Main Propagation Mechanisms

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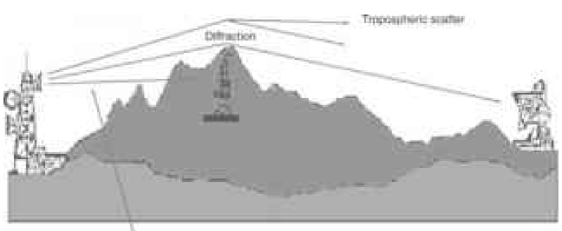
The first researches on interferences confirmed that seven main mechanisms of propagation are to be considered in the prediction procedures of these interferences (ITU-R P.452). These propagation mechanisms can be classified into two categories:

- long-term mechanisms or normal propagation mechanisms: line-of-sight propagation, propagation by diffraction and tropospheric scatter.

- short-term mechanisms or abnormal propagation mechanisms: tropospheric radio duct, reflection and/or refraction at elevated layers of the atmosphere, line-of-sight propagation with possible enhancement of the signal, scattering by hydrometeors.

While interferences may occur through different propagation mechanisms, the prevalence of each of these mechanisms depends on several different parameters, including the climate, the frequency band used for the link, the time percentages, the length of the link and the topography. Here are the main propagation mechanisms:

- line-of-sight propagation: the most direct mode of propagation is line-of-sight propagation under homogeneous atmospheric conditions. An additional factor complexity may however appear in the presence of multiple paths creating constructive interferences, thus resulting in an increase in the signal level.

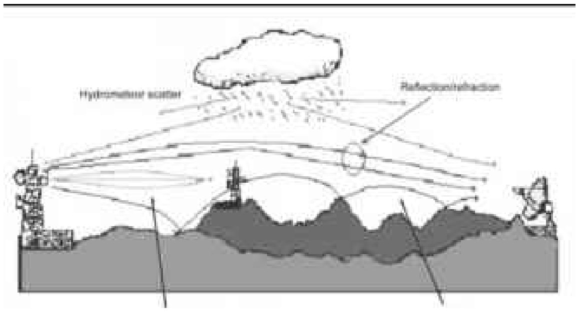


Line-of-sighi propagation

Fig. 5.14. Long-term propagation mechanism (ITU-R P.452)

Line-of-sighi propagation

Fig. 5.14. Long-term propagation mechanism (ITU-R P.452)



Line-of-sighl propagation with reinforcement of the signal

Fig. 5.15. Short-term propagation mechanisms (ITU-R P.452)

Line-of-sighl propagation with reinforcement of the signal

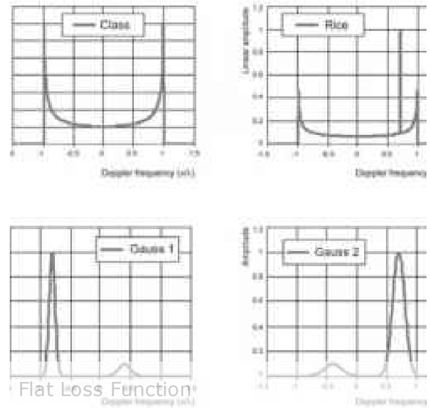


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Fig. 5.15. Short-term propagation mechanisms (ITU-R P.452)

- diffraction: the effects induced by diffraction become prevalent beyond direct line-of-sight and in normal clear air situation. For services where problems of short-term abnormal propagation are of limited importance, the degree of accuracy to which diffraction can be modelled often determines the density of the radio systems which can be set up over a given area. Further, the effects induced by diffraction must be predicted in such diverse situations as a regular ground, the presence of discrete obstacles or an irregular ground.

- tropospheric scatter: scattering in the troposphere is the propagation mechanism which defines the background level of interferences for long paths (between 100 and 150 kilometres) where the diffraction field is low. However, with the exception of special cases of sensitive stations or strong transmitters (radar systems), interferences associated with tropospheric scatter are negligible due their low levels.

- tropospheric radio duct: this is the most important short-term interference mechanism above water surfaces or coastal regions with slight relief. This phenomenon may result in high amplitudes of the signals propagated over long distances (larger than 500 kilometres above the sea surface). If certain conditions are fulfilled, relating for example to the frequency or to the thickness and homogeneity of the duct, the level of these signals may be higher than the corresponding free-space level.

- reflection and/or refraction at elevated layers of the atmosphere: the analysis of reflection and refraction phenomena occurring at layers located at an altitude of a few hundreds of metres has a great importance since this propagation mode may, if a favourable path geometry exists, compensate for the attenuation induced by ground diffraction in the case of relatively long distances, ranging from 250 to 300 kilometres.

Two other propagation mechanisms which, they are unrelated to problems of clear air propagation, may nevertheless induce interferences, can be mentioned here:

- the diffraction induced by the ground and by buildings. Although this propagation mechanism was of very limited importance until recently, this may change in view of the development of high density networks (ITU-R P. 452-8 1997),

- the reflection of waves at airplanes: this mechanism is not negligible in areas with high air traffic density (CCIR 1990).

While all the propagation mechanisms discussed above are associated with variations of the refractive index, it is necessary here to introduce a distinction between propagation mechanisms created by large scale variations of the refractive index and propagation mechanisms induced by small-scale variations. For instance, phenomena like tropospheric radio ducts and spherical diffraction are the result of large scale variations of the refractive index, whereas phenomena like tropospheric scatter and reflection at elevated layers are caused by local variations of the refractive index.

5.6.1 Line-of-Sight Propagation

The simplest mode of propagation of radio waves is the propagation along line-of-sight paths. The concept of line of sight has its origins in geometrical Optics: in this context, the concept of a wave is replaced with the concept of a trajectory or a ray, while Maxwell's equations give way to simpler relations involving geometrical angles, like for instance the reflection law or Snell-Descartes law. In the terrestrial environment however, the presence along a given path of heterogeneous media, for example maritime or rural areas, may significantly modify the behaviour of the waves : indeed, in situations where geometrical optics would predict a null field, the propagation of the signals may still occur through diffraction phenomena involving obstacles present in these different media.

Propagation will generally be said to be in line-of-sight when diffraction phenomena are negligible, i.e. if there are no obstacles in the first Fresnel ellipsoid. As is described in more detail in Chap. 3, this ellipsoid delimits the region of space where almost all the energy is contained.

5.6.2 Tropospheric Scatter

Basic Principles of Tropospheric Scatter

During the 1940-1950 decade, the performances of radar and radio relay systems went through rapid and significant improvements due to such factors as the increase of the emission power in UHF, the increase of the antenna gains and the enhancement of the noise factors of the receivers. These technological advances led to the discovery of the existence, at a distance of several hundreds of kilometres, of fluctuating fields with an average amplitude significantly higher than the amplitude predicted for spherical diffraction.

Different theories were developed at this time in order to explain this phenomenon in terms for instance of atmospheric layers or whirlwinds. These theories were intended at constructing mathematical models for the prediction of the amplitude of the received fields, and at correlating the values thus predicted with actual measurements. However, this phenomenon could not be fully explained by any of these theories.

Unlike other phenomena, for example the phenomenon of ducting propagation described earlier in this chapter, tropospheric scatter is a quasi-permanent phenomenon. This property was therefore used for developing forward-scatter transhorizon radio links. Tropospheric scatter radio relay systems were thus set up in the early 1950s between stations distant from 200 to 350 kilometres, and even from 600 to 800 kilometres under favourable weather conditions. These systems enabled to provide rapidly and at a relatively low cost the radio coverage of such remote and almost inaccessible regions like the Far North or African deserts (Ne-mirovsky 1987).

In order to explain the propagation of radio waves over very long distances at very short wavelengths, it turned out necessary to consider the structure of the atmosphere at a significantly lower scale than is usual in meteorological studies. The very possibility of such a mode of propagation was demonstrated at relatively late a time since the corresponding attenuation, even though it is much lower than the attenuation that would result from the diffraction by the curvature of the Earth, still remains extremely high.

The different theories developed in order to account for this mode of propagation are based on the low amplitude of the air refractive index. According to some of these theories, the atmosphere, when considered at an adequate scale, behaves like a turbid medium and would therefore scatter in all directions a part of the energy which propagates inside it (scattering theories).

A different approach is based on the idea that the heterogeneities present in the atmosphere cannot be assumed to be isotropic: their dimensions are smaller along the vertical direction than along the horizontal direction. These heterogeneities would therefore act more or less like mirrors, i.e. reflect a part of the incident energy (partial reflection theory). This model actually seems quite plausible: the movements of the air in the atmosphere evidently occur at very different scales in the vertical and in the horizontal directions, and the same is probably true of the heterogeneities present in the atmosphere.

In practice, neither of these theories leads to results that would be directly usable for the prediction of propagation characteristics. As a matter of fact, these theories are based on the consideration of atmospheric magnitudes, like for instance the turbulence scale or the fluctuation spectrum, which are not routinely measurable at meteorological stations.

Without necessarily choosing one of these theories, the energy transmission system can be described as follows: the heterogeneities of the refractive index within the common volume of the antennas receive energy from the emission antenna and return a small part of this energy towards all directions, including the direction of the reception antenna. Since these heterogeneities fluctuate in time, the received level undergoes the same fluctuations. The study proceeds therefore in two steps, first the study of the average level of the received signal, then the study of the fluctuations about this mean level.

Fluctuations of the Scattering Field

Seasonal fluctuations. In areas with temperate climates, seasonal fluctuations of the scattering field can be observed, which very often result in higher degrees of attenuation in winter. The difference between the worst month average value and the annual average value may reach the order of 12 dB: this difference decreases with increasing distance, and it might be reduced to 3 dB for links with lengths from 500 to 1000 kilometres.

In areas with desert climates, the opposite phenomenon can be observed: in summer the average monthly values of attenuation may be 20 dB higher than the averages annual values. Due to these important fluctuations, the unavailability rates may be very different from one season to another, depending on the margin selected for maintaining the link.

A consequence of these variations is the recording time necessary for validating a radio link or a radio system. This difficulty indicates the importance of being able to rapidly perform a reliable evaluation of the annual average attenuation.

Daily Fluctuations. These fluctuations of the scattering field are associated with traditional meteorological variations. In areas with temperate climates, attenuations are generally minimal during the morning and maximal during the afternoon. While these variations reach very high levels in desert climates, they are small in equatorial zones.

Hourly variations follow approximately a lognormal law, with a a standard deviation dependent on the length of the link. Indeed, the longer the link, the highest the probability that superrefraction phenomena may compensate the effects induced by subrefraction. The values which can be admitted from a statistical point of view are a = 9 dB for links with a length of approximately 100 kilometres and a = 3 dB for links with a length of several hundred kilometres (Boithias 1987).

The 80 and 99.9 percent attenuations can be deduced from the value found for a using the two following relations:

Fast Fluctuations. The fast variations of the received field which can be observed are the consequence of the chronic instability of the atmospheric layers and whirlwinds. The resulting wave is the vector combination of several waves with no significant difference in amplitude, yet randomly out of phase. The fast fluctuations of the field therefore follow a Rayleigh law (10 dB per time decade), and several successive fades of the signal per second can be observed in UHF.

As far as interferences are considered here, it might be stressed here that scatter propagation takes place over long distances and along all directions, including directions towards areas where the signal is not desired, although the amplitude of the signal in this case is low compared with other abnormal propagation phenomena. When studying interferences problems, the interest lies more specifically in small percentages of time, contrary to the case where an operating time close to 100 percent is desired.

Scattering Geometry

In scattering problems, an important parameter is the scattering angle formed by the pointing directions of the antennas. This angle depends on the distance along the great circle and on the angles of sight a and a. The geometry of a tropo-spheric link and the parameters to be considered in this context are represented in Fig. 5.16. The scattering angle in this figure is equal to:

where the altitude and the distance to the horizon are expressed according to the modified Earth radius factor ka. After some simplifications, the following equation for the angles of sight a and a is obtained:

The equivalent distance used in attenuation calculations is defined by the following equation:

Path Loss

Since the field may significantly vary in time, the need arises of considering its annual median value. Different models have therefore been developed in order to determine the annual median value of the field. In these models, the following parameters are used:

- the average refractive index along the vertical of the scatter area,

- the geographical distance,

- the scattering angle or the equivalent distance,

- the frequency, generally with a 30 log(f) law accounting for free-space attenuation.

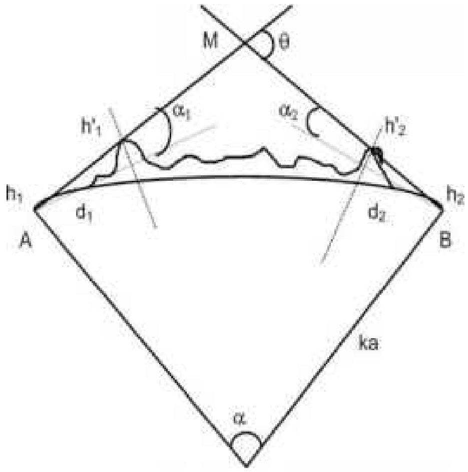

Fig. 5.16. Geometrical parameters of a tropospheric link

The correlation between climatic data and the average field is not always easy to achieve since only in temperate areas are data like the ground refractivity known with a relatively high degree of precision. More generally, although many models require that the ground refractivity be known, data for this parameter are unfortunately difficult to obtain.

Early models. The approximations that were used during the 1950s were extremely simple. As an example, here is the formula recommended at this time by RCA:

where Ao is the attenuation in free space, f is the frequency in MHz, and DE is the equivalent distance in kilometres.

A more elaborate model, developed on the basis of a large number of experimental data, can be found in the Technical Note 101 of the National Office of Standards (Rice 1967). Although this model can be theoretically applied to a large number of different climates, it nonetheless has the disadvantage of using a function of the product 6D which requires the introduction of curve networks param-eterised with a dissymmetry factor and dependent upon the ground refractivity.

For Ns = 301 and 6d < 10, this method nonetheless provides a simple formula which can still be used. Including free-space attenuation, the median annual transmission loss is given by the equation:

Ap = 135,8 + 30 logio (f) + 30 logio (6) + 10 logio (D) + 0,34 6D (5.34)

where 6is expressed in radians, D is in kilometres and f is in MHz,

BTRL-YEH Model. This solution recommended by the COST 210 (COST 210 1991) has been developed from the Yeh model by British Telecom Laboratories Radio communications (BTRL). In this model, the median transmission loss is given by the following equation:

Ap = 190,1 + K (f) + 20 logio D + 0,573 6 - 0,15 No + Ag - Cs (5.35)

where D is in kilometres and 6 is in milliradians, while:

- Ag (in dB) is a term accounting for atmospheric absorption,

- Cs (in dB) is a corrective term introduced in order to take into account the dissymmetry of the path. The following equation yields the factor S which characterises the asymmetry of the path :

where the angles are expressed in milliradians, the heights are in metres and the distance d is in kilometres. Cs is then defined as follows:

The COST 210 recommends considering the value for the refractivity at the sea level in order to use the data published by Bean et al (Bean 1966). In addition, the selected value should be the value at the middle of the path.

For the estimation of interferences, the attenuation not exceeded during a percentage of time p ranging between 0.001 and 50 percent can be determined from the median attenuation by using the following relation:

This equation shows that the level of the signal at the reception may increase from approximately 20 dB during 0.1 percent of the time, thereby inducing interferences.

Other Models. Different other models allowing the determination of the path loss could have been discussed here, among which we should in particular mention the model developed by the CCIR 1990 or the CNET model empirically developed by Boithias from the study of propagation data should be mentioned. A survey of these different models is provided by Deygout (Deygout 1994). The indicative curves given by Boithias for the values path loss observed in different climates, either for different percentages of time, or for the worst month, are also of interest (Boithias 1987).

5.6.3 Duct Propagation

If the gradient of the refractive index is lower than -157 N units/km, then the curvature of the trajectories followed by waves will be higher than the curvature of the terrestrial surface. A region of the atmospheric where these superrefraction conditions exist is referred to as a ducting layer. Ducting layers have significant effects on line-of-sight paths as well as on transhorizon links. In the presence of a duct, the very notion of radio horizon has no longer any precise meaning, since

points located beyond the horizon can be reached. Further, the level of the received signal at the time of such a phenomenon may reach and even exceed its free-space level (Rana 1993; Shen 1995; Vilar 1988). Therefore, ducting layers are among the main causes of interferences occurring between communication services using the same frequency band. If the ducting layer extends at a relatively low altitude and if the ground is sufficiently reflective, then the duct is referred to as a surface-based duct. If the layer extends on the contrary at a high altitude, waves are bent successively towards the Earth and towards space, and are therefore caught between two altitudes: if these waves do not touch the ground, the duct thus formed is referred to as an elevated duct.

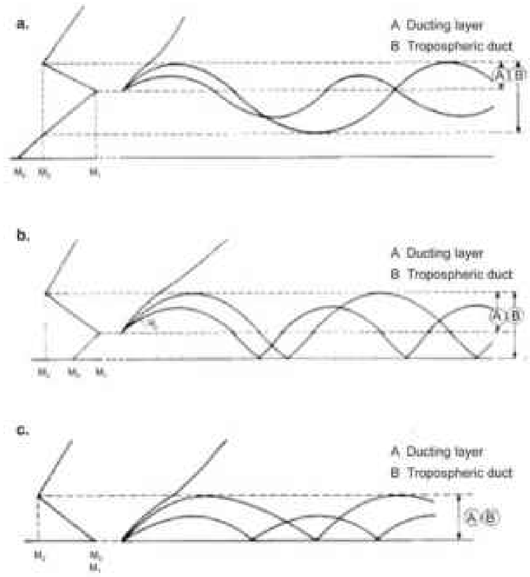

Fig. 5.17. Different types of ducting layers *a.* elevated duct *b.* surface-based duct *c.* surface duct (Boithias 1987)

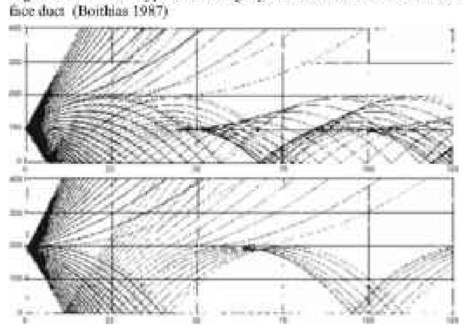

Fig. 5.18. Effects induced by the presence of a ducting layer (ray tracing) (Boithias 1987)

Ducting layers cause waves emitted by a given transmitting antenna to cross each other at certain points of space. This leads to the appearance of interference zones where waves associated to multiple paths cross each other and of zones where almost no waves propagates and where the signal level is low, the latter being referred to as radio holes. The boundary between these two zones constitutes a caustic along which the level of the signal is very high. As the refraction conditions are variable in time, a given point of space may thus be alternatively in one or the other of these zones, which results in abrupt fluctuations of the level of the received signal.

The effect of the height of the emission antennas can be observed in Fig. 5.18: waves are trapped inside the ducting layer and, assuming the antenna to be located within this layer, only a very limited amount of energy leaks away. If on the contrary the antenna is located above the ducting layer, a leakage of energy into the region extending above the ducting layer occurs.

While the thickness of a duct seldom exceeds a few hundred metres, ducting layers may extend over several hundred square kilometres, especially above coastal regions or very humid regions. The evaporation ducts which may appear due to the large negative gradients of water vapour near the sea surface have a thickness of the order of only ten metres, but they remain present during a high percentage of time.

When an emission antenna is located inside a radio duct with horizontal layers, only waves emitted at very small angles of elevation can be trapped inside the ducting layer. In the simplified case of a normal refractivity profile above a surface duct, and assuming the gradient of the refractive index to be constant, the critical angle at which waves are trapped is given by the following equation (ITU-R P.453 1997):

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