REPORT 1008-1

REFLECTION FROM THE SURFACE OF THE EARTH

(Question 1/5)

(1986-1990)

1. Introduction

This Report describes the influence of the reflection of signals from the surface of the Earth on the performance of telecommunications systems. This is important when the reflected signal is sufficiently strong to interfere significantly with the direct signal, either constructively or destructively. The strength of the reflected signal at the receiving antenna terminals will depend upon the directivity of the antennas, the height of the terminals above the Earth, the nature of the surface and the length of the path.

Reflected signals are usually important in those systems which employ low directivity antennas, such as those employed in the mobile services. Reflected signals have been a necessary design consideration in the aeronautical mobile service. The same conditions also exist for the maritime and land mobile satellite services because a line of sight path exists over the entire service area.

The remainder of this Report consists of three sections. The first of these describes specular reflection from a plane Earth surface. The next section describes specular reflection from a smooth spherical Earth as a basis for practical cases. The final section contains a qualitative description of diffuse reflection or scattering from rough surfaces and is concerned with the combination of direct specularly reflected and diffusely reflected signals and their statistical behaviour.

2. Specular reflection from a plane Earth surface

The reflection coefficient, R_0, of a plane surface is given by the expression:

$$R_0 = \frac{\sin \varphi - \sqrt{C}}{\sin \varphi + \sqrt{C}} \tag{1}$$

where φ is the grazing angle and

$C = \eta - \cos^2 \varphi$ for horizontal polarization

$C = (\eta - \cos^2 \varphi)/\eta^2$ for vertical polarization

with:

$$\eta = \varepsilon_r(f) - j\,60\lambda\sigma(f)$$

where:

$\varepsilon_r(f)$: relative permittivity of the surface at frequency f

$\sigma(f)$: conductivity (S/m) of the surface at frequency f

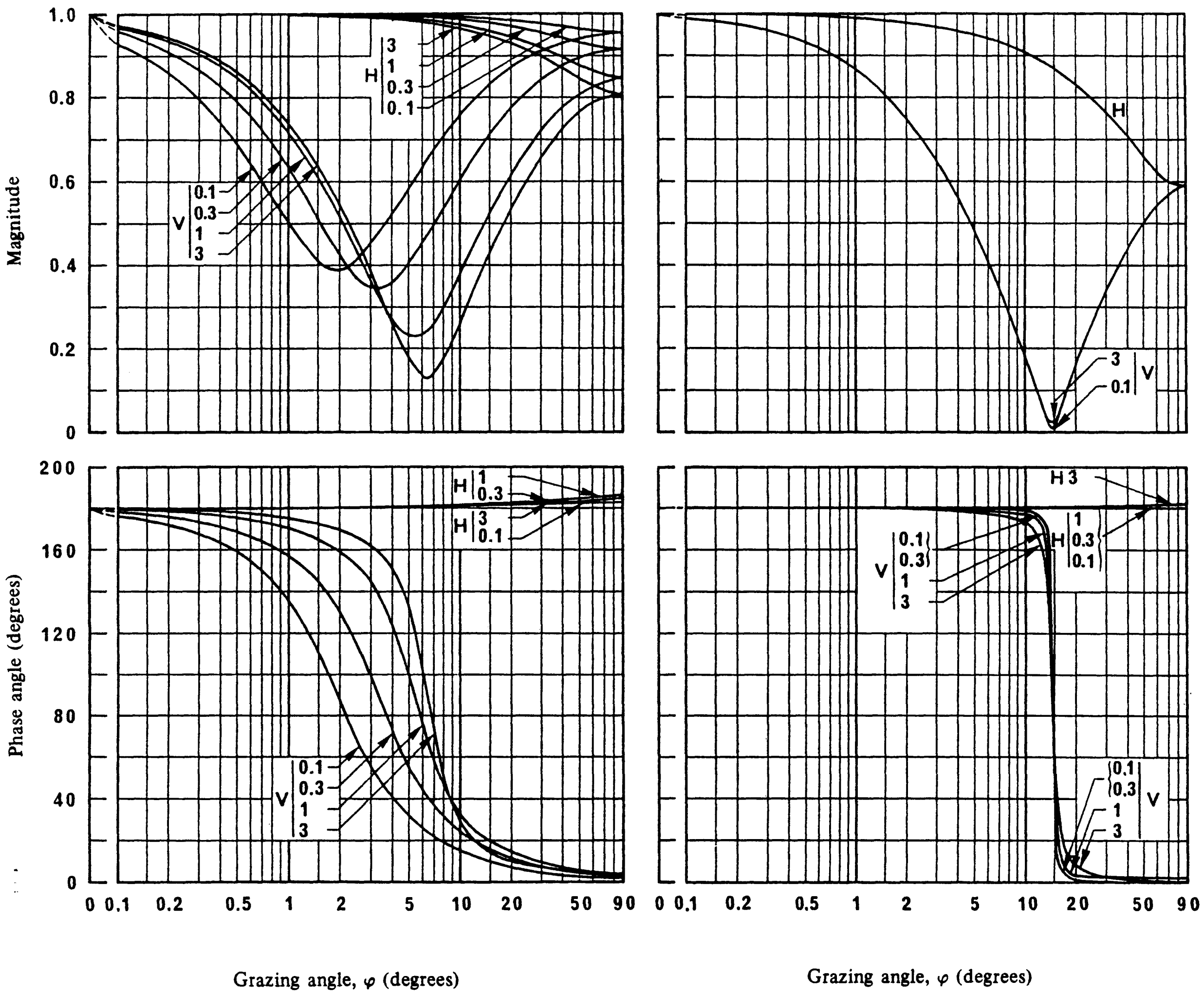
λ: free space wavelength (m)

This function is shown in Fig. 1 as a function of the grazing angle for various frequencies and two sets of values for $\varepsilon_r(f)$ and $\sigma(f)$ corresponding to sea water and dry ground respectively [Hall, 1979]. The angle at which the modulus of the reflection coefficient for vertical polarization is a minimum is known as the Brewster angle. This angle, φ_p, is approximately equal to $\sin^{-1} (1/\sqrt{|\eta|})$.

Special considerations concerning the Brewster angle can be important in coastal areas [Furnes, 1984; Stokke, 1984] in order to reduce problems caused by reflections from the sea.

2.1 *Polarization effects*

The terms horizontal and vertical polarization were originally defined with reference to reflection from a plane Earth surface because of the analytical convenience of treating separately the electric field components of a radio wave which are parallel or perpendicular to the reflecting surface. This concept may be generalized to include both terrestrial and Earth-space paths by defining a polarization reference plane. This plane contains the centre of the Earth and the two terminals of the path. The component of the electric field of the radio wave normal to this plane is the horizontally polarized component. The component of the electric field of the radio wave parallel to this plane is the vertically polarized component.



(a) Sea water

(b) Medium dry ground

FIGURE 1 – *Magnitude and phase of the reflection coefficient of a plane surface as functions of grazing angle, φ, for vertical V and horizontal H polarizations*

The frequencies are given in GHz.

Note. – The characteristics of sea water and medium dry ground are given in Recommendation 527.

The specular reflection coefficient for vertical polarization is less than or equal to the coefficient for horizontal polarization. Thus the polarization of the reflected wave will be different from the polarization of the incident wave if the incident polarization is not purely horizontal or purely vertical. For example, a circularly polarized incident wave becomes elliptically polarized after reflection. Also, the sense of the rotation becomes reversed if the grazing angle is greater than the Brewster angle.

The calculation of magnitude and polarization of the reflected wave is usually accomplished by resolving the incident wave into horizontal and vertical components and then computing the magnitude and phase of each component of the reflected wave using equation (1) [Kraus and Carver, 1984].

3. Specular reflection from a smooth spherical Earth

A signal reflected from a smooth spherical Earth, as shown in Fig. 2, is called a specularly reflected signal because the incident grazing angle, φ, is equal to the angle of reflection. The amplitude of the reflected signal is equal to the amplitude of the incident signal multiplied by the modulus of the reflection coefficient, R. The phase of the reflected signal is the sum of the phase changes due to reflection plus that due to the path length difference between the direct and reflected signal paths.

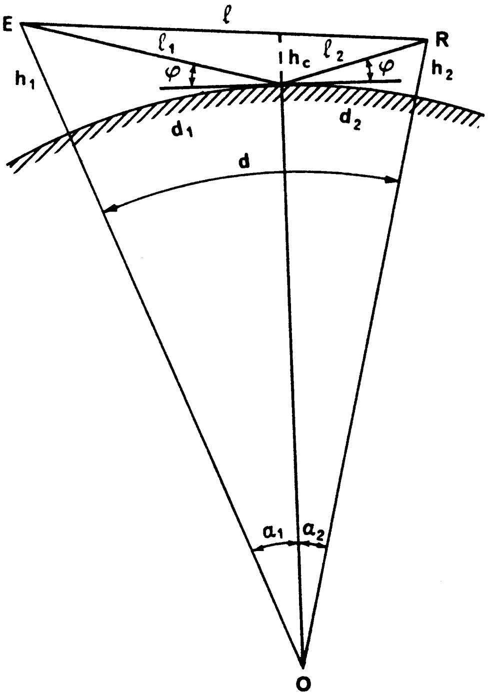


FIGURE 2 – *Geometrical elements of reflection from a spherical Earth*

3.1 *Reflection at low grazing angles*

In the majority of terrestrial communications systems, reflection occurs at very small grazing angles. In these cases, the reflection coefficient R approaches a value of -1. This results in a received field in which the direct and reflected fields are of equal magnitude and have nearly a 180° phase difference. The actual phase difference is determined by the path length difference.

It is convenient to express the path clearance by determining which Fresnel ellipsoid (see Report 715) is tangential to the ground, taking into account the fact that the number n characterizing that ellipsoid is not necessarily a whole number. It may then be shown that the received level is less than the free-space level if n is less than 1/3, i.e. if the equatorial radius of the ellipsoid tangential to the ground is less than the fraction $1/\sqrt{3}$ of the equatorial radius of the first Fresnel ellipsoid.

Another clearance value which is also useful to know is the value below which geometrical optics can no longer be used because diffraction phenomena become preponderant. This value is expressed using the grazing angle of the reflected ray. The limit value of this angle is given by the approximate relation:

$$\varphi(\text{mrad}) = \left\{ \frac{2100}{f(\text{MHz})} \right\}^{1/3} \tag{2}$$

which gives, for example, a limit angle of 5.94 mrad at 10 MHz, 2.76 mrad at 100 MHz and 1.28 mrad at 1 GHz [Boithias, 1984].

3.2 *Reflection geometry*

An analysis of surface reflections requires a determination of the geometrical specular reflection point located at some distance, d_1, from one of the terminals. This is not easy to determine as an exact solution exists only for a flat Earth. Approximate solutions are available for small angular distances for terminals near the surface of the Earth and for very large distances between terminals such as the case of an earth terminal and a geostationary satellite [Boithias, 1984; Kerr, 1965].

In the first case, it is convenient to define two intermediate quantities, m and c:

$$m = \frac{d^2}{4\, a_e (h_1 + h_2)} \tag{3}$$

$$c = (h_1 - h_2)/(h_1 + h_2) \qquad h_1 > h_2 \tag{4}$$

where a_e is the effective radius of the Earth and the other quantities are those shown in Fig. 2. Then one finds a third quantity, b:

$$b = 2\sqrt{\frac{m+1}{3m}} \cdot \cos\left[\frac{\pi}{3} + \frac{1}{3} \arccos\left(\frac{3c}{2}\sqrt{\frac{3m}{(m+1)^3}}\right)\right] \tag{5}$$

and the quantities of interest, namely the distance d_1, the path length difference Δ, and the grazing angle φ (rad) are given by:

$$d_1 = \frac{d}{2}(1 + b) \tag{6}$$

$$\Delta = \frac{2 d_1 d_2}{d} \varphi^2 \tag{7}$$

$$\varphi = \frac{h_1 + h_2}{d} [1 - m(1 + b^2)] \tag{8}$$

For Earth-space paths l and l_1 are nearly parallel because of great distances involved. In this case:

$$d_1 \simeq h \cot E \tag{9}$$

$$\Delta \simeq 2h \sin E \tag{10}$$

$$\varphi \simeq E + \frac{h}{a_e + h} \cot E \text{ (radians)} \tag{11}$$

where E is the elevation angle of the satellite and h is the height of the earth station above the surface.

An experimental method for locating the reflection point which uses measured variations in the received field strength with height has been developed [Furnes, 1984] and has been used successfully in broadcasting applications.

3.3 *Divergence factor*

When rays are specularly reflected from a spherical surface, there is an effective reduction in the reflection coefficient which is actually a geometrical effect arising from the divergence of the rays. This effect is taken into account by writing the smooth spherical Earth reflection coefficient as

$$R = D\,R_0 \tag{12}$$

where R_0 is the plane surface coefficient of equation (1) and D is a divergence factor.

The divergence factor for terrestrial paths is given by the expression:

$$D = \left[1 + \frac{2}{a_e \sin \varphi} \, \frac{l_1 l_2}{l_1 + l_2} \right]^{-1/2} \tag{13}$$

for Earth-space paths this may be written:

$$D \simeq \left[1 + \frac{2h \tan E}{a_e \sin \varphi} \right]^{-1/2} \tag{14}$$

Equation (14) has a value of ≈ 1 for elevation angles above about 5° and terminal heights below 2 km. The divergence factor concept no longer applies if the value of the grazing angle, φ, is less than the limit value given by equation (2).

3.4 *Partial reflection from the Earth*

On a smooth spherical Earth, one can consider the reflection mechanism as the reflection of a single incident ray from a single geometrical point. The entire surface however, contributes to the reflected signal with the major contribution coming from the surface Fresnel zones close to the geometrical reflection point.

The previous considerations of reflection from the surface of the Earth have assumed that the Earth is a smooth uniform sphere. Three non-ideal situations or combinations of them may be encountered in practice. The first case is that of a rough surface, i.e. a surface with irregularities which are not too large in comparison to a wavelength. Reflection from rough surfaces is described in greater detail in § 4.

The second case is that in which the reflection coefficient is non-uniform, i.e. its value varies with position on the surface. An example of this is a reflecting surface consisting of a lake surrounded by soil of low reflectivity.

The third case is that of a limited reflecting area. This occurs when buildings, trees, hills, etc. obstruct a line of sight path from either terminal to any region on the reflecting surface.

The concept of a reflection coefficient can still be used in these non-ideal cases if the reflection coefficient for a smooth spherical Earth is modified in order to account for the effects of these non-ideal surfaces.

An estimate of the reflected field can be obtained in the second and third cases by the method of physical optics. This approach generally makes use of image theory, Babinet's principle and Fresnel integration [Boithias, 1984]. The result of these calculations is a partial reflection factor, F, which is the ratio of the amplitude of the reflected field from the non-uniform surface to that reflected by a uniform surface.

From a purely theoretical viewpoint, F can have a value between zero and two. A value of two is obtained if only the first Fresnel zone located about the reflection is illuminated by the incident wave. In actual practice, in the majority of cases, F is found to have a value between 0.1 and 1.2.

3.5 *Effective reflection coefficient of a spherical Earth*

The effective reflection coefficient of a spherical Earth, including the effects of divergence and partial reflection, is:

$$R = FDR_0$$

4. Reflection from rough surfaces

In many practical cases, the surface of the Earth is not smooth. The reflection of radio signals from rough surfaces has been studied extensively [Beckmann and Spizzichino, 1963] but the complexity of the problem has prevented the development of engineering formulae which fully describe the reflection process.

One useful formula is a quantitative definition of the Rayleigh roughness criterion:

$$g = 4\pi(S_h/\lambda) \sin \varphi \tag{15}$$

where:

S_h: standard deviation of the surface height about the local mean value within the first Fresnel zone;

λ: free-space wavelength; and

φ: grazing angle measured with respect to a tangent to the surface.

In general, a surface can be considered smooth for $g < 0.3$. When the surface is rough, the reflected signal has two components: one is a specular component which is coherent with the incident signal, the other is a diffuse component which fluctuates in amplitude and phase with a Rayleigh distribution.

4.1 *Specular reflection coefficient for rough surfaces*

The specular component arises from coherent reflection, in the plane of incidence, from the Fresnel zones located about the geometrical reflection point. It can be described by a reflection coefficient $R_s = \rho_s R$ where ρ_s is a reduction factor which is model dependent. For slightly rough surfaces with a random height distribution:

$$\rho_s = \exp(-1/2\ g^2) \tag{16}$$

For very rough surfaces equation (16) tends to under-estimate ρ_s. Theoretical models which consider multiple reflections [DeSanto, 1981] agree with experimental data but require numerical integration techniques to compute.

A recent derivation of ρ_s for sea surfaces [Miller *et al.*, 1984] suggests that a better estimate is given by the expression:

$$\rho_s = \exp(-1/2\ g^2)\ I_0\,(1/2\ g^2) \tag{16a}$$

where I_0 is the modified Bessel function of zero order. This expression produces good agreement for measured sea surface reflection coefficients [Beard, 1961].

A simple approximate expression of this formula is the following:

$$\rho_s = \frac{1}{\sqrt{3.2x - 2 + \sqrt{(3.2x)^2 - 7x + 9}}} \qquad (16b)$$

where

$$x = 0.5\, g^2$$

4.2 *Amplitude of the diffuse reflection coefficient*

The diffuse component of the reflected signal arises from scattering over a large area with the major contribution coming from regions well outside the first Fresnel zone. The region contributing to the diffuse scatter is known as the "glistening surface". Signals are scattered from this surface without any preferential direction. It is possible to define a diffuse amplitude reflection coefficient:

$$R_d = \rho_d |R| \qquad (17)$$

where ρ_d is a coefficient which depends only on the surface irregularities.

There is no simple expression for ρ_d in the literature. It has a value of zero for a smooth earth. It has a maximum value for very rough surfaces and this upper limit depends on antenna directivity and the nature of the surface. For low directivity antennas over bare ground or the sea, it lies between 0.2 (−14 dB) and 0.4 (−8 dB) with a most probable value of 0.35 for very rough surfaces. For cases where the glistening surface is not fully illuminated because of high directivity antennas, screening or where surface vegetation introduces significant surface absorption, ρ_d is less than 0.2 and may be negligible.

Experimental measurements and theoretical analysis indicate that the diffuse component is statistically random with a Rayleigh distribution.

4.3 *Total reflected field*

Figure 3 illustrates the specular and diffuse reduction factors measured for a sea surface [Beard, 1961]. Equation (16) is also plotted in the figure. The total field above a reflecting surface is the resultant of the direct field, the coherent specular component and the random diffuse component. The resultant field has a Nakagami-Rice distribution. If it is assumed that the total forward scattered power is constant, then the relationship:

$$<\rho_s>^2 + <\rho_d>^2 = \text{constant} \qquad (18)$$

where $<\rho>$ indicates r.m.s. values, may be useful in estimating the reflected field. Antenna directivity must also be considered in computing this resultant field.

The reflection from rough surfaces is the subject of several theoretical studies. Unfortunately no convenient engineering formulae exist at present for estimating the multipath fading which results from this type of reflection, although significant progress has been made for sea surfaces at frequencies near 1.5 GHz [Karasawa and Shiokawa, 1984]. The methodology developed for this frequency is probably valid at lower frequencies and could be a basis for extension to higher frequencies.

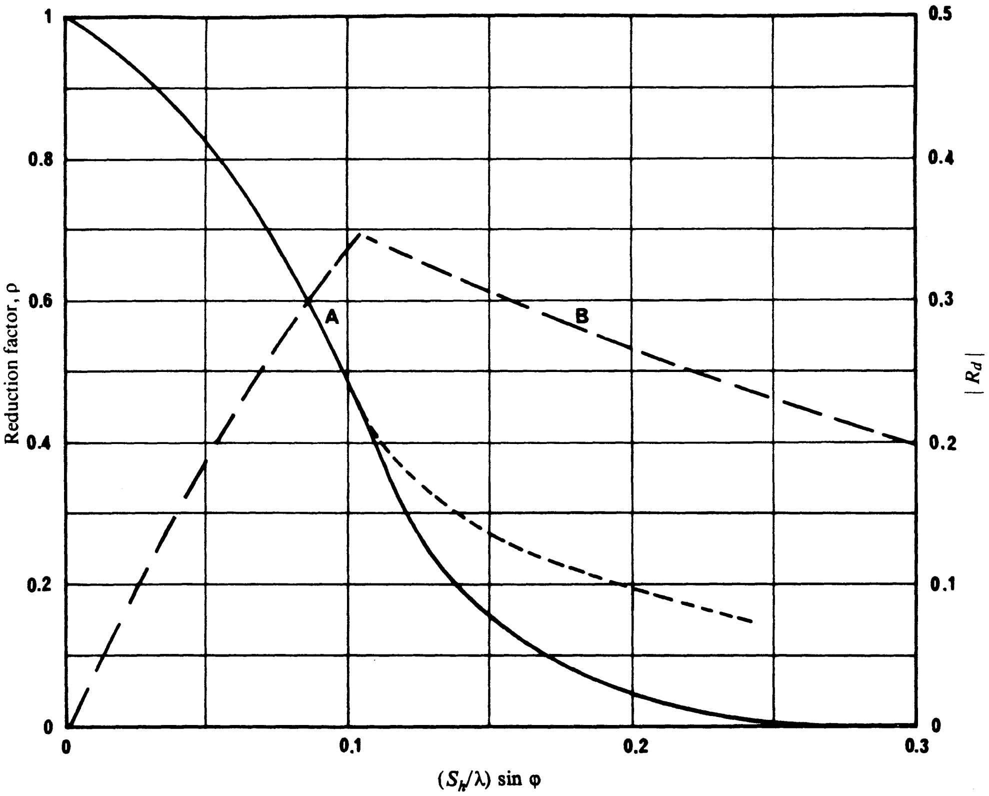


FIGURE 3 – *Reflection from rough surfaces*

Curve A is for the specular component. The solid line is calculated from equation (16).
The dashed line represents experimental data.
Curve B is an experimentally-measured diffuse reflection coefficient, R_d [Beard, 1961].

REFERENCES

BEARD, C. I. [1961] Coherent and incoherent scattering of microwaves from the ocean. *IRE Trans. Ant. Prop.*, Vol. AP-9, **5**, 470-483.

BECKMANN, P. and SPIZZICHINO, A. [1963] *The Scattering of Electromagnetic Waves from Rough Surfaces.* Pergamon Press, Oxford, United Kingdom.

BOITHIAS, L. [1984] *Propagation des ondes radioélectriques dans l'environnement terrestre, Collection Technique et Scientifique des Télécommunications*, 2nd edition, Dunod, Paris, France. English translation [1987] Radio-wave Propagation, McGraw Hill, New York.

DeSANTO, J. A. [November-December, 1981] Scattering from a rough interface. *Radio Sci.*, Vol. 16, **6**, 1021-1024.

FURNES, N. [1984] Practical results from FM broadcasting coverage in coastal areas and mountainous terrain in Norway. Use of methods to reduce or avoid propagation problems. *Telektronikk*, **1**, 57-78.

HALL, M. P. M. [1979] *Effects of the Troposphere on Radio Communication.* IEE Electromagnetic Wave Series, **8**, Peter Peregrinus Ltd., London, UK.

KARASAWA, Y. and SHIOKAWA, T. [June, 1984] Characteristics of L-band multipath fading due to sea surface reflection. *IEEE Trans. Ant. prop.*, Vol. AP-32, **6**, 618-623.

KERR, D. E. [1965] *Propagation of Short Radio Waves.* Dover Publications Inc., New York, NY, USA.

KRAUS, J. D. and CARVER, C. R. [1984] *Electromagnetics*, 3rd edition, McGraw-Hill Book Company, Inc., New York, NY, USA.

MILLER, A. R., BROWN, R. M. and VEGH, E. [April, 1984] New derivation for the rough-surface reflection coefficient and for the distribution of sea-wave elevations. *IEE Proc.*, Vol. 131, Part H, **2**, 114-116.

STOKKE, K. N. [1984] Problems concerning FM broadcasting in coastal areas and mountainous terrain. Methods to reduce the influence of such problems. *Telektronikk*, **1**, 44-56.