REPORT 1145*

PROPAGATION OVER IRREGULAR TERRAIN WITH AND WITHOUT VEGETATION

(Question 9/5)

(1990)

1. Introduction

This Report describes the theoretical bases and empirical methods which have been developed to estimate the transmission loss over irregular terrain, which may be covered by vegetation. The transmission loss over irregular terrain is a complex function of frequency, path geometry, vegetation density and other less significant variables. This complexity requires the use of approximation methods which, nevertheless, may yield satisfactory results. These approximation methods generally fall into two classes.

One class results from mathematical regression techniques applied to experimental data. These yield formulae which describe the measured transmission loss as a function of the various variables which describe the path. While this method may correctly predict the transmission loss over nearly identical paths for the same frequency range as the measured data, attempts to extend these predictions to other frequency ranges and paths which are described by variables which lie outside the observed data set usually result in large errors.

The other class of approximation is often described as semi-empirical. It consists of theoretical estimates of the transmission loss based on an ideal representation of the terrain and modified by empirically determined corrections for the actual terrain irregularity and vegetation cover. The mathematical forms of these corrections are usually based on theoretical methods.

2. Idealization of terrain irregularities

Various idealizations of irregular terrain have been developed to permit the use of theoretical methods in computing transmission loss. In many cases the terrain profile can be replaced by a series of prominent features which can be represented by ideal knife-edges or rounded obstacles. Most experimental evidence suggests that only a few of the most prominent features are important. The diffraction fields from the other obstacles can be neglected.

The additional transmission loss due to a series of multiple knife-edges can be estimated by a number of methods based on the application of geometrical optics and the single knife-edge diffraction loss described in Report 715. The commonly used approximation methods of Deygout [1966], Epstein-Peterson [1953], Bullington [1947] and Giovanelli [1984] are described and compared by Grosskopf [1987; 1988]. All these methods tend towards larger errors as the number of knife-edges is increased. If more precision is required in special cases with a large number of significant knife-edges, a computer method which can be used for up to ten knife-edges is avaiable [Vogler, 1982].

Methods for calculating the transmission loss over multiple rounded obstacles have not yet been fully developed and further study is required. An approximation method is available [Assis, 1971] and a promising method has been suggested [Whitteker, 1988].

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* This Report replaces Report 236.

3. Small scale irregularities

If the variation in terrain height about some mean value is small in comparison to a wavelength and the slopes of the terrain are small, then one can use the smooth earth curves of Recommendation 368 if the actual terrain surface impedance is replaced with a higher effective value [Barrick, 1971]. This effective surface impedance can be anisotropic since the additional attenuation is greater for paths which cross a series of ridge lines than that for paths which are parallel to the ridge lines. Hansen [1977] has obtained excellent experimental confirmation of this method over a sea path in the 2 to 20 MHz range.

This method can be extended to an effective surface impedance method for urban areas [Causebrook, 1978] and forested terrain when the heights of the buildings and trees are much smaller than a wavelength.

An integral equation method approximation is also available for special cases where the required accuracy of the predicted field justifies the extra complexity and computational resources. An example application is the estimation of field strength around a coastal station located on a cliff above the sea.

Integral equation methods can be employed at frequencies below about 30 MHz for paths with both irregular terrain and non-homogeneous electrical characteristics. Ott [1971] has formulated methods for applying the basic integral equation and a computer code has been developed for making propagation predictions [Ott *et al.*, 1979]. The 30 MHz limitation is based on using field points that are not necessarily optimum, but yield reasonable computational time.

Using another algorithm for the field points, it has been shown that the model can be used up to at least 300 MHz [Engdahl, 1982].

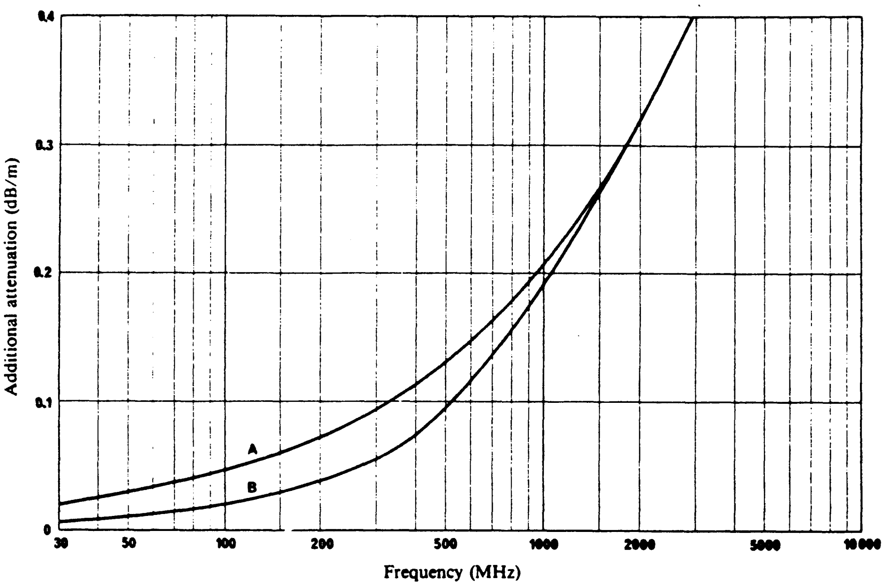
Computational times and memory requirements tend to become uneconomical at higher frequencies.

Irregularities in the crest of mountain ridges cause fading varying both in space and time due to interference in the diffraction field. Additional losses are caused by the finite width of the ridge. These irregularities cause a widening of the diffraction pattern of the ridge. This leads to a degradation in the effective antenna gain as well as to frequency and phase distortion of the signal [Troitsky, 1975 and 1977].

4. Vegetation

At frequencies below about 1 000 MHz, it is useful to model a forest as a lossy dielectric slab [Tamir, 1977] covering the terrain. At frequencies below about 30 MHz, a two-layer effective surface impedance model [Wait, 1970] can be employed such that the curves of Recommendation 368 can be used to estimate the transmission loss.

In the VHF and UHF bands, other approximation methods must be used. The specific attenuation of the vegetation in a forest is very high and, as shown in Figure 1, is of the order of 0.1 dB/m [Saxton and Lane, 1955; Josephson and Blomquist, 1958] in the UHF bands. Thus direct transmission through a forest is limited at these frequencies to only a few hundreds of metres. The lossy slab model, however, identifies a new propagation mode which makes radiocommunication possible in forests. The new mode is a lateral surface wave which propagates along the boundary between the top of the forest and the air above it. (This lateral surface wave is analogous to the optical surface ray which is created when a light ray emerges from a dense optical medium at precisely the Brewster angle.) The lateral wave continuously leaks energy back down into the forest with $1/d^2$ spreading loss for the electric field. If the forest-air interface is irregular, then further corrections may be required. The basic theory [Tamir, 1977] also suggests methods of calculating transmission loss over mixed paths of open ground and forest by idealization of the forest boundary as a diffraction wedge. This theoretical treatment can be used as a guide for determining the mathematical form for empirical corrections for vegetation loss in transmission loss models.



A: vertical polarization
B: horizontal polarization

FIGURE 1

Specific attenuation of woodland

5. Semi-empirical models of transmission loss

More than a dozen semi-empirical models of transmission loss over irregular terrain can be found in the recent telecommunications literature. Comparisons of these models have also been published [Grosskopf, 1987, 1988; Delisle et al., 1985]. Most of these models employ theoretical estimates of transmission loss over an idealized terrain represented by a series of knife-edges. Some include additional losses due to vegetation and buildings explicitly. All contain various correction factors which are based on the analysis of experimental measurements over a number of paths. A representative semi-empirical transmission loss model is given in detail in Annex I.

Before using any semi-empirical model, the appropriate references should be consulted to determine if the terrain and vegetation density for which the model has been developed matches the new terrain over which the model is to be applied.

6. Very irregular and mountainous terrain

The theoretical and semi-empirical models described above contain an implicit assumption that the propagation is confined to be two-dimensional along a great circle path between the transmitter and reception point. If the terrain surrounding the great circle path is very irregular, e.g. mountainous, then other propagation paths may significantly modify the transmission loss.

If the diffracting terrain feature, which is represented by a knife-edge in these models, is irregular in the direction perpendicular to the great circle path between transmitter and reception point, variations in the transmission loss of as much as 10 dB can be expected. A numerical method [Assis, 1981] has been developed for correcting the single knife-edge diffracting loss in these cases. Another way of handling this form of multipath propagation is to assume that the theoretical and semi-empirical models represent the median transmission loss of a Rayleigh or of a Nakagami-Rice distribution of transmission loss (see Report 1007).

In very irregular terrain, reflection or scatter from terrain features adjacent to the great circle path should be examined to determine if the additional fields contribute significantly to the field at the reception point.

Theoretical and experimental studies carried out in the USSR [Troitsky, 1976] have shown that SHF and UHF waves may be propagated into the shadow zone of mountain ridges by wave refraction and anisotropic scattering in the dielectric layer formed by the snow cover. This phenomenon may result in a significant increase in the field strength in the shadow of mountain peaks and ridges over the diffraction field strength.

On very long paths tropospheric-scatter fields (see Report 238) may combine significantly with the diffraction field and further modify the transmission loss.

In mountainous areas when there are dominating peaks and ranges which are visible from both the receiving and transmitting stations, a field is often produced by backscatter from the mountain slopes. This field may be fairly strong. Experimental studies carried out in the USSR [Troitsky, 1986] have shown that as a result of this phenomenon radio waves may be propagated up to distances of the order of 100 kilometres or more in areas of deep shadow. The studies also show that the scatter field is highly frequency dependent, with a maximum in the VHF band.

Fluctuations in signal level due to interference are prevalent in the UHF and SHF bands. Severe spatial non-homogeneities in field strength are observed, which are caused by interference from waves backscattered from different sections of the mountain slope. This inhomogeneity causes a reduction in antenna gain if the angular dimensions of the scattering area are wider than the antenna pattern.

For reception of a wideband signal, severe selective frequency distortions are observed, due to the fact that the components of the scattered signal display significantly different values of delay. If the scattering area is part of a large mountain range, the resulting differences in the distances travelled may be tens of kilometres, or tens of metres with relatively small-sized scattering areas. As antenna directivity is increased, the corresponding delays are reduced.

The phenomenon studied has two practical effects. On the one hand, it produces interference; on the other, in certain cases it enables some radio systems to be operated over large distances when the receiving site is in a deep shadow area.

7. Obstacle gain

Mountain ridges can effectively reduce both transmission loss and the fading below the values to be expected with smooth earth spherical diffraction. This occurs when the direct path is non-optical, but both transmitter and receiver can be seen from the top of the mountain. The phenomenon is known as obstacle gain. When using this term quantitatively, it must be stated whether it refers to gain relative to the calculated field over a homogeneous spherical earth, where only diffraction and standard atmospheric refraction are involved (propagation curves of the CCIR Atlases), or whether scattering and super-refraction are considered as well (curves of Recommendation 370). The latter case occurs when it is possible to compare propagation over two neighbouring paths of comparable distances and antenna heights, one of which has a mountain ridge which causes knife-edge diffraction and the other is clear of obstacles. Measurements made under such conditions have confirmed that such gains do occur and can be of the order of 20 dB [Fukami et al., 1961; Kirby et al., 1955].

Some calculations of obstacle shielding and gain effects in the microwave region have been made in the United Kingdom [CCIR 1986-1990]. These assume a diffraction mode, an obstacle with its peak visible from both terminals and extended transversely to the direction of propagation on an otherwise smooth-Earth path, path lengths of 75 - 150 km, frequencies of 1, 4, 10 and 20 GHz, and k factors of 4/3, 2 and 5. For practical antenna heights and obstacle heights of 20 - 100 m, in many cases the shielding effect is lost when the obstacle-receiver distance exceeds about 2 km. When this distance is less than, say, 0.5 km shielding increases with obstacle height, but this is not necessarily true for longer distances. Furthermore, unlike the case of a smooth-Earth path, the loss on the obstructed path is not very dependent on frequency or k value.

ANNEX I

A model for transmission loss predictions in hilly woodland

1. Introduction

The following semi-empirical model [Blomquist and Ladell, 1975; Ladell, 1986; Ladell et al., 1987] has been developed for use in the frequency range 30 to 1 000 MHz. It is presented here as an example of this type of model. The model has been tested in field trials in Sweden for over ten years. The model has also been subjected to a comparison test in Germany [Grosskopf, 1987] where it yielded the best standard deviation in the VHF range of the 11 models which were examined. An additional comparison with five models has been made in Canada [Delisle et al., 1985].

This model is computer oriented and uses a terrain data base to obtain terrain and vegetation information. It consists of several basic propagation models brought together by a unique empirical bridging function.

2. Basic propagation models in hilly woodland

2.1 Smooth spherical earth model

Assume that the terrain irregularities can be neglected. Thus a smooth spherical earth can be dealt with, using the method described in section 3 of Report 715, to compute a propagation factor F_s. (In this model, the term "propagation factor" is the ratio of the field strength to the free space field strength at the same distance.)

2.2 Diffraction by terrain obstacles

In the case of diffraction by terrain obstacles such as hills and mountains, many different methods are available giving more or less reliable results. Both for the sake of its simplicity and accuracy over very rough terrain the discussion here is confined to the diffraction models due to Epstein and Peterson [1953] and Deygout [1966].

Assuming that the ground reflection can be neglected, the overall propagation factor in dB can be calculated as the sum of the propagation factors for each obstacle. For a case with three obstacles, that means that the propagation factor for diffraction can be written

$$F_D = F(v_1) + F(v_2) + F(v_3) \qquad (1)$$

where F(v) is the well-known Fresnel-Kirchhoff diffraction propagation factor for a perfectly absorbing knife-edge which can be calculated using section 4.1 of Report 715.

2.3 Vegetation loss model

The proposed vegetation loss model is obtained by using empirical results, mainly because of the limited frequency coverage of the well-known lateral wave model [Tamir, 1977].

Characterize the forest between the transmitter and receiver by two parameters, the vegetation density $\rho(\%)$ and the percentage of wood on the tranmission path $\eta(\%)$. The vegetation density is a measure of the number of trees per square unit and their average diameters. The empirical results behind this vegetation model were obtained in an average dense forest in Sweden where $\rho_0 = 100\%$ and the average percentage of wood, derived form the topographical data base, is $\eta_0 = 75\%$.

The vegetation loss relative to the spherical earth model (dB) as a function of frequency (MHz) and distance (km) is denoted V(f,d) and may be calulated from

$$V(f,d) = V_0(f,d)\ (\eta/\eta_0)\ (\rho/\rho_0) \qquad (2)$$

where

$$V_0(f,d) = \begin{cases} -29.6 + 9.8. \cdot \log_{10} f + 45 \cdot \log_{10} d \cdot (\log_{10} f - 2) \ (\text{hor.pol.}) & (3a) \\ 46 - 15.5 \cdot \log_{10} f + 45 \cdot \log_{10} d \cdot (\log_{10} f - 2) \ (\text{vert.pol.}) & (3b) \end{cases}$$

assuming a frequency between 100 and 1 000 MHz and antenna heights below tree-top height. For $d < 2$ km, V_0 should be calulated for a distance of 2 km and the result in dB multiplied by 0.5d. For $d > 20$ km, the value calculated for a distance of 20 km should be used.

3. Combined transmission loss model and bridging function

Assume at first that there is no vegetation present. Then for very low frequencies the terrain irregularities can be neglected and the basic transmission loss is given by the smooth spherical earth model. The other extreme case is for very high frequencies when diffraction by hills and mountains is the dominating mechanism. For a given terrain profile these two cases indicate the low and high frequency extremes respectively. To solve the problem of finding a prediction model for the whole frequency range of interest, a bridge-function has to be specified in terms of the propagation factors of these two extreme cases.

Such a bridge-function is the propagation factor calculated as the negative square root of the sum of the squares of the propagation factors for smooth spherical earth and diffraction, expressed in dB, and thus written

$$F_R = -(F_S{}^2 + F_D{}^2)^{1/2} \qquad (4)$$

This square root model always gives a propagation factor (dB) less than either of the two calculated components. It is a semi-empirical model having a low-frequency asymptotic value given by the smooth spherical earth model and a high-frequency asymptotic value given by the diffraction model in accordance with the assumption. The effects of vegetation may now be included giving the final prediction model for the propagation factor or the basic transmission loss (dB).

These equations may be written

$$F = F_R - V \text{ (where } F \leq F_R\text{) and } L_b = L_{b0} - F_R + V \qquad (5)$$

where

$$L_{b0} = 20 \cdot \log_{10} (4\pi d/\lambda) = \text{free space transmission loss.}$$

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