VHF-BAND SAR FOR FOREST STEM VOLUME APPLICATIONS

Lars M.H. Ulander(1), **Johan Fransson**(2), **Anders Gustavsson**(3), **Gary Smith**(4) **and Fredrik Walter**(5)

(1)Swedish Defence Research Agency (FOI), P.O. Box 1165, SE-581 11 Linköping, Sweden, Email: ulander@foi.se

(2) Swedish University of Agricultural Sciences (SLU), Department of Forest Resource Management and Geomatics,
SE-901 83 Umeå, Sweden, Email: Johan.Fransson@resgeom.slu.se

(3)As (1) above, but Email: andgus@foi.se

(4)Chalmers University of Technology, Department of Radio and Space Science, SE-412 96 Göteborg, Sweden,
Email: smith@rss.chalmers.se

(5)Dianthus, Sommarstigen 13, SE-961 32 Boden, Sweden, Email: Fredrik.Walter@Dianthus.nu

ABSTRACT

VHF-band SAR holds great promise for forest stem volume mapping. The paper describes a coherent scattering model and demonstrates that radar backscattering is mainly proportional to stem volume in coniferous forests. The model is also used to develop inverse methods. It is noted that a sloping ground may change the backscattering significantly and therefore needs compensation. Results of stem volume retrieval using the CARABAS-II SAR (20-90 MHz, HH-polarisation) are shown for several coniferous forests including both flat and topographic areas. The rms error is about 20% when compared with ground truth.

INTRODUCTION

There is strong interest in applying remote sensing techniques in forestry, i.e. techniques which are able to provide relevant forest information in a cost-efficient manner. The main commercial application is mapping for the timber industry which needs data for forest planning and inventory. The most important parameter is stem volume, i.e. trunk volume per unit area which includes bark but excludes branches and stumps. Ultimately, the objective is to identify and characterise individual trees in terms of their volume, diameter, height, species, vitality *etc*, but this will certainly involve a multi-sensor approach. A related environmental application is to monitor changes in carbon stock, which is important for global climate change since it directly affects atmospheric concentrations of CO_2 and other greenhouse gases. The UN Kyoto protocol is an example of an international agreement where nations have committed themselves to reducing greenhouse gas emissions and where changes in forest carbon stock is of major concern.

Synthetic aperture radar (SAR) has a number of attractive benefits for forestry. Firstly, it provides high-resolution images with high quality independent of clouds, fog, rain and time of day. Secondly, it provides its own source of illumination and thus controls viewing conditions which facilitates detection of changes such as growth, thinning, and storm damage. However, traditional radar frequencies in the microwave region do not provide useful information on trunk geometry since the wave is strongly attenuated and most radar backscattering originates from the upper canopy layers. The forest becomes increasingly transparent by lowering the radar frequency [1-3]. When the frequency is reduced even further, i.e. when the wavelength becomes larger than the diameter of the trunk, the trunk scattering is in the Rayleigh regime and the amplitude becomes proportional to the trunk volume. This condition requires the radar wavelength to be in the metric wavelength band.

POLARIMETRIC RADAR SCATTERING MODEL

Several models have been used to understand the radar backscattering from forests in the lower VHF-band. Early work followed the developments in the microwave band, in particular the MIMICS model based on radiative transfer theory. However, omission of the in-phase addition of the ground-trunk and trunk-ground contribution in this model motivated the development of a coherent scattering model [4]. Multiple scattering effects were also investigated by comparing single scattering models with numerical models, e.g. finite-difference time-domain (FDTD). It was concluded that multiple scattering effects are small for a typical forest geometry except for the ground reflection component. A new model based on the distorted Born approximation was therefore developed [5-6] which we summarise in the following.

Consider a vertical trunk standing on sloping ground as illustrated in Fig. 1. The planar air-ground interface has normal unit vector, and the ground-trunk interaction is modelled by treating the ground as a reflecting dielectric half-space. This approximation neglects higher-order terms but numerical experiments have shown that it is an accurate model for typical tree geometries [4]. The model therefore has four different components, i.e. direct backscatter from the trunk, trunk-ground specular scattering, ground-trunk specular scattering, and scattering from the ground, backscattered from the trunk and reflected by the ground. Thus, the total scattering matrix for the trunk can be written as the coherent addition of four scattering matrices

$$\mathbf{S} = \mathbf{S}\left(\hat{\boldsymbol{k}}_i, \hat{\boldsymbol{k}}_s\right) = \mathbf{S}_t + \mathbf{S}_{gt} + \mathbf{S}_{tg} + \mathbf{S}_{gtg} \tag{1}$$

where the subscripts *t* and *g* represent scattering from the trunk and reflection from the ground, respectively.

Each scattering matrix can be expressed in terms of the far-field scattering matrix of the isolated trunk, $\mathbf{S}^0$, and the reflection matrix for the ground surface, Γ, as [7]

$$\begin{aligned}
\mathbf{S}_t &= \mathbf{S}^0\left(\hat{\mathbf{k}}_s, \hat{\mathbf{k}}_i\right) \\
\mathbf{S}_{gt} &= e^{i\tau_s}\Gamma\left(\hat{\mathbf{k}}_s, \hat{\mathbf{k}}_{sg}\right)\cdot \mathbf{S}^0\left(\hat{\mathbf{k}}_{sg}, \hat{\mathbf{k}}_i\right) \\
\mathbf{S}_{tg} &= e^{i\tau_i}\mathbf{S}^0\left(\hat{\mathbf{k}}_s, \hat{\mathbf{k}}_{gi}\right)\cdot \Gamma\left(\hat{\mathbf{k}}_{gi}, \hat{\mathbf{k}}_i\right) \\
\mathbf{S}_{gtg} &= e^{i(\tau_i+\tau_s)}\Gamma\left(\hat{\mathbf{k}}_s, \hat{\mathbf{k}}_{sg}\right)\cdot \mathbf{S}^0\left(\hat{\mathbf{k}}_{sg}, \hat{\mathbf{k}}_{gi}\right)\cdot \Gamma\left(\hat{\mathbf{k}}_{gi}, \hat{\mathbf{k}}_i\right)
\end{aligned} \tag{2}$$

where

$$\hat{\mathbf{k}}_{gi} = \hat{\mathbf{k}}_i - 2\hat{\mathbf{n}}_g\left(\hat{\mathbf{n}}_g \cdot \hat{\mathbf{k}}_i\right) \text{ and } \hat{\mathbf{k}}_{sg} = \hat{\mathbf{k}}_s - 2\hat{\mathbf{n}}_g\left(\hat{\mathbf{n}}_g \cdot \hat{\mathbf{k}}_s\right) \tag{3}$$

In the backscattering direction, where $\mathbf{k}_s = -\mathbf{k}_i$ and $\mathbf{k}_{sg} = -\mathbf{k}_{gi}$, reciprocity requires that $\mathbf{S}_{gt} = \mathbf{S}_{tg}$ and we will refer to the sum of these scattering matrices as a dihedral scattering term, $\mathbf{S}_{gt} + \mathbf{S}_{tg} = 2\mathbf{S}_{tg}$. When adding the scattering matrices coherently, the phase changes τ_i and τ_s due to the different optical path lengths must also be included.

The model used for calculating the scattering matrix of a tree trunk is a dielectric cylinder with radius, a, length, l, and relative dielectric permittivity ε_r. The bistatic scattering matrix for a finite-length cylinder is computed using the infinite cylinder approximation. For long thin cylinders, however, the generalized Rayleigh-Gans (GRG) approximation provides a simple analytical model that is useful for interpreting the results. In this approximation, the scattering matrix elements of the cylinder are given by [8]

$$S^0_{pq}\left(\hat{\mathbf{k}}_s, \hat{\mathbf{k}}_i\right) = V\left(\frac{\varepsilon_r - 1}{\varepsilon_r + 1}\right)\frac{k^2}{4\pi}\left[2(\hat{\mathbf{p}}\cdot\hat{\mathbf{q}}) + (\varepsilon_r - 1)(\hat{\mathbf{p}}\cdot\hat{\mathbf{z}})(\hat{\mathbf{z}}\cdot\hat{\mathbf{q}})\right]\,\mu\left(\hat{\mathbf{k}}_s, \hat{\mathbf{k}}_i\right) \tag{4}$$

where V is the volume of the cylinder, $\hat{\mathbf{q}}$ and $\hat{\mathbf{p}}$ are the transmit and received polarisations, and $\mu(\mathbf{k}_s, \mathbf{k}_i)$ is the modifying function

$$\mu\left(\hat{\mathbf{k}}_s, \hat{\mathbf{k}}_i\right) = sinc\left(\frac{kl}{2}\left(\hat{\mathbf{k}}_s - \hat{\mathbf{k}}_i\right)\cdot\hat{\mathbf{z}}\right) \tag{5}$$

where $sinc(x) = \dfrac{\sin(x)}{x}$, and the conditions of validity for the GRG approximation are $k \cdot a << 1$, and $l/a > 20\sqrt{\varepsilon_r}$.
Note that the scattering matrix is proportional to trunk volume V and frequency squared which is a characteristic of Rayleigh scattering. For horizontal polarisation, only the first term within brackets in (7) contributes. Both terms contribute for vertical polarisation. In the specular direction, $\mu = 1$, so that the radar cross-section is determined by the cylinder volume, and hence is the same for all shapes considered. However, the width of this main scattering lobe (and the form of the sidelobes) is determined by the modifying function. For cylinders which are short compared to the wavelength the main lobe will be wide, while longer cylinders at higher frequencies will have a narrower peak centred on the forward scattering cone.

For a tree inside a forest, the incident and scattered waves are also attenuated by the surrounding forest canopy. The forest canopy may be modelled as a layered dielectric, where the effective propagation constants can be calculated using the effective field approximation (EFA) [9]. For an azimuthally isotropic medium, the characteristic waves correspond to vertical and horizontal polarizations, and their associated propagation constants, k_p, for the direction, $\hat{\mathbf{k}}$, are given by

$$k_p' = k + \frac{2\pi}{k}\left\langle \rho\, \mathbf{S}_{pp}^0\left(\hat{\mathbf{k}}, \hat{\mathbf{k}}\right)\right\rangle \tag{6}$$

where ρ is the volume number density of scatterers, and $\langle\ \rangle$ represents ensemble averaging over the scatterer properties (permittivity, size, orientation and number density). The attenuation and phase delay caused by propagation in this effective medium can then be modeled by including the transmissivity matrix. The EFA is used to compute the effective propagation constants, which indicates that the 2-way power loss for vertically polarized waves is of the order of 10 dB for high stem volumes, compared to about 1 dB for horizontal polarisation. The high attenuation for vertical polarization tends to counter the stronger scattering for this polarization, so that the net backscattering is similar for both horizontal and vertical polarisation.

A scattering model which can be compared with SAR measurements must also account for the imaging process. This means including changes in the scattering by averaging over bandwidth and aperture angle. It is particularly important for CARABAS-II VHF-band SAR [10] since the fractional bandwidth is large (~ 0.8) and the aperture wide (~ 90º). A comparison between the model and SAR measurements for an old forest on sloping ground is shown in Fig. 2. The different data points correspond to measurements of a sloping forest stand from four orthogonal flight tracks. The solid line is the full scattering model whereas the dot-dash line is a simplified model where essentially polarisation effects are neglected [6]. The measurements and model are in good agreement.

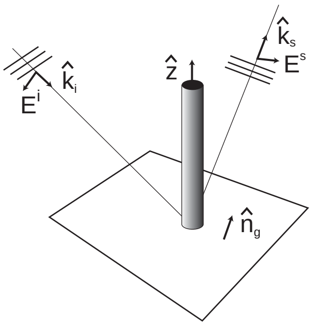

Figure 1. Radar scattering geometry of a vertical cylinder on a flat and sloping ground surface.

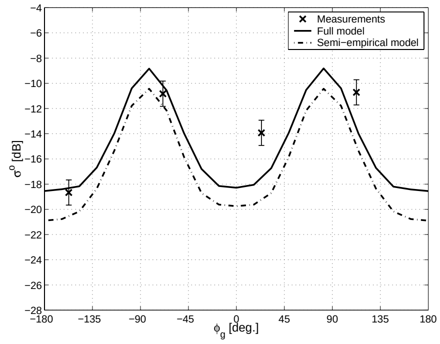

Figure 2. Comparison of measurements with the distorted Born model. The following parameters apply: stem volume 620 m^3/ha, tree height 34 m, ground slope 12º. The horizontal axis is azimuth angle with 0º corresponding to the ground sloping towards the radar.

The scattering model shows that the effect of sloping depends on the azimuth angle and tree height. For small trees, or long wavelengths, the ground slope effects are small since the modifying function is always close to unity. Significant azimuthal variation appears when the ground slope exceeds the width of the modifying function, i.e. dihedral scattering lobe in the specular direction. However, analysis has shown that the slope sensitivity can be minimised by careful selection of the radar line-of-sight. An experiment was therefore performed to investigate whether stem volume could be retrieved in a topographic area based on this observation.

STEM VOLUME MAPPING IN A TOPOGRAPHIC AREA

The test site chosen for the topography study was the Tönnersjöheden research forest park in southern Sweden [2]. The park consists mainly of Norway spruce (*Picea abies*) with a wide spread of stem volumes up to about 700 m^3/ha. Standwise field measurements were carried out in 1998-2000, including both a subjective and an objective inventory. The latter is based on systematic statistical sampling which results in predictable confidence limits, whereas the former is based on visual estimations in combination with a limited set of measurements. The standard error for the subjective measurements is difficult to determine but a typical value is 20-30% of the estimated stem volume. The objective inventory in Tönnersjöheden has a much smaller standard error, i.e. 10% of the stem volume.

The CARABAS-II SAR collected data along several flight tracks over Tönnersjöheden in 1999, see Fig. 3. A DEM was used to compute average ground slopes and values up to 25º were found in the analysed stands. Backscattering amplitudes were determined for each stand in order to minimise topographic effects. Results from the data analysis are shown in Fig. 4. A good correlation is obtained between backscattering amplitude and the objective inventory of stem volume. The deviation from the resulting linear regression is 67 m^3/ha (RMSE).

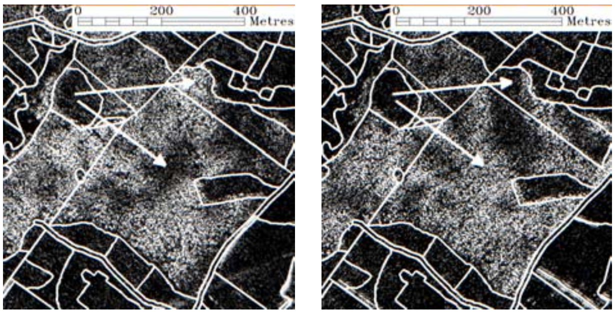

Figure 3. CARABAS-II images for a densely forested area in Tönnersjöheden with stand borders shown. A comparison of the two images shows that apparent within-stand variations of high and low backscatter are reversed when imaged from an orthogonal direction.

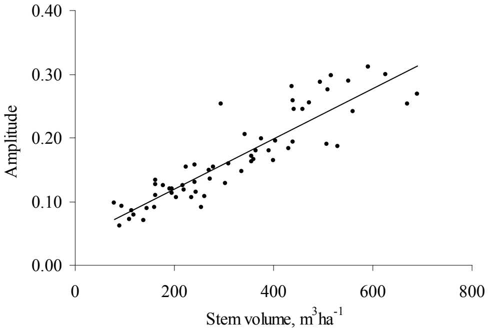

Figure 4. Backscattering amplitude against stem volume for 60 objectively inventoried spruce stands, with corresponding fitted regression function. The RMSE is 67 m^3/ha.

CONCLUSIONS

The advent of VHF-band SAR during the last decade provides new and promising forest mapping capabilities. The technique is based on the fact that tree trunks are Rayleigh scattering objects when their diameter is much less than the radar wavelength. A coherent scattering model based on the distorted Born approximation has been developed and verified with measurements. The model demonstrates that backscattering in this frequency band is mainly proportional to trunk volume. The model has also been used to develop methods for retrieval of stem volume using CARABAS-II SAR which operates in the 20-90 MHz band. Comparison with ground truth over horizontal as well as sloping ground gives a rms error of about 20%.

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