REPORT ITU-R P.2090

Measuring the input parameters for the radiative energy transfer model of vegetation attenuation

(2006)

1 Introduction

The radiative energy transfer (RET) theory allows an analytical calculation of the attenuation of a scattering medium, such as vegetation. Recommendation ITU-R P.833-5 details the RET-based model and gives the necessary input parameters for several tree species. However, if the vegetation is different to that found in Recommendation ITU-R P.833-5, one may derive the input parameters for RET from measurements. This Report details how to derive the RET parameters from a measurement.

2 RET input parameters

The RET requires six input parameters, four of which are specific for the scattering medium and two are geometry and system descriptors. The four medium dependent parameters need to be established experimentally and are dependent on the type of vegetation, frequency and state of foliation.

i) α, the ratio of the forward scattered power to the total scattered power;

ii) β, the beamwidth of the phase function;

iii) σ_τ, the combined absorption and scatter cross-section ($\alpha_a + \alpha_S$);

iv) W, the albedo;

v) $\Delta\gamma_R$, the beamwidth of the receiving antenna;

vi) d, the distance into the vegetation (m).

Parameters α and β are best determined by measuring the scatter function usually referred to as the "phase" function of the vegetation medium. The phase function characterizes the scattering behaviour of the medium at short distances after the air/vegetation interface. When the four RET parameters are extracted from the vegetation attenuation data only, the resulting parameters may be lacking in real physical properties of vegetation scattering in most of cases, even though the parameters could fit the measurement data well. So, it is strongly recommended that the phase function measurement must be performed whenever possible. Paragraph 3 describes the phase function measurements and the method of determining the parameters α and β in more detail. Parameters σ_τ and W can be determined from attenuation curve measurements into the vegetation medium as described in § 4.

3 Phase function measurements

The phase function forms an integral part in the determination of the parameters needed for the RET theory. This Report presents a guide outlining how to conduct phase function measurements. The main purpose of such measurements will be to extract parameters α and β required for the derivation of the RET model. The method of determining parameters α and β from measurement data is also described in this Report.

3.1 Choosing the measurement site

Phase function measurements are necessary to derive parameters α and β for the vegetation medium, which in turn enables RET modelling of excess attenuation in the medium. In many cases the phase function measurement will therefore be conducted in conjunction with measurements of the excess attenuation experienced in the vegetation medium as a function of vegetation depth. An ideal site will comprise of a group of trees, behind which receiver access at various depth locations is possible. The site requires a reasonable foreground clearance to enable the tree group to be illuminated by the transmitter, thus fulfilling the condition of a half space of vegetation, illuminated with an incident plane wave signal. Furthermore, the site needs to be free of objects that can cause spurious reflected signals to interfere with the scattered signal from the trees to the receiver location.

Phase function measurements combined with excess attenuation measurements, performed for a line of trees made up of the same tree species can jointly provide the RET parameters. The results can be used to develop a prediction model for the behaviour of excess attenuation as a function of vegetation depth.

3.2 Measurement geometry

The RET describes the energy transfer in a medium exhibiting both scattering and absorbing properties. This is treated by the RET as homogenous infinite half space. Both transmit and receive antennas are arranged to have a common volume irradiated in the scattering medium. Under these conditions the RET postulates a phase function with Gaussian shaped forward lobe and an isotropic background. The two parameters α and β, define the exact shape of the phase function, which for the vegetation medium is dependent on factors such as the species and density of vegetation and foliation state. The location at which the phase function is measured is also important. The RET predicts that the forward lobe broadens as the observation point moves inside the medium. This occurs due to the attenuation of the coherent component and the relative increase in the level of the isotropic scatter. This suggests that there is an optimum region within which the measurement should be conducted.

The following conditions are proposed for the measurement geometry:

i) The region in which the phase function measurement is carried out needs to lie within that defined by the initial predominately linear (dB scale) slope of the excess attenuation curve. A location two to three trees deep into the medium is recommended. This allows sufficient amount of scattering medium after the interface to be present to result in an isotropic back-scatter coherent forward lobe, without the widening of the forward lobe yet taking place.

ii) The assumption of homogeneity of the medium in the RET is more easily satisfied in the canopy region of the tree rather than that containing the trunk. A further benefit of largely confining the common volume to the canopy region accrues from the avoidance of strong diffracted and reflected signal components emanating from trunks and the ground. In single tree measurements of the phase function it was found that illuminating around 70% to 90% of the tree canopy yields good results. When groups of trees are considered, the transmit antenna vegetation distance should be fixed carefully. This distance, in combination with the transmit antenna elevation beamwidth, is utilized to ensure that ground reflections and diffraction components over the top of the canopy are minimized.

iii) The phase function forward lobe is aligned with the direction of propagation of the incident signal. It is therefore preferable to place the transmit and receive antennas at the same height. This also ensures normal incidence conditions. If the heights differ the phase function will be tilted with respect to the horizontal and the direction of incidence. The orientation of the receiver antenna as well as that of the axis of rotation needs to be adjusted accordingly. The beamwidth of the phase function is relatively narrow, so that tilts of a few degrees with respect to the receiver alignment will lead to significant reduction of the magnitude of the forward lobe and consequently the determination of α.

3.3 Antenna characteristics

3.3.1 Transmit antenna

The beamwidth of the transmit antenna needs to be wide enough to illuminate sufficient width and height of vegetation in order to provide, together with the receive antenna, sufficient excited common volume for the measurement. However the beamwidth must be, relatively speaking, narrow so as not to give rise to diffracted and reflected signal components, which will influence the measured phase function pattern.

3.3.2 Receive antenna

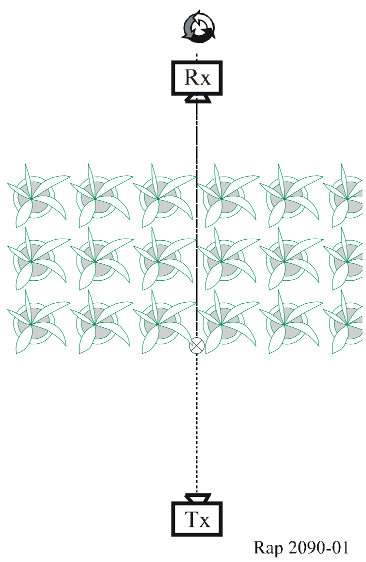
The receive antenna ideally has a very small beamwidth, in order to measure the relatively narrow beamwidth of the phase function itself. In practice a receive antenna of a few degrees beamwidth gives good results.

3.4 Receiver antenna displacement

The most practical and most accurate method to measure the phase function is to place the receiver antenna inside the vegetation medium at a distance from the air vegetation interface specified in § 3.2. At this location the receiver antenna needs to be rotated about its vertical axis in discrete increments; after each increment the signal level needs to be recorded. Since the beamwidth of the phase function is considered to be relatively narrow the antenna only needs to be rotated over a section of a circle, e.g. ±40° with respect to the line receiver – transmitter. The principal set-up is sketched in Fig. 1.

FIGURE 1

Principal measurement set up for phase function measurement



3.5 Link budget considerations

Apart from the free space loss due to the distance between transmitter and receiver the excess attenuation of the vegetation as well as the difference between forward lobe and isotropic back-scatter region of the phase function have to be considered. At millimetre and near millimetre frequencies the attenuation resulting from one large dense tree can be considerable, i.e. in the region of a few tens of dB. Even at 11 GHz a large horse chestnut tree in full leaf was found to give as much as 35 dB attenuation.

The difference between forward lobe and back-scatter regions of the phase function, is expected to be between 20 and 50 dB depending on the values of α. The measurement system must have sufficient dynamic range to overcome the strong initial excess attenuation due to vegetation, and the difference in level between the forward lobe signal and the back-scatter. As a guide the dynamic range of the receiver needs to be about 80 dB to yield the phase function shape and parameters.

3.6 Determination of parameters α and β

Parameters α and β can be determined from the measurement data via best-fit curve fitting. In order to extract parameters α and β, the following model of phase function needs to be calculated:

$$p(\theta) = \alpha f(\theta) + (1 - \alpha) \quad (1a)$$

where:

$$f(\theta) = \left(\frac{2}{\beta}\right)^2 e^{-(\theta/\beta)^2} \quad (1b)$$

Figure 2 illustrates the fitting of predicted phase function curve to measurement data.

4 Excess attenuation curve measurements

Excess attenuation curve measurements are obtained by measuring the signal level at various depths into the vegetation medium. The RET predicts a graph with an initially linear part (dB) and a transition region into a final attenuation rate. The slope of the initial slope is used to obtain parameter σ_τ. Whereas the transition region and the final attenuation rate are used to find parameter W (albedo) via best-fit curve fitting. In the case when phase function data are not available, parameters W, α and β must be determined by curve fitting.

4.1 Determination of parameter σ_τ using initial slope

The first term I_{ri} of the RET equation describes the initial slope of the attenuation function with distance z (m).

$$P = P_0 \cdot e^{-\sigma_\tau z} \quad (2)$$

where:

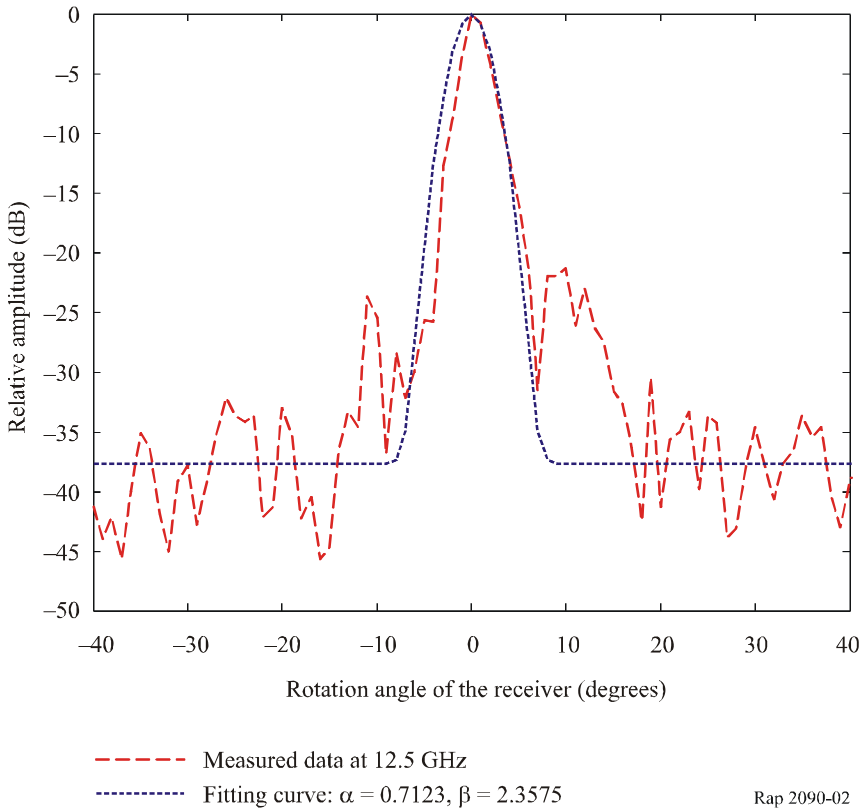
P: measured signal power inside the vegetation

P_0: power received at the incident air-vegetation interface.

The RET describes excess attenuation due to vegetation, so that the signal decay, due to free space loss, is not included in P.

FIGURE 2

Predicted and measured phase function vs. rotation angle



If the attenuation curve is displayed in dB, equation (2) can be written as:

$$10 \cdot \log \frac{P}{P_0} = -10 \cdot \log(\sigma_\tau z \log e) \qquad (3)$$

The initial slope of the graph (dB/m) is given by:

$$\frac{\Delta A}{\Delta z} = -4.43 \cdot \sigma_\tau \qquad (4)$$

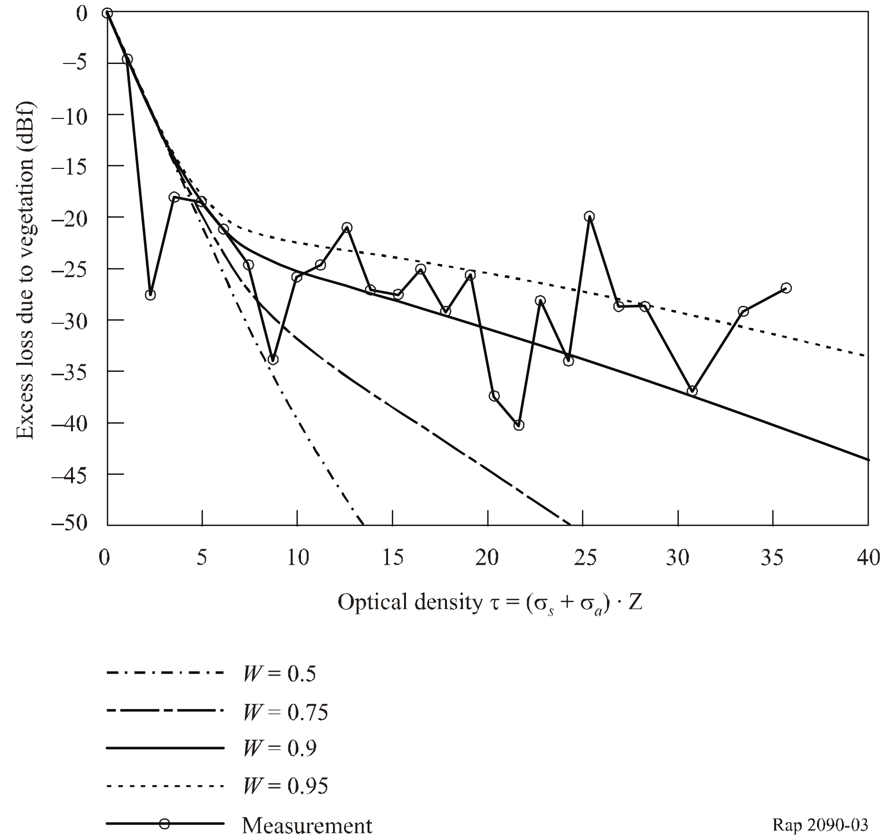
where A is the attenuation (dB).

4.2 Determination of parameter *W* (albedo) by curve fitting

Figure 3 illustrates the fitting of predicted attenuation curves with different albedos to measured excess attenuation.

FIGURE 3

Predicted and measured excess attenuation vs. optical density τ for different albedos



In order to model the RET attenuation curves the RET equation needs to be calculated. The RET equation is as follows:

$$\frac{P_R}{P_{\max}} = e^{-\tau} \qquad (I_{ri})$$

$$\left. \begin{aligned} &+ \frac{\Delta\gamma_R^2}{4} \cdot \{[e^{-\hat{\tau}} - e^{-\tau}] \cdot \bar{q}_M \\ &+ e^{-\tau} \cdot \sum_{m=1}^{M} \frac{1}{m!} (\alpha W \tau)^m \ [\bar{q}_m - \bar{q}_M]\} \end{aligned} \right\} \qquad (I_1) \qquad (5)$$

$$+ \frac{\Delta\gamma_R^2}{2} \cdot \{-e^{-\hat{\tau}} \cdot \frac{1}{P_N} + \sum_{k=\frac{N+1}{2}}^{N} [A_k e^{-\frac{\hat{\tau}}{s_k}} \cdot \frac{1}{1 - \frac{\mu_N}{s_k}}]\} \qquad (I_2)$$

where:

P_R: received power by the receiving antenna with its gain pattern

$P_{\max}$: received signal strength received in the absence of vegetation

$\Delta\gamma_R$: beamwidth of the receiving antenna

m: order of the term I_1.

The term I_1 is more accurately evaluated for higher values of m, however it will not change significantly for $m > 10$.

The following relations also apply:

$$\tau = (\sigma_a + \sigma_s) \cdot z$$

τ defines the optical density and z is the distance (m).

$$P_N = \sin^2(\frac{\pi}{2N}) \tag{6}$$

$$\hat{\tau} = (1 - \alpha W)\tau$$

The line in the RHS of equation (5) represents I_{ri}, which is usually referred to as the "*first*" term, whereas the sum of the second and third line give I_1, referred to as the "*second*" term. These appear in explicit form. The fourth line represents the "*third*" term I_2 of the RET equation, which contains the attenuation coefficients s_k and the amplitude factors A_k. These need to be determined numerically using the following expressions:

The attenuation coefficients s_k are determined by the characteristic equation:

$$\frac{\hat{W}}{2} \cdot \sum_{n=0}^{N} \frac{P_n}{1 - \frac{\mu_n}{s}} = 1 \tag{7}$$

where:

$$P_n = \sin\left(\frac{\pi}{N}\right) \cdot \sin\left(\frac{n\pi}{N}\right), \quad (n = 1, ..., N-1)$$

$$\hat{W} = \frac{(1-\alpha)W}{1 - \alpha W}$$ $\hat{W}$ is referred to as the reduced albedo.

The amplitude factors A_k are determined by a system of linear equations given by:

$$\sum_{k=\frac{N+1}{2}}^{N} \frac{A_k}{1 - \frac{\mu_n}{s_k}} = \frac{\delta_n}{P_N} \qquad \text{for} \qquad n = \frac{N+1}{2} \;....\; N$$

where:

$$\mu_n = -\cos\left(\frac{n\pi}{N}\right)$$

$$\delta_n = 0 \quad \text{for} \quad n \neq N$$

and:

$$\delta_n = 1 \quad \text{for} \quad n = N \tag{8}$$

The antenna gain beamwidth and the scatter function beamwidth in equation (5) have been assumed to be Gaussian, in which the main lobe of the power radiation pattern is reduced by 1/e. This angle is related to the 3 dB beamwidth by $\Delta\gamma_R = 0.6 \cdot \Delta\gamma_{3db}$.

4.3 Determination of parameter *W*, α and β by curve fitting, when phase function data are not available

When phase function data are not available, three parameters *W* (albedo), α and β must be determined from the measured excess attenuation data via best-fit curve fitting of equation (5). In this case, the extracted parameters may lack physical meaning as mentioned before.