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Three-dimensional X-band SAR imaging of a small conifer tree

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Abstract. High spatial resolution 3-D SAR imagery was recorded by the UK's Natural Environment Research Council GB-SAR Microwave Measurement Facility at the University of Sheffield. *X*-band *VV* polarisation measurements were made using a near-field monostatic imaging system inside an anechoic chamber. The measurement process employs vector network analyser techniques to sample backscattered signals over a 2-D aperture, allowing a 3-D reconstruction of a target. This technique is used to provide a detailed 3-D map of the spatial scattering behaviour of a small Colorado Blue Spruce tree (*Picea pungens glauca*). The images produced are at a sufficiently high spatial resolution (~5 cm) that individual plant components can be discerned. An ability to select any volume pixel from within the target allows features in the microwave reconstruction to be readily associated with structures in the tree. The scattering behaviour associated with the uppermost set of branches shows it to be dominated by scattering from the branch tips.

1. Introduction

The use of Synthetic Aperture Radar (SAR) in the remote sensing of our environment has seen major developments during the 1990s. SAR offers an important tool in the monitoring of forestry and agriculture (Lim *et al.* 1989, Dobson *et al.* 1995), which is the particular concern of this work. However, effective use of the data requires proper understanding of the interaction between the radar wave and vegetation. Current understanding is largely based on theoretical models that involve considerable generalisations and simplifications about plant canopies and scattering within them. It is therefore important to assess how far these models provide an accurate, or at least viable, description of the scattering process. Scatterometer measurements provide useful information on the gross interaction of a radar wave with a target (Ulaby *et al.* 1981). Conventional SAR measurements of vegetation in the laboratory can provide very detailed 2-D maps of a target's scattering behaviour (Morrison and Bennett 1996, Brown and Bennett 1999), but are ambiguous as to where in a target's volume the scattering arises. To characterise the target unambiguously requires a complete 3-D mapping of its spatial scattering pattern. An Inverse

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SAR (ISAR) technique has been used previously to obtain a 3-D image of a conifer tree between 1–5.5 GHz (Fortuny and Sieber 1999); this, however, is the first report of a SAR technique and at the higher frequency of 8–12 GHz.

2. Measurements

SAR imaging was carried out in a 6 m × 4 m × 3 m microwave anechoic chamber. To emulate a SAR configuration, a quasi-monostatic transmit-receive horn antenna was located on a high-precision two-axis roof scanner, which was elevated so as to illuminate the target at an appropriate geometry. The antenna was connected via coaxial cables to the ports of a Hewlett Packard 8720D vector network analyser. A schematic of the scanning geometry for the measurements is shown in figure 1. The target was a small Colorado Blue Spruce tree (*Picea pungens glauca*), shown in figure 2. The tree has a height of 83 cm and maximum width of 84 cm. The data were collected over an aperture of 98 cm × 98 cm, at spatial intervals of 1.75 cm in both the X and Y dimensions. At each position the discrete frequency response of the target was measured at 20 MHz steps over the bandwidth 8–12 GHz. Whilst each point on the target is viewed over a range of angles as the synthetic aperture is constructed, we describe the viewing in terms of the inclination angle from the centre of the aperture to the centre of the target measured from the vertical. An angle of 23° was used, representative of the geometry favoured by some remote sensing satellites such as ERS. It is convenient to consider the collected data as a superposition of plane waves, each fixed in frequency but variable in X and Y, in order that the principles of plane-to-plane backward propagation can be exploited for the image reconstruction (Sherman 1967, Goodman 1968, Shewell and Wolf 1968, Bennett and Morrison 1996). The reconstructions are presented with spatial resolutions of ~ 5 cm in X, Y and Z.

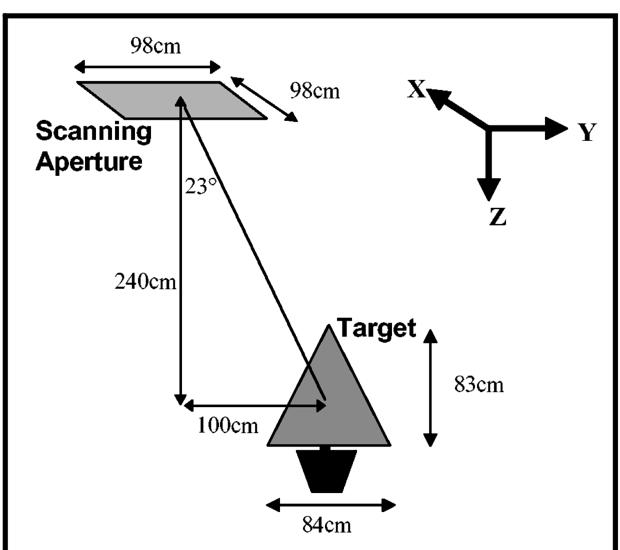

Figure 1. Schematic of the set-up used for the imaging experiments. The antenna looked down and forward at 23°.

Figure 2. Front face-on view of *Picea pungens glauca.*

3. Results

The 3-D backscatter pattern of the tree is presented in figure 3 as a series of horizontal slices down through its volume. The high resolution and ability to select any pixel from within the image volume allows features in the microwave reconstruction to be associated with the physical attributes of the tree. By reference to figure 2 we can interpret the features seen in the microwave imagery; the uppermost slice contains only the leading vertical branch of the tree, as we move down through the tree we can see the area of backscatter broaden commensurate with the tree's structure. Of particular interest is the return from the lowest slice. There appears to be a large area towards the back of the tree from which there is no return, but which actually corresponds to a region of dense growth on the tree. A similar, though weaker, feature is seen in the next slice up. These effects arise due to the attenuation of the signal as it passes through the tree. This attenuation is most acute for the greatest path length through the tree, which is the lowest part of the tree on the far side from the scanner. Knowledge of the spatial scattering and extinction patterns for natural targets is likely to be increasingly important with the development of interferometric coherence techniques for DEM generation and retrieval of vegetation height (Fortuny *et al.* 1999). The low-level features apparent at the edges of the slices detached from the main body of the returns are artefacts unrelated to the target.

Figure 4 presents reconstructions along vertical slices through the centre of the tree, aligned along the X and Y directions—the left-hand image again clearly shows the lack of return from the lower part at the back of the tree due to attenuation. Although the vertical profiles of figure 4 laterally bisect the leading vertical branch, it appears in the imagery as an isolated spot above the main body of the tree. Further

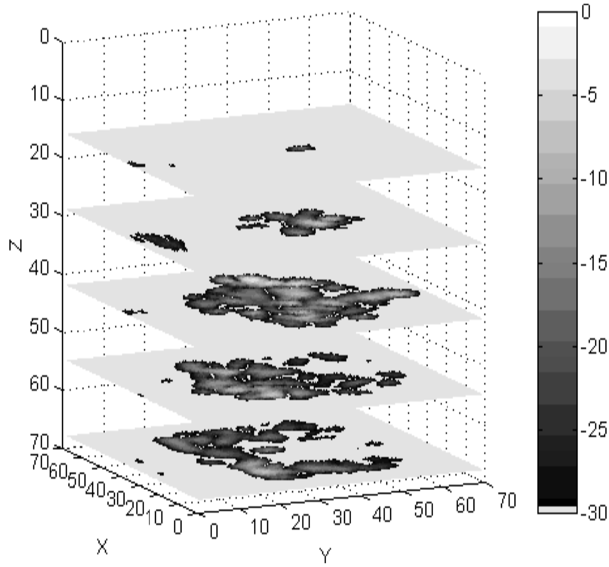

Figure 3. The 3-D imaging for the tree as a series of horizontal slices, displayed over a 30 dB dynamic range. The scales are in units of the spatial sampling (1.75 cm) used in the scanning process.

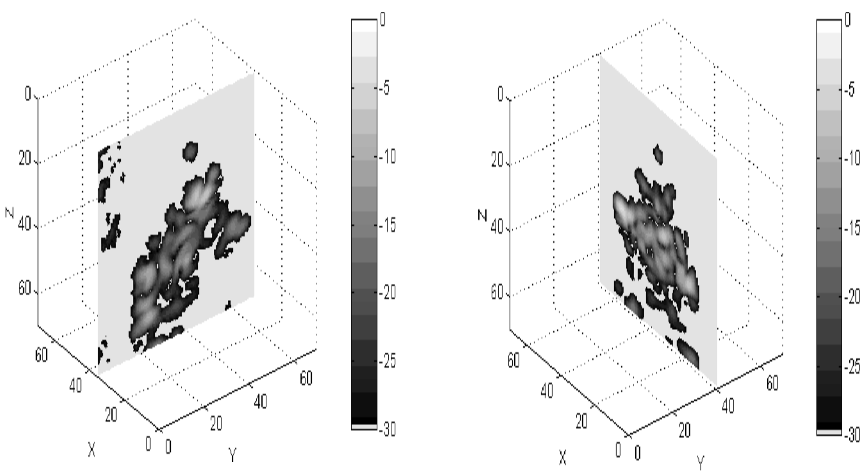

Figure 4. Reconstructions showing vertical slices through the centre of the tree, displayed over a 30 dB dynamic range. The front face of the tree is aligned along the *X*-direction. The scales are in units of the spatial sampling (1.75 cm) used in scanning process.

investigation shows the spot is spatially coincident with the branch tip, whereas the length of the branch itself produces little return. The top of the tree consisted of the leading vertical branch surrounded by a ring of eight branches with orientations close to 45°. In support of the result for the leading vertical, figure 5 shows the close correspondence between the measured positions of the branch ends and the bright points in the microwave imagery. This is what is expected if the branches behave like long thin rods, where the branches are long compared to the wavelength used.

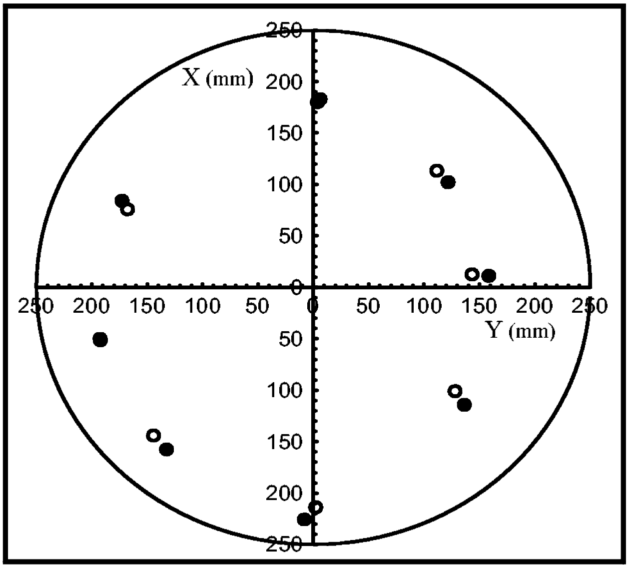

Figure 5. Radial plot comparing measured branch-end positions (solid circles) with those from the microwave imagery (open circles).

The rods will have narrow backscatter patterns that only provide significant backscatter from the body of the rod back to the antenna at angles close to broadside. Consideration of the imaging geometry suggests therefore, that there will be little return from the body of a branch. Instead, the return is dominated by scattering from the ends of the branches which can be expected to give a return over a large angular range.

4. Conclusions

The work described here has demonstrated a powerful technique for measuring the 3-D spatial scattering characteristics of a complex target at very high-resolution. This greatly enhances the viewer's appreciation of the spatial dependence of the target's scattering behaviour The reconstructed 3-D scattering map of a small conifer tree was of sufficient resolution that individual plant components could be resolved within the target volume. Indeed, close examination of the 3-D scattering behaviour associated with the uppermost set of branches showed it to be dominated by scattering from the branch tips, understandable if the branches are seen as long thin rods by the radar wave. The technique will be of great value in the understanding of radar-vegetation interactions, both to check the validity of extant scattering models and to develop the next generation of models.

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