Quantifying the biomass of Australian subtropical woodlands using SAR inversion models

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Abstract – **This paper presents an approach to quantifying the biomass (crown and stem) and structure of mixed species woodlands in Australia that is based on an inversion algorithm for SAR data. When applied to AIRSAR data acquired in 2000 over selected woodlands in Queensland, a close correspondence with ground-based estimates of biomass was observed.**

1. INTRODUCTION

In Australia, remote sensing data are increasingly required to facilitate quantification of the biomass (carbon) sources and sinks associated with the clearance, degradation and regeneration of forests and woodlands. Data relating to woodland structure are also important for assessing habitat quality. For lower biomass woodlands in Queensland, empirical relationships established with SAR backscatter at different wavelengths and polarisations have indicated that biomass may potentially be retrieved [1]. However, more recent studies using AIRSAR data acquired over central Queensland have confirmed that these relationships are complicated by the diversity of structures associated with different species and growth stages, particularly at higher biomass levels. The use of SAR for retrieving information on the structure of woodlands is also limited when empirical approaches are considered. For these reasons, this research investigated the inversion of a numerical closed-form forest scattering model for quantifying woodland biomass and structure.

2. FIELD AND REMOTE SENSING DATA

The study focused on a 60 x 40 km area of mixed species woodlands near Injune, central Queensland. Across the study area, large scale (1:4000) stereo colour aerial photographs (LSP) and both LIDAR and Compact Airborne Spectrographic Imager (CASI) data (1 m nominal spatial resolution) were acquired (in July and September, 2000, respectively) over 150 Primary Sampling Units (PSUs) arranged on a 4 km grid. Four strips (~ 15 x 80 km) of polarimetric AIRSAR (POLSAR) data were also acquired over the grid.

Each 150 x 500 m PSU was divided into 30 50 x 50 m Secondary Sampling Units (SSUs), giving a total of 4500 for the entire study area. Interpretation of the LSP for the PSUs confirmed that the majority of woodlands were dominated or co-dominated by the softwood species White Cypress Pine (*C. glaucophylla*) and the hardwood species Poplar Box (*Eucalyptus populnea*), Silver-leaved Ironbark (*Eucalyptus melanaphloia*) and Smooth barked Apple (*Angophera leiocarpa*). Brigalow (*Acacia harpophylla*) and Sandalwood Box (*Eremophila mitchelli*) were also common, particularly in regenerating woodlands. Typically, these species were found in combination, with *C. glaucophylla* and *A. leiocarpa* dominating the higher biomass woodlands. Over 50% of woodlands contained within the area of the PSUs supported an above ground biomass of 100 Mg ha^{-1}.

Within 34 SSUs considered representative of the main woodland communities and regeneration stages, measurements relating to structure and species/community composition were recorded over the period of remote sensing data acquisition. Destructive harvesting was also undertaken to generate new allometric equations for estimating the total and component (leaf, branch and stem) biomass of common species or evaluate those that already existed [2]. A more detailed description of the sampling methods can be found in [3].

3. MODEL PARAMETERISATION

To simulate and verify the SAR return from these woodlands at different frequencies and polarisations and to identify dominant scattering mechanisms, an existing numerical discrete-component forest scattering model developed at JPL [4] was used. The model input parameters, which relate to the geometric and dielectric properties of the woodlands, were derived from a combination of woodland inventory and harvesting data. Specifically, the above ground and component (leaf, branch and trunk) biomass of all trees measured in each of the 34 SSUs was estimated using existing allometric equations or those established on-site. These estimates were subsequently summed and scaled to give a biomass density (Mg ha^{-1}). Individual trees of the dominant species that supported a leaf, branch and stem (trunk) biomass approximating the average for that species within each SSU were then identified. Where available, digital photographs were viewed to establish whether the structure of the selected tree approximated that of trees of similar size and species within the SSU. All trees of that species contained with the SSU were then assumed to be identical in terms of their geometric and dielectric properties. Tree stems were assumed to have vertical orientation and their density was based on the number of individuals of the selected species within the SSU.

For the main species, the radius, length, orientation (and exponent of the probability density function) of small (< 1 cm) and large (> 1 cm) branches was established from field measurements and analysis of ground photographs of individual trees. For each species, leaf length/width and thickness was determined from digital photographs and field measurements respectively.

The number of branches (small and large) and leaves was estimated by dividing the biomass of these components summed at the plot level (for all trees) by the biomass of each component (e.g., an individual leaf). The density of these components (# m^{-3}) was then calculated by dividing their number by the volume of the canopy layer (m^3). The parameterisation ensured that the product of the biomass of individual components (i.e., leaves, branches, trunks) equated approximately to the biomass of these components as estimated for all trees within the SSUs. The dielectric properties of the soil and vegetation were also determined from knowledge of soil type (clay/sand) and measurement of the moisture content of soil and vegetation (obtained through destructive harvesting).

4. SIMULATION RESULTS

To first establish how well the forward model performed using the calculated input parameters and to determine the dominant scattering mechanisms, AIRSAR backscatter data (C-, L- and P-band) were extracted from SSUs contiguous with and supporting the same woodland community classification and similar biomass as the SSU sampled in the field. For this purpose, all 4500 SSUs were classified according to species composition, as established through interpretation of stereo aerial photography. For SSUs not sampled in the field, biomass was estimated using relationships between total biomass and frequency of lidar returns within selected height intervals [3]. The comparison confirmed a close correspondence at most frequencies and polarisations between simulated and actual SAR backscatter. There were, however, some mismatches observed especially at HV polarizations in C-band over sparse canopies where backscatter from the ground surface was significant. The reason is the simple treatment of ground backscatter in the forest model, which does not include a cross-polarized component.

The model was used first to simulate the SAR channels primarily responsible for volume scattering from the crown. These are generally all C-band polarizations and L-band HV. The decision is made by first performing a three-component scattering classification to determine the dominant scattering mechanisms at each frequency and polarization. The volume scattering simulations consisted of successively varying (to acceptable degrees) the input parameters relating to the crown layer (e.g., crown depth, stem/crown density, and crown component moisture content). Parametric families of curves relating the magnitude of these parameters to the SAR return at different frequencies and polarizations were then established, and fitted with higher-order (generally 4th order) multi-dimensional polynomials to produce closed-form representations of the complex numerical scattering process.

A similar set of polynomials was established for double-bounce scattering mechanism, which involves the stem height, diameter, dielectric constant, as well as soil dielectric constant and root mean square (rms) roughness. Example polynomials surfaces established for woodlands dominated by the coniferous trees are illustrated in Figure 1.

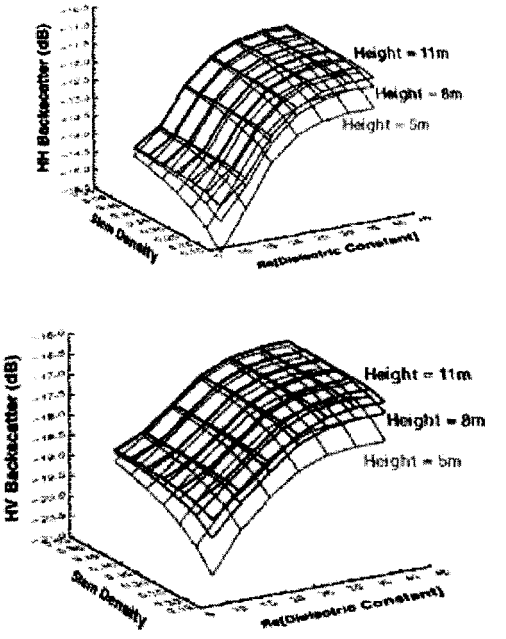

Figure 1: Examples of SAR backscatter simulations for woodlands dominated by conifers. Shown here are C-band HH and HV backscatter for various canopy height, stem density, and crown component dielectric constants.

5. INVERSION

For inversion, C-, L- and P-band backscatter coefficients were extracted from the AIRSAR data for woodlands of the same type as those represented by the selected SSUs. Estimates of free variables were then obtained through an algorithm that produces the optimal variable resulting in the best match between SAR measurements and the closed form polynomial model. In particular, C-band data were used to estimate crown layer characteristics (e.g., branch densities and moisture contents). These estimates were then used to simulate their contribution at lower frequencies, thereby allowing the backscatter to be adjusted such that only stem and ground effects remained at these lower frequencies and subsequently the generation of a closed-form model with fewer variables for inversion of the lower vegetation layer. L and P band data were used to estimate stem and ground variables (e.g., stem moisture content). Based on the resulting data layers derived through the modelling process, and by applying known ratios of wet to dry biomass for key species, spatial estimates of total and component biomass were generated, examples of which are given in Figures 2 and 3.

6. VALIDATION

For the selected SSUs, a correspondence was observed between the variables of crown/stem density, crown depth and total (sum of crown and stem) biomass mapped through the inversion of the actual AIRSAR data and these same variables mapped through integration of field data with finer spatial resolution lidar and CASI data. Quantitative comparisons are still being performed .

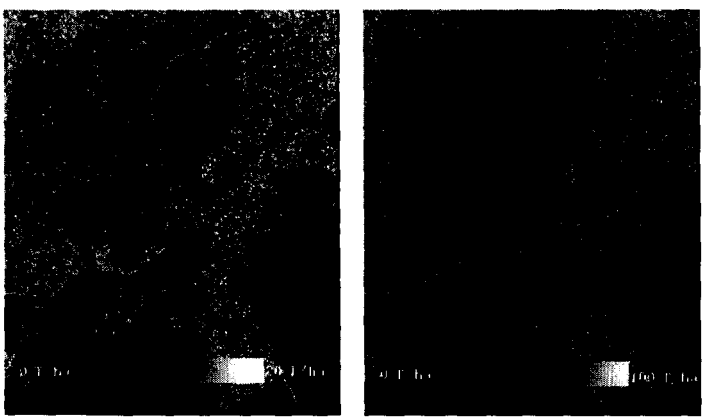

Figure 2. Estimates of crown (left) and stem (right) biomass generated for SSUs dominated by *C. glaucophylla.*

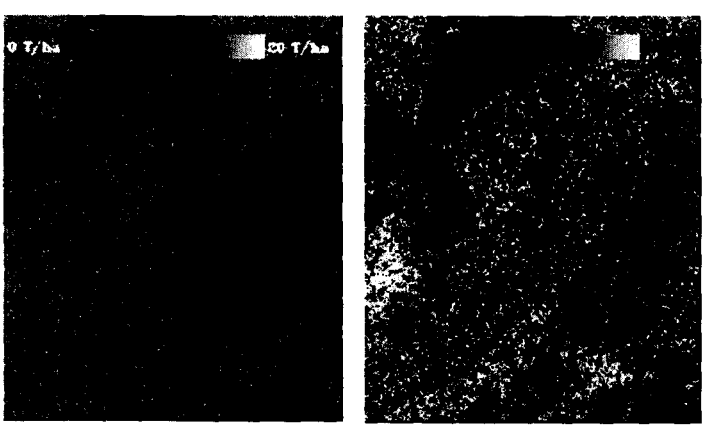

Figure 3. Estimates crown (left) and stem (right) biomass generated for SSUs dominated by *E. populnea.*

7. WIDER APPLICATION

Biomass estimates generated through empirical or regression-type relationships established with SAR data are generally limited as only the backscattering data alone are used. However, the algorithm used here considers both the structural and moisture content of the vegetation in the model formulation and therefore is more reliable. For this reason, more accurate estimates of biomass and also structural attributes are anticipated. Furthermore, the problems of saturation of SAR backscatter with increasing biomass have been largely overcome. In contrast to our previous versions of this algorithm, which was applicable to uniform tree stands only; the option of including mixed species with different size classes was introduced.

For wider application, the algorithm will perform best in woodland communities of similar type and structure. For this purpose, a vegetation map giving the distribution of different woodland communities is desirable. Using Landsat sensor data, such maps are difficult to obtain due to the low dynamic range of the data and the complexity of the woodlands. For this reason, hyperspectral data of finer spatial resolution and greater radiometric content are essential. The inversion model can, nevertheless, be applied to all woodland types, although the accuracy of biomass estimation is reduced.

The study was unique in that it was the first to invert SAR data for retrieving woodland biomass and structure in Australia and to consider vegetation of mixed species composition. The algorithm is now being refined to cover a wider range of woodland types. Inversion of spaceborne SAR data from the ENVISAT Advanced SAR (ASAR) and Advanced Land Observing System (ALOS) Phase Arrayed L-band SAR (PALSAR) could also be achieved although further investigations are required.

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