Vertical backscatter profile of forests predicted by a macroecological plant model

Matthew Brolly a & Iain H. Woodhouse b

a Department of Geographical Sciences, University of Maryland, College Park, MD, 20742, USA
b School of Geosciences, The University of Edinburgh, Edinburgh, EH8 9XP, UK

Vertical backscatter profile of forests predicted by a macroecological plant model

Matthew Brolly and Iain H. Woodhouse

Department of Geographical Sciences, University of Maryland, College Park, MD 20742, USA; School of Geosciences, The University of Edinburgh, Edinburgh EH8 9XP, UK

(Received 25 July 2011; accepted 1 January 2012)

This study describes a new application of a macroecological model to describe the vertical profile of radar backscatter through forest canopy. Given layers of equally sized cylindrical scatterers, the model predicts that one layer within the forest canopy dominates the backscatter profile. This prediction is based on first-order theoretical approximations, in addition to results from a radiative transfer model parameterized by the macroecological model. This model is used to pre-empt specific backscatter trends with results predicting that Rayleigh and Optical backscatter follow negative and positive exponential trends respectively when plotted with respect to backsattering coefficient and branching level through the canopy. A maximum value is predicted by the model associated with the branching level located at the transitional zone between Rayleigh and Optical scattering. This finding follows directly from the size density distribution within a forest combined with dramatic reductions in cross-sectional trends exhibited through the transition. It is a result unrelated to resonant scattering or the effects of penetration depth. The feasibility of describing radar interactions using geometric optics is explored when limits are imposed on the physical optics scattering solution.

The findings offer a significantly new way of understanding the distribution of scattering from differently sized elements in a canopy, and challenge the widely held assumption that backscatter–biomass relationships saturate due to increased opacity of the canopy.

1. Introduction

In Woodhouse (2006b), it was described how the macroecological plant model described by West, Brown, and Enquist (1997) could be used to parameterize a radar backscatter model, with the aim of predicting trends in backscatter and height as a function of vegetation biomass. This approach provided a new framework for making the random volume over ground (RVoG) (Treuhaft and Siqueira 2000) model incrementally more realistic.

The aim of this article is to consider how this macroecological approach to simplifying forest structure can describe the vertical profile of the backscatter response. The vertical profile is important in determining the relationship between scattering phase centre and forest height (Sarabandi and Lin 2000), in the modelling of polarimetric interferometry (Lavalle et al. 2009), and in radar tomography (Cloude and Papathanassiou 2003, 2008; Cloude, Brolly, and Woodhouse 2009).

*Corresponding author. Email: m.brolly@sms.ed.ac.uk; mbrolly@umd.edu

ISSN 0143-1161 print/ISSN 1366-5901 online
© 2013 Taylor & Francis
http://dx.doi.org/10.1080/01431161.2012.715777
http://www.tandfonline.com
2. The forest structure model

The macroecological model used is the ‘general model for structure and allometry of plant vascular systems’ (WBE) developed by West, Brown, and Enquist (1997, 1999). The WBE model has roots in a macroecological approach to explain allometric scaling law origins (Niklas 1994), later modified to describe plants with branching architectures. Despite some important limitations, this model has key advantages, making it an appropriate first-order linkage between simple backscatter modelling and models of biological function.

The WBE model is also generically based on the constraints of biomechanics and resource distribution. The generic nature means that it can adequately describe ‘tree-like’ branching that results as a consequence of underlying biophysical constraints of fluid flow and rigidity (unlike fractal scaling models), but as a consequence of its genericness it is not well suited for describing the properties of specific species.

3. Plant structure from the WBE model

The advantages and disadvantages of using WBE for radar backscatter studies have been discussed in depth in Woodhouse (2006b) and are not repeated here. We also take from this work the rationale for considering a range of empirical values of many key variables, rather than relying solely on generalized macroecological predictions favoured by West, Brown, and Enquist. For completeness, however, the main power-law relationships are summarized below.

3.1. Generalized allometric predictions

The WBE model characterizes geometric plant structure through a number of power laws derived from biological and biomechanical considerations of resource distribution within the plant (West, Brown, and Enquist 1997, 1999; Enquist, Brown, and West 1998; Enquist et al. 1999).

The model uses five variables to describe the size and number of branch elements of a tree: (1) a scaling factor, \( a \), determining how radii of branches change, or scale, within the plant; (2) the branching ratio, \( n \), the number of daughter branches derived from one parent; (3) the length-to-radius constant of proportionality; (4) the radius of the leaf petiole, \( r_N \); and (5) the number of branching levels, \( N \). In actual trees, all five of these parameters lie within a small range of values, and are likely species-specific. In broadleaf species, \( N \) is likely to be related to the tree age and is the only variable that would normally change over time. The age of conifers should perhaps be more appropriately represented by increasing \( n \), with older branches producing a greater number of daughters, but further development of WBE would be required for full incorporation of such a trend.

The WBE branching network runs from the trunk (level 0) to the leaf petiole (level \( N \)) (see Figure 1), with an arbitrary level in the plant branching network denoted by \( k \). Note, however, that we might expect biomechanical properties of tilted branches in the canopy to differ from those of vertical stems. The value of \( n \) is typically 2 for broadleaf (decurrent) species, and larger (up to 5 or more) for conifers (excurrent). Within empirical studies, and specifically within the literature on modelling radar backscatter, the value of \( a \) ranges from 2/3 to 4/3, with outwith values occurring very rarely, and are usually stem allometry associated (Zianis and Mencuccini 2004; Woodhouse 2006b). For excurrent trees, the value of \( a \) in the branching structure is often approximately 2/3, representing geometric similitude, but stems can be better represented by some value greater than 7/6, similar to the case of...
stress similarity related to $a = 4/3$. Note that a value of $a = 2/3$ coincides with geometric similitude models of plant structure, consistent with many observations of conifers (Niklas 1994), but not dicots, which are more appropriately described by the elastic similarity model, $a \approx 1$. Values of $a > 1$ for stems are also suggested by other empirical data (Zianis and Mencuccini 2004). When the scaling factor is $a = 1$, this describes the special case of the area-preserving ‘pipe model’ (Shinozaki et al. 1964), whereby the plant is described by tightly packed pipe bundles.

### 3.2. Branch length

The WBE model utilizes biomechanical constraints that predict some optimal relationship between branch length, $l$, and radius, $r$, such that

$$l_k \propto r_k^{2/3a}.\tag{1}$$

The stem level is represented by $k = 0$, so that $l_0$ represents trunk height, and $r_0$ its radius (assumed to equate to half diameter at breast height (dbh) in field studies).

### 4. Modelling strategy

Using branching descriptions given in the previous section, it is possible to model a tree canopy as $N$ levels of branching cylinders, going from $k = 0$ to $k = Z$, as shown in Figure 1. The WBE model can then be used in one of two ways. First, it is possible to make a first-order estimate of backscatter trends with height using some approximations based on whether the cylinders lie in the Rayleigh or Optical scattering domain. Second, the WBE model can be used to parameterize a full multi-layered radiative transfer model to predict backscatter response.

#### 4.1. First-order estimate of trends

In this case, we consider the backscatter trends as a function of branching level, $k$. If we further assume that the length at each branching level is indicative of layer depth, we can also consider the trends as a function of height, $z$. Note, however, that while $k$ need not correlate directly with $z$, it will tend to correlate with depth into crown, such that smallest elements are located on outer parts of the crown. The crown shape itself is not described
Let us consider two extreme cases: (1) where the branch cylinders lie completely in the Rayleigh scattering domain, and (2) where they lie entirely in the domain of Optical scattering. Although these theories were developed for spherical elements, the Rayleigh, Optical, and Mie theories can be used with other fundamental shapes such as ‘spheres, plates, cylinders and the like’ (Woodhouse 2006a). Previous work by Karam and Fung (1988) suggested that the generalized Rayleigh–Gans (GRG) approximation would be appropriate for the consideration of infinite cylinders, but it is also clear in this work that the trends remain the same between both the Rayleigh approximation and the GRG with the radiative transfer model used in this work regarding the scatterers as ‘infinite cylinders’. In the Rayleigh case we assume that the backscatter from each cylinder increases with the square of the volume (Smith and Ulander 2000), while for Optical it increases with the physical cross section (Kononov and Ka 2008). At the transition between these regimes lies Mie scattering – here we make an approximation that assumes that resonant behaviour ‘averages out’ across this region giving the cumulative effect of a distribution of branch sizes, an assumption supported by empirical results in Crispin Jr. and Maffett (1965), Lopes et al. (1991), and Mougin et al. (1993).

WBE allows us to address the relative contribution to the backscatter from the different branching levels as both branch size and number density vary. In both Rayleigh and Optical scattering, the backscatter is greater for larger cylinders, as both area and volume will be larger, but for any given canopy the number density increases as the cylinders get smaller. Higher in the canopy, there are a greater number of smaller scatterers. The dominating factor must then be determined: is it the increase in the size of scatterers or the decrease in their number that dominates the backscatter? As this study is grounded firmly on the importance of backscattering trends, the following equations are presented as a series of proportionality. The coefficients are as outlined by the WBE model parameters.

For Rayleigh scattering, the total radar cross section (RCS), \( \sigma_{k,\text{Rayleigh}} \), of the \( k \)th branch level, which has \( N_k \) elements, is given by the square of the branch volume at that level, \( V_k \), multiplied by the number of branch elements:

\[
\sigma_{k,\text{Rayleigh}} \propto N_k V_k^2.
\] (2)

Using the relationship between length and radius of Equation (1), we can then write the proportional relationship using the already introduced variables and manipulate as follows:

\[
\begin{align*}
\sigma_{k,\text{Rayleigh}} &\propto N_k r_k^4 \frac{1}{a} \\
\Rightarrow \sigma_{k,\text{Rayleigh}} &\propto N_k r_k^4 (12a+4)/3a \\
&\propto n^{-k(6a−1)/3}.
\end{align*}
\] (4)

The relationship \( r_k = r_N r_n^{(N-k)n/2} \) can then be introduced, which is a rewritten expression from WBE, recognizing \( r_N \), \( r_0 \), and \( n \), the number of daughter branches from any parent, to be constant for any individual tree allowing the expression for \( \sigma_{k,\text{Rayleigh}} \) to become

\[
\sigma_{k,\text{Rayleigh}} \propto n^{-k(6a−1)/3}.
\] (4)
The trend for Rayleigh scattering is shown here as an inverse exponential of branching level, $k$, governed by $n$, the number of daughter branches, and $a$, the scaling parameter. The maximum backscatter originates from the largest branches, with size dominating over number density when all branches are in the Rayleigh scattering regime. This result is most amply illustrated by very high frequency (VHF) radar measurements, whereby the stems of the trees dominate the backscatter response. While this derived result could be taken for granted, it should be noted that, theoretically at least, a branching structure could exist with $a = 1/6$, meaning that the backscatter contribution would be equal for all branching levels. However, we have not yet encountered evidence for such a low value of $a$.

In a similar manner, the scenario whereby the radii of all the branches are large enough for the cylinders to scatter completely in the Optical region is now considered. In this case, the RCS, $\sigma_{k,\text{Optical}}$, for level $k$ scales with the physical cross section:

$$
\sigma_{k,\text{Optical}} \propto N_k A_k
\Rightarrow \sigma_{k,\text{Optical}} \propto N_k r_k l_k
\propto r_0 r_k^{2/a} r_k^{(3a-4)/3a}
\Rightarrow \sigma_{k,\text{Optical}} \propto n^{k(4-3a)/6}.
$$

Here we assume a sufficiently thin canopy, that occlusion is insignificant, and that geometric optics applies.

Again this is an exponential trend, but positive as a result of number density exerting greater influence than increasing cylinder sizes. For complete Rayleigh scattering the maximum contribution is at $k = 0$ (the stem), whereas for complete Optical scattering the maximum contribution is at $k = N$, with the majority of the scattered energy coming from the smallest branch elements at the top of the canopy. This corresponds to the common understanding that at short wavelengths, backscatter is dominated by smaller elements and is influenced more by number density. (Note that this is the case even when canopy density is low and attenuation is negligible.)

However, this need not always be the case – the Optical exponent is significantly smaller so that the effect is not as dramatic, and reduces as $a$ gets larger, such that it will be independent of $k$ when $a = 4/3$, and negative thereafter. Again we have not found sufficient empirical evidence to suggest values of $a$ larger than 4/3 for trees, although investigations by Chave, Riera, and Dubois (2001) and Zianis and Mencuccini (2004) have published values that slightly exceed 4/3 based on previously published data. The expression ultimately shows that under normal circumstances, within forests with regard to Optical scattering, the number density has the dominant effect on backscatter.

In both cases, the result is an exponential trend of total backscatter per branching level, but with opposite signs (for $1/6 < a < 4/3$) such that in the general case there will be a stage whereby the top of the canopy is still in the Rayleigh scattering region but the lower, larger branches have entered the Optical region. The combined effect is one branching level that dominates the scattering. When canopy opacity is low, this dominant level will correspond to the layer where the radii of the branches lie within the Mie scattering region. This result is in keeping with the established understanding of backscatter from forests – that scattering is dominated by a particular branch size in the Mie region defined as $0.1 \lambda < 2\pi r < 10\lambda$, where $\lambda$ is the wavelength (Woodhouse 2006a; Moosmuller and Arnott 2009). Note, however, that here the result follows directly from the size density distribution combined with dramatic reduction in cross section from Rayleigh to Optical,
and is not related to ‘resonant’ scattering or penetration depth. This presents a new way of understanding the distribution of scattering from differently sized canopy elements.

4.2. Geometric optics assumptions

In this section, we provide further justification for the use of a simplified geometric optics approach to modelling the trend in backscatter from a cylinder. The physical optics formula for the RCS of a cylinder, \( \sigma^0_{cyl} \), is shown below, where \( k \) is the wave number, \( r \) is the cylinder radius, \( l \) is the cylinder length, and \( \theta \) represents the incident angle from broadside:

\[
\sigma_{cyl}^0 = kr^2 \cos^2 \theta \left[ \frac{\sin(kl \sin \theta)}{kl \sin \theta} \right]^2. \tag{6}
\]

By taking an average value over a symmetric window of incidence angles centred at \(-\theta_w \leq 0 \leq \theta_w\), the average RCS of a cylinder becomes the integral:

\[
\overline{\sigma}_{cyl}^0 = \frac{1}{\theta_w} \int_{0}^{\theta_w} kr^2 \cos^2 \theta \left[ \frac{\sin(kl \sin \theta)}{kl \sin \theta} \right]^2 d\theta. \tag{7}
\]

As this window approaches zero, the small-angle approximations of \( \cos \theta = 1 \) and \( \sin \theta = 0 \) apply, and following a change of variable and subsequent integration we get the closed-form formula for the average RCS of a cylinder around broadside (Equation (8)) (see also Hestilow 2000):

\[
\overline{\sigma}_{cyl}^0 = \frac{rl}{\theta_w} \left[ \text{Si}(2kl\theta_w) - \frac{\sin^2(kl\theta_w)}{kl\theta_w} \right]. \tag{8}
\]

According to the rules of the sine integral function \( \text{Si}(x) \), as the argument \( x \) approaches zero, \( \text{Si}(x) \) will tend to \( x \). Similarly, by taking the limit of the angular window tending to zero, we can rewrite Equation (8) as below:

\[
\overline{\sigma}_{cyl}^0 = \lim_{\theta_w \to 0} \frac{rl}{\theta_w} \left[ \text{Si}(2kl\theta_w) - \frac{\sin^2(kl\theta_w)}{kl\theta_w} \right] = \frac{rl}{\theta_w} [2kl\theta_w - kl\theta_w] = kr^2. \tag{9}
\]

Where the window tends to zero and is approximately representative of the broadside angle, the average RCS is proportional to the frequency and the cylinder volume. But in the limit of large arguments where \( 2kl\theta_w \) is large, the value of the function \( \text{Si} \) tends to \( \pi/2 \). Under the limits of \( kl\theta_w \) tending to infinity (Equation (10)) we can write the equation for average RCS of a cylinder as in Equation (11):

\[
\lim_{kl\theta_w \to \infty} \frac{\sin^2(kl\theta_w)}{kl\theta_w} \to 0, \tag{10}
\]

\[
\overline{\sigma}_{cyl}^0 = \frac{\pi rl}{2\theta_w}. \tag{11}
\]
This frequency-invariant equation is then a function of the physical cross section of the cylinder in accordance with geometric optics. A full analysis of the working is found in Hestilow (2000).

4.3. Attenuation considerations

As a forest matures, the dominant layer rises higher in the canopy, with additional growth concentrated in the lowest branching levels, specifically in the stem. When forest thinning maintains a constant forest basal area, the upper part of the canopy does not change with forest growth as increasing branch numbers for individual trees are exactly balanced by decreasing tree numbers. The result is that saturation on backscatter biomass plots could occur not because of increasing opacity, but because of the biophysical constraints of forest growth combined with Rayleigh–Optical transitions. The role attenuation plays in this work is considered negligible and is visualized in Figure 2 consisting of a high- (20 layers) and low-attenuation (13 layers) example, with similar trends being exhibited independent of frequency. Similarly in Figure 3, where attenuation varies by reducing the number of trees present. In each case, penetration is monitored to ensure transmission through each layer. Visualizing the role of attenuation is necessary due to the inbuilt attenuation considerations found in radiative transfer models when energy is transmitted to deeper lying layers, as shown in Figure 4, where backscatter from a series of uniform layers is modelled. The effects of layer attenuation are shown here to enforce the understanding that the vertical backscatter trends exhibited in this work will not be driven by attenuation, with other factors clearly playing a part.

4.4. Radiative transfer modelling

RT2 (Cookmartin et al. 2000), a multi-layer second-order radiative transfer model (similar to the MIMICS (Michigan Microwave Canopy Scattering) model used in Imhoff (1995) and the UTACAN (University of Texas at Arlington CANopy scattering model) model used in Woodhouse and Hoekman (2000)), was used to investigate trends in vertical backscatter profiles relative to different WBE-associated values, with an emphasis on $a$, at the P band (0.7 m).

![Figure 2. P-band HH backscatter from 20- and 13-layer forests. Trends remain the same with respect to branch radii although when compared with the branching layer the trend differs due to the dominant radius being located on different branching levels when scaling is varied.](image-url)
Figure 3. P-band HV (Horizontal transmit, vertical receive) polarization backscatter from each branching level of forest consisting of 18 branching levels with initial planting densities of 10,000 and 50,000 ha⁻¹. Trends remain regardless of planting density.

Figure 4. HV polarization P-band backscatter variation in the presence of seven identical branching layers in terms of numbers and size. Attenuation from each layer results in reduced backscatter from the lowest layers.

RT2 is a fully polarimetric, second-order solution to the radiative transfer equations that treats vegetation canopy as a plane-stratified multi-layer region over a rough surface. In this model, simple geometric forms are used, for example, plant stems are represented as finite-length cylinders, while leaves can be modelled as plane-circular or elliptical discs. The multi-layer facet of this package allows differently sized cylinders to be positioned on different layers in accordance with the WBE model structure. For the branches and stems in this instance, scatterer shapes are cylinders based on the ‘infinite cylinder’ scattering solution with uniform axial distribution. The branches also have spherical distribution.

Each layer of the RT2 model comprised equal-sized, randomly oriented cylinders parameterized by WBE for a given $n$ (which determines branching rate) and $a$ (which determines subsequent size scaling of branches). This includes the stems ($k = 0$), with
the comparison between vertical and non-vertical stems and their effect on the backscatter also considered (and identified to produce higher volume backscatter when oriented non-vertically but with negligible effect on important trends). Each layer in RT2 corresponds to a branching layer in WBE. The petiole radius, the dielectric properties of each cylinder, and the constant of proportionality all remain fixed with a radar incidence of 25° used throughout. Note that in this study, the contribution from the ground is ignored since interest lies only in the vertical profile through the canopy, not total backscatter.

The result of parameterizing RT2 using WBE is that total backscatter can be broken down into contributions from different branching levels and therefore heights within the canopy. This is shown in Figure 5, in which it is shown how backscatter with respect to height matches with the theoretical contributions of Optical and Rayleigh scattering derived from Equations (4) and (5). In this scenario, the theoretical Optical backscatter appears to be the main contributor at levels below $k = 4$, corresponding to the lowest branching levels and largest branches. At heights above $k = 4$, the contribution is Rayleigh dominated, hence the shape of the RT2 response as a function of branching level with the gradient of the Rayleigh section matching closely with the modelled solution based on (4).

A similar relationship is seen for the VHF band shown in Figure 6(b), where again, distinctive contributions to the backscatter are associated with Rayleigh and Optical scattering. In both Figures 5 and 6(b), the peak backscatter contribution originates at the branching level and height corresponding to the interception of the theoretical Rayleigh and Optical scattering contributions. As we know, there exists a region of Mie scattering between these scattering regimes. We assume that this region averages out due to its periodic behaviour with respect to the size of the object and wavelength; we then define this point as the transition from Rayleigh to Optical scattering. This result supports the theoretical prediction that this transition is the most probable cause, and location, of a dominant scattering layer. Figure 7 shows the dominant height, branching radius, and branching level, illustrating that the dominant radius location reduces in height within the canopy when the incident frequency is reduced, with the relationship between backscatter and the ratio of wavelength to scatterer size being a relationship of mutual dependence. Within the WBE model, this indicates that the dominant radius will become larger with an increasing wavelength. The resultant backscatter distribution among the branching levels for the VHF band of 50 MHz

![Figure 5](image)

Figure 5. P-band backscatter as a function of branching level and height showing the vertical profile of scattering cross section for a relatively sparse forest case. Theoretical Optical and Rayleigh trends from Equations (4) and (5) are included using arbitrary units. RT2 modelling results are shown for HH and HV polarizations as a function of the branching level, $k$. HV results are also shown as a function of normalized height in the canopy, based on height being proportional to the length of branching level.
Figure 6. RT2 model results for (a) X-band and (b) VHF SAR data parameterized using WBE under identical scaling parameters (different from Figure 2). Theoretical Optical and Rayleigh trends from Equations (4) and (5) are included using arbitrary units.

Figure 7. Multi-frequency backscatter analysis as a result of particular branch radii occupying branching levels and dominating backscatter. The branching radius of the dominant branching layer reduces with the reduction in incident wavelength.

shows that the dominant branching layer appears to be at the branching layer 0 but does not identically match the theoretical description of Rayleigh scattering.

In Figure 6(a), it is shown that there is no contribution to the backscatter from Rayleigh scattering due to the minimum size of the branching elements used in the modelled forest with respect to the wavelength of the X band (0.03 m). The minimum branch size, the petiole radius, is 0.0015 m in comparison with the expected Rayleigh–Mie transition radius of
As a consequence of this, the Rayleigh relationship of (4) has no contribution to the backscatter, a fact that does not escape inspection in Figure 6(a). The lack of transition from Rayleigh to Optical scattering does not indicate that backscatter saturation effects will not occur with respect to volume but simply that the initial Rayleigh scattering component will be absent. Modelling of much smaller scattering elements reveals the existence of the dominant branch size at the X band and likewise for larger branches at VHF (see Figure 7), which also includes P-band data. The absence of a dominant scattering layer in a natural setting may be due to multi-age or multi-species stand composition.

For the 10 GHz (X-band) case (Figure 6(a)), the opposite relationship to that of VHF is seen, with the HH (horizontal transmit, horizontal receive) modelled data matching the theoretical representation of Optical scattering. In this case, the dominant scattering level is clearly the highest branching level appearing to contain little contribution from Rayleigh scattering with the ratio of wavelength to branch radius at this frequency such that the smallest branches of the forest are completely within the Optical scattering regime.

The effect of the scaling parameter on the vertical backscatter distribution is investigated in Figure 8 and is such that the larger the scaling parameter the higher the location of the dominant branching level. Within the vertical profile, this suggests that the branching radius of dominance remains the same irrespective of the overall forest scaling parameter value, a result verified through multiple simulations and shown as a function of radius in Figure 7. One consequence of varying the scaling parameter is that the number density per unit volume of the branches at a similar branching level will differ, although for each modelled backscatter response the number of branching elements in a particular branching level will remain the same due to the constant value of \( n \). The number density per unit volume will vary in such a way that it will be lower for the larger branch length increments incurred by lower scaling parameters. This is a consequence of the WBE relationship of Equation (1). Several planting densities have been trialled through this study ranging from 50 to 500,000 trees per hectare with the same conclusions evident. Typical basal areas of investigation are around 30 m\(^2\) ha\(^{-1}\) (Chave, Riera, and Dubois 2001).

![Figure 8. RT2 model results for P-band SAR parameterized using WBE, backscatter trends shown against branching level at a large planting density of 100,000 trees per ha. Backscatter values show trends and not absolute values. Theoretical trends for Optical and Rayleigh contributions from Equations (4) and (5) are included using arbitrary units. Results are shown for scaling parameters \( a = 2/3, a = 1, \) and \( a = 4/3 \). Stem dbh and height for \( a = 1 \) are 0.096 and 11.800 m, respectively; for \( a = 2/3 \), they are 0.030 and 1.350 m, respectively; and for \( a = 4/3 \), they are 0.30 and 34.87 m, respectively.](image-url)
The peak backscatter response in the 429 MHz (P-band) case corresponds to the branching layer with a radius of approximately 0.010–0.015 m lying within the expected transition from Rayleigh to Optical scattering with regard to the approximate limits of the Mie scattering regime stated as \(0.1\lambda < 2\pi r < 10\lambda\) (Woodhouse 2006a; Moosmuller and Arnott 2009), with the transition to Mie scattering from Rayleigh scattering in the region where \(2\pi r\) is approximately \(0.1\lambda\). The value 0.011 m would therefore satisfy the radius value in the equation \(kr/0.1 = 1\) for the P band. For 10 GHz (X band) the expected radius value is smaller than the petiole radius (0.0015 m) used in this study, whereas for 50 MHz (VHF band) this value would be in the region of 0.09 m. For any given modelled canopy, as a forest develops, the dominant layer becomes higher in the canopy since further additional growth takes place mostly in the lowest branching levels. Note that when \(a = 1\), and the basal area remains constant as volume increases (signifying a forest in balance with its resources, \(d = 2\) (Woodhouse 2006b)), the upper part of the canopy does not change with growth so that the number density of the dominant layer remains constant with increasing biomass. However, when the rate of thinning is such that the basal area increases, or for a scaling parameter less than 1, the canopy properties change, with the upper layers progressively becoming denser, increasing the proportion of Rayleigh scatterers.

5. Predictions and implications

This work offers one key prediction: that backscatter will be dominated by a single scattering layer, resulting from the transition from Rayleigh to Optical scattering. For the low-opacity case, the trends are exponential relationships, but with opposite signs – for Rayleigh scattering the backscattered power decreases with depth into the canopy, whereas for Optical scattering it decreases with height. Once the largest branching elements encroach upon the Optical regime, results indicate a single dominant scattering level. Both trends are governed by the scale parameter and are based on an assumption that backscatter for each layer scales as the number density multiplied by the square of the cylinder volume for Rayleigh scattering or by the physical cross-sectional area for Optical scattering.

An important follow-up use of this model would be to explicitly consider the impact of number density variations on the height profile since a high thinning rate would reduce canopy opacity and therefore influence penetration depth through the canopy. One important implication of this work is that it may offer an explanation for the varieties of behaviour observed in standard radar backscatter–biomass plots. In some cases, there are transitions from positive to negative correlations, following apparent ‘saturation’ in the literature for X-, C-, and L-band data in Ranson et al. (1997) and Rauste et al. (1994) and less obviously (but still apparent) in Baker et al. (1994), Imhoff (1995), and Dobson et al. (1992). Elsewhere, Ranson et al. (1997) observed an increasing positive correlation with the P band beyond the widely recorded saturation limit of 100–200 t ha\(^{-1}\) (tonnes per hectare). It is proposed that these patterns are a result of the backscatter being dominated by a single scattering layer, which can change as canopy number densities vary, influencing not only the total backscatter, but also the penetration depth due to increasing attenuation.

Explicit empirical data revealing synthetic aperture radar (SAR) vertical profiles of forests are largely unavailable, with SAR tomography producing the closest and most relevant comparison data (Reigber and Moreira 2000). An example of this is given in Cloude, Brolly, and Woodhouse (2009), where RT2 data are used in a SAR coherence tomography investigation. The main differences between the methods of this study and those of other empirical studies regarding vertical profiles is that backscatter intensity alone is used here...
for profile definition while vertical profile data using SAR typically have inherent assumptions of the nature of the vertical profile embedded using models such as RVoG (Mette, Papathanassiou, and Hajnsek 2004), which is not required here.

6. Conclusions

Sensitivity at longer wavelengths to deeper, larger elements in a forest canopy need not happen because of resonance (larger elements always scatter more), nor need it be related to opacity (penetration depth) of the canopy. The particular sensitivities appear to relate to the balance of an individual element’s cross sections and number densities at each branching level. The geometric construction of a tree is such that the number density of branching elements is greater at higher levels and decreases with canopy depth, inverse to increasing branch size. The level of this increase can be described by macroscopic scaling properties.

Simulations involving the RT2 radiative transfer model at several planting densities and using multi-frequency measurements correspond with the theory that a dominant scattering level is present due to transition in scattering from Rayleigh to Optical caused by the increase in the size of branching elements with canopy depth and a switch in dependence from number density, with regard to Optical scattering, to size, with regard to Rayleigh scattering. This holds true for the majority of typical microwave frequencies used in forestry applications but different situations exist at the extremes such as for VHF (Fransson, Walter, and Ulander 2000). In the case of VHF, branching elements are believed to predominantly scatter in the Rayleigh regime due to the large wavelength to branch radii ratio. On the other hand, the relationship at high-frequency bands such as C or X will always be dominated by Optical scattering by the smallest scatterers on the canopy top surface.

Explicit 3D forest models for canopy scattering exist in the literature such as shown in Disney, Lewis, and Saich (2006), Woodhouse, Wallington, and Turner (2006), and Marino et al. (2008). In this study, we have not considered explicit 3D modelling of the backscatter, with only backscatter relative to height levels considered (i.e. horizontal homogeneity but vertical variability). The modelling methods chosen in this study have been implemented to primarily emphasize the change in backscatter intensity resulting from size and number density variations with height. By not considering horizontal variability across the structure we remain consistent with the RVoG approach used in polarimetric interferometry and similar simplified approaches.

This work opens up the possibility for future investigations into the use of SAR backscatter profiles for specific forest structural analysis. These profiling techniques could then be used to distinguish between typical forest structures related to forest biomes whether tropical, temperate, or boreal.

References


