospheric noise.

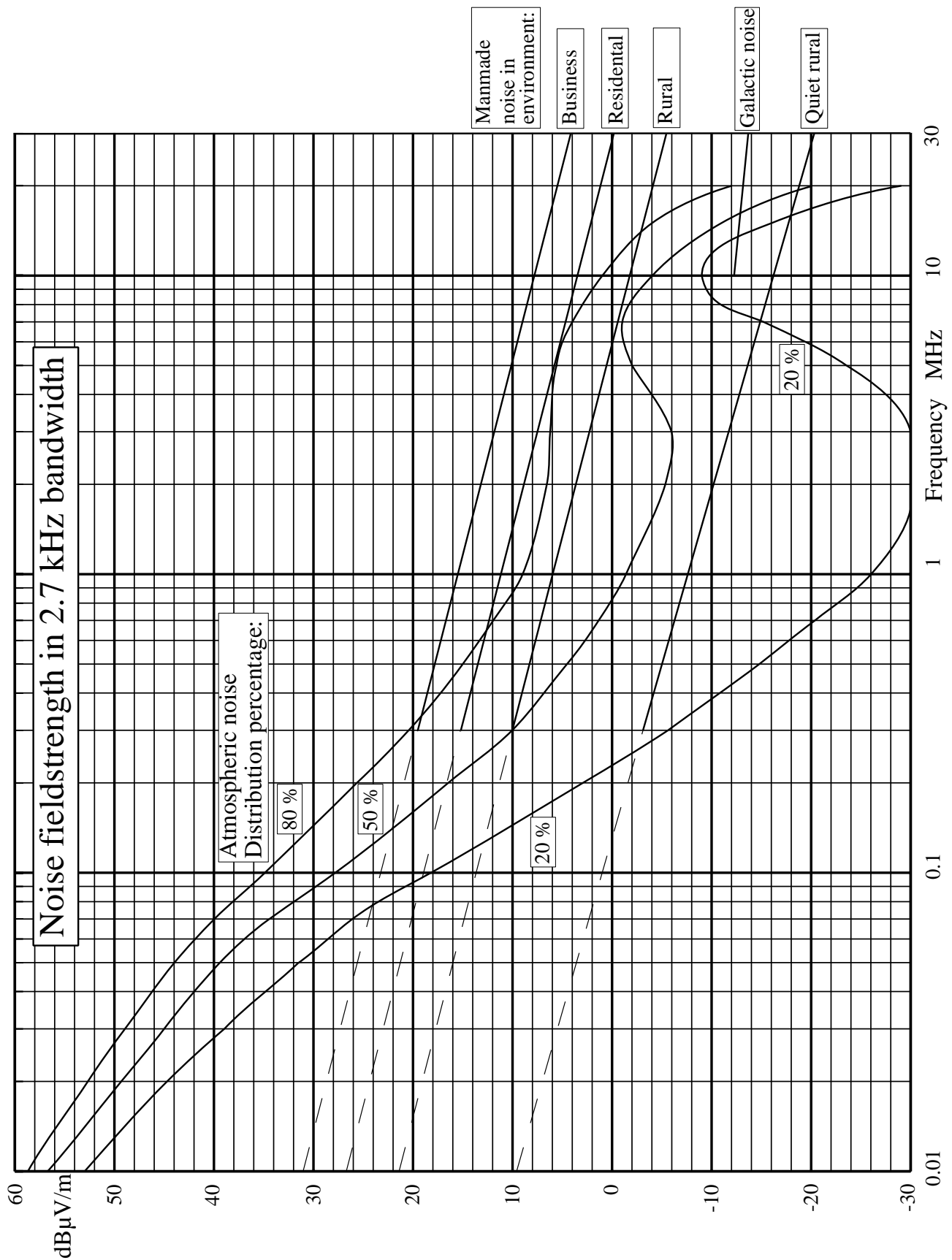


Figure B1. Noise field strength levels.