ESTIMATION OF FOREST BIOMASS FROM L-BAND POLARIMETRIC DECOMPOSITION COMPONENTS

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ABSTRACT

Using an airborne L-band system the impact of increased spatial resolution and a fully polarized sensor on biomass retrieval was investigated. A water cloud type model was used to retrieve biomass from backscatter intensities and polarimetric target decomposition components. The analysis revealed similar biomass estimation errors (around 60%) when using backscatter intensity and polarimetric decomposition metrics. These results indicate that fully polarized L-band missions would not significantly improve the accuracy of biomass estimation using existing modelling approaches. New methods, such as polarimetric interferometry, have to be perfected and tested over a wide range of conditions to take advantage of their increased capabilities.

Index Terms- Biomass estimation, polarimetric target decomposition, L-band SAR

1. INTRODUCTION

The past decades have witnessed an unprecedented development of remote sensing sensors for land monitoring. The increasing availability of Synthetic Aperture Radar (SAR) data has enabled research in numerous fields which in turn has led to the development of diverse applications. Forest carbon stocks estimation is undoubtedly one of the most sensitive research topics nowadays since information on forest spatial distribution, biomass levels and dynamics is needed for accurate greenhouse gass flux estimation, biodiversity-related species extinction or policy implementation. Although a variety of polarimetric model-based decomposition techniques have been developed, the limited availability of fully polarized data has restricted their use and validation under a wide range of forest and environmental conditions. In addition, most studies have used polarimetric decomposition techniques for classification purposes [1] rather than direct biomass estimation [2]. The objective of this study was to *investigate polarimetric target decomposition techniques and assess if improved spatial resolution has a beneficial effect on biomass estimation accuracy.*

2. STUDY AREA AND DATASETS

The study area is located in the western plains of the Murrumbidgee catchment near the township of Narrandera, in Australia. A relatively small forest area (approximately 1800 ha) dominated by white cypress pine (*Calitris glucophylla*) with dispersed (10%) grey box trees (*Eucalyptus microcarpa*) was the focus of this investigation. The topography is nearly flat with most slopes being less than 5°. A biometric survey was conducted on 60 circular plots (500 m^2 or 0.05 ha each) clustered in 12 sites on which data were collected in September 2011. A cluster site consisted of a centre plot with four surrounding plots whose centres were spaced at 35 m in the cardinal directions. The location, circumference and height of trees with a diameter at breast height (DBH) greater than 5 cm was recorded while smaller trees were counted and their average height recorded. Information on grass surface cover and average height from 10 additional sparsely vegetated plots was also collected. Total above-ground biomass (AGB) and biomass components (leaves, branches, stem wood) were estimated for each tree using species-specific allometric equations [3, 4] with the information for individual trees being aggregated to plot level. The total AGB for individual plots varied between 1.5 and 180 t ha^{-1}.

The remote sensing data were acquired by two airborne sensors: the Polarimetric L-band Imaging Synthetic aperture radar (PLIS) and the Airborne Laser Scanning (ALS) Q560. PLIS is a full polarimetric L-band (1.26 GHz) SAR sensor that illuminates the ground on either side of the aircraft with an incidence angle varying from 15° to 45° across the swath. Using a 30 MHz bandwidth, the single-look slant range resolution is around 6 m. The azimuth resolution is around 0.8 m [5]. The PLIS sensor was flown several times (Table 1) at an altitude of 3000m with an average ground swath of 2200m on both sides of the aircraft. The SAR metrics were divided into two groups. The first group corresponds to the backscatter intensity metrics (BI) and is formed by the intensity of the individual channels (i.e., HH, HV, VH and VV). The second group corresponds to the backscatter components after polarimetric target decomposition (TD). This second group contains 11 metrics derived from the fully polarized PLIS data: total span, Pauli components (HH

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Table 1 Acquisition dates of the SAR data and the cumulative precipitation (three days prior to acquisition) recorded at Narrandera airport (10 km north). Rainfall recorded during the SAR acquisition in parentheses.

	Day1	Day2	Day3	Day4
Date	05.09	07.09	10.09	13.09
Rain (mm)	0.2 (0.2)	3.6 (3.4)	1.6 (1.6)	1.6 (0.0)
	Day5	Day6	Day7	Day8
Date	15.09	19.09	21.09	23.09
Rain (mm)	0 (0)	0 (0)	0 (0)	0 (0)

+VV, HH-VV, and 2*HV), Cloude [6] and Freeman-Durden [7] decomposition components (surface, dihedral and volume), and the entropy component from the H/A/α decomposition [8]. All SAR metrics were geocoded to the UTM coordinate system using a lookup table that described the transformation between the radar and the map geometries.

The ALS Q560 was flown over the forest area at an altitude of about 300m AGL from two different directions (N-S and E-W) with a 50% swath overlap. The system recorded all echo pulses within a small footprint (~15cm). An average first return pulse density of 40 ppm was obtained after combining all the flight lines. The software package RiAnalyze was used to extract discrete returns from the raw lidar data. These returns were combined with the navigation data to yield geo-referenced point clouds. Accuracies of this procedure are approximately 0.4m horizontally and 0.15m vertically, with higher accuracies present within individual scan lines. The point clouds were then classed into ground and non-ground returns. All non-ground returns were considered vegetation since no man-made features are located within the forest perimeter.

3. METHODS

3.1. Lidar based estimation of the AGB reference map

Multiple linear regression has been used to create a biomass reference map from lidar measurements. Grid metrics (e.g., cover and density for various height strata, canopy surface area) were produced at 5 m spatial resolution, aggregated to plot level and correlated with ground-based plot estimates of AGB to select the best AGB predictor variables. The aim was to select one predictor variable corresponding to each forest stratum (i.e., overstory and understorey) and a general descriptor of the entire plot. The selected predictor variables were used in multiple linear regression analysis to derive spatially explicit AGB estimates for the area cover by the lidar flight. Arcsine and log transformations were used to normalize the distribution of the lidar-based metrics and the field-based biomass, respectively.

3.2. SAR based estimation of AGB

Since previous studies [9] showed that including multiple polarizations within parametric models does not significantly improve the biomass estimation error attention was focussed on models using single SAR metrics. The estimation principle was to automatically decompose polarimetric SAR data (PolSAR) into ground and volume contributions and to use the parameters obtained for biomass estimation within the parametric model proposed in [10]. Backscatter intensities were also modelled to provide a reference estimation error. The selected model (equation 1) is similar to the water cloud model with the total forest backscatter (σ°_{for}) being modelled as the sum of ground scattering (direct and attenuated by the vegetation layer) (σ°_{gr}) and the direct scattering of the vegetation (σ°_{veg}). The model was parameterized for all SAR metrics (i.e., BI and TD metrics) as a function of the reference biomass estimated from the lidar data. The relationships were subsequently inverted to produce spatially explicit biomass estimates for each SAR acquisition date and SAR metric. It is not uncommon that some measurements of either BI or TD metrics fall outside of the modelled interval. There are different ways to treat such values. For example, [10] proposes the direct assignment of the minimum and maximum biomass values measured in the area of interest when the backscatter intensity values fall below or above, respectively, the modelled interval (i.e. σ°_{gr} to σ°_{veg}). In this study, however, such values were simply discarded during the inversion since our objective was not to produce a spatially explicit biomass map but rather to analyse the biomass estimation error using different SAR metrics. Retaining such values would have defeated the purpose of the study due to the dependence of the estimation error on the number and distribution of such outliers in each particular SAR metric analysed. For data extraction (i.e., lidar-based biomass reference values and SAR metrics) plots with a radius of 15m (~0.07 ha) were used.

$$\sigma^\circ_{for} = \sigma^\circ_{gr} e^{-\beta AGB} + \sigma^\circ_{veg}\left(1 - e^{-\beta AGB}\right) \quad (1)$$

4. RESULTS

4.1 Biomass reference map

To obtain a reference AGB map the pulse density of the 1-12m height stratum ($D_{1\text{-}12}$) was selected to represent the dense understorey layer while for the overstory layer the canopy cover in the 6-8m height stratum ($C_{6\text{-}8}$) was retained. As a general descriptor for the entire forest structure the volume under the canopy surface (C_{vol}) was used. This metric had the highest correlation with all biomass components and was always included as a predictor variable by the stepwise regression analysis. At plot level, the AGB average absolute retrieval error was 17.8 t ha^{-1} (28 % relative). When analysed for each cluster site the retrieval error was significantly lower, -- i.e., as small as 14% relative. This is explained by the lower variability of the forest structure at such spatial scales, the higher confidence in the ground measured biomass aggregates and the reduced effect of the plot positioning errors.

4.2. SAR-based estimation of AGB

The AGB was retrieved by parameterizing the model (equation 1) for each SAR metric and acquisition day. The relative retrieval error with respect to the reference lidar-based biomass is plotted in Fig. 1 for each acquisition day (D) for the HH polarization and the second component of the Cloude decomposition (related to dihedral scattering). The error analysis for each BI and TD metric is given in Tables 2 and 3. Fig. 1 and Table 2 show that daily retrieval errors can fluctuate up to 13% depending on polarization (e.g., Day 1 vs. Day 2). The HH polarization presented the lowest daily error (54%). For TD metrics the variability of the AGB estimation error was similar (up to 17%) when compared to BI metrics (Table 3). However, one particular TD metric (entropy) presented a higher variability (60%) for the daily AGB estimation error. The TD metrics with the highest stability of estimates and lowest errors were usually those obtained using the Cloude (Cl) and Freeman-Durden decompositions (FD). In particular, the TD metrics related to the dihedral and volume scattering components had the lowest estimation errors (~52% for the $Cl_{dihedral}$ component) and day-to-day variability (4% for the Cl_{volume} component). In Fig. 2 the influence of the plot size on the modelled relationships between SAR metrics and AGB is presented. For all metrics there was a significant influence of the plot size with the estimation errors decreasing with increasing plot size. The decrease was between 10 and 25% depending on the day and SAR metric. A strong correlation (R^2=0.86, p<0.001) between the AGB estimation error and the forest variability (CV %) was also observed.

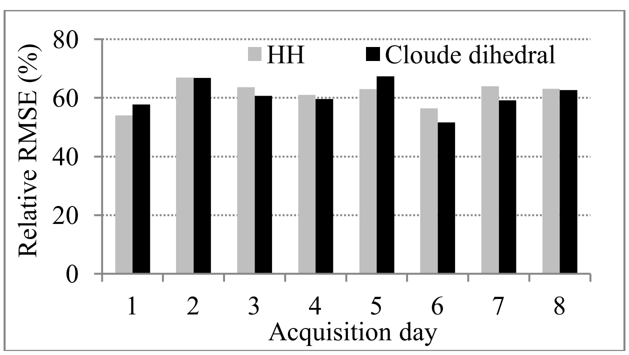

Fig.1Relative retrieval error (RMSE %) for HH polarization and the dihedral backscattering component of Cloude decomposition.

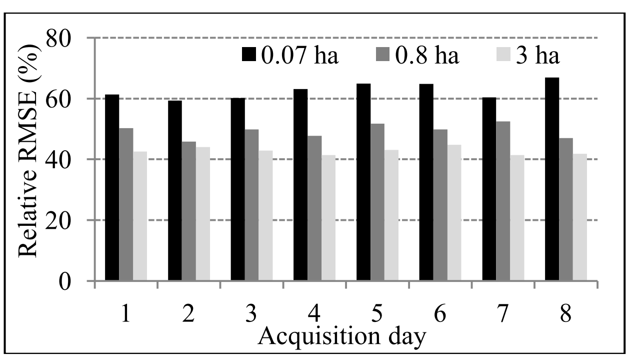

Fig.2 The influence of plot size on the above-ground biomass (AGB) estimation error for HH polarized data.

Table 2 Above-ground biomass (AGB) relative retrieval error (%) for backscatter intensity metrics.

BI metric	D1	D2	D3	D4	D5	D6	D7	D8
HH	54	67	64	61	63	56	64	63
HV	61	59	60	63	65	65	60	67
VH	60	56	58	64	59	67	62	66
VV	63	62	57	65	62	63	64	61

Table 3 Above-ground biomass (AGB) relative retrieval error (%) for polarimetric target decomposition metrics.

TD metric	D1	D2	D3	D4	D5	D6	D7	D8
Span	66	63	68	65	63	61	63	66
Pauli1	61	61	72	69	67	70	65	63
Pauli2	66	66	60	68	69	61	67	61
Pauli3	65	63	67	68	65	68	69	69
$Cl_{surface}$	64	62	59	59	59	62	64	66
$Cl_{dihedral}$	58	67	61	60	67	52	59	63
Cl_{volume}	63	62	62	63	65	66	66	62
$FD_{surface}$	59	62	75	63	71	59	66	63
$FD_{dihedral}$	59	66	60	70	69	62	72	64
FD_{volume}	67	65	66	68	71	65	67	74
Entropy	110	91	81	110	80	127	69	86

5. DISCUSSION

Previous studies showed biomass estimation errors from SAR data to be around 45 to 80% with respect to reference values [9, 11]. With the exclusion of the oldest stands or the selection of the most homogeneous ones such estimation errors could decrease to 25% to 40% [10, 12]. This analysis revealed similar AGB estimation errors (around 60%) when using backscatter intensity metrics within a single-date approach. The analysis showed that retrieval accuracy of forest biomass from L-band radar backscatter observations is highly variable (> 10%) even for images acquired at short intervals. Such variability could be related to variations in soil moisture and vegetation water content at the time of acquisition. From the beginning to the end of the experiment the soil moisture (under the forest canopy) and the canopy water content decreased by approximately 9% and 30%, respectively. For the same acquisition date, the variation in retrieval accuracy among channels was around 5% to 10%. Contrary to other studies [9, 11, 12] slightly lower errors were obtained for the HH polarization. This could be attributed to the specific forest structure characterized by the relatively low height of the overstory layer and the gaps among larger trees. Such forest structures coupled with the long L-band wavelength allows for greater wave penetration and thus more interactions with the ground surface to which the HH polarization is more sensitive. Special attention was given to polarimetric target decomposition metrics since future L-band missions (ALOS PALSAR2 and SAOCOM) will feature fully polarized sensors. The sensitivity to biomass level was comparable between TD and BI metrics. In particular, minimum and maximum daily AGB estimation errors were almost identical although the values were recorded for different acquisition dates. Although for a different environment and forest type, these results confirm the findings in [13] which state that at L-band better correlations with AGB are obtained from backscatter intensities rather than PolSAR-derived metrics.

Further improvements in retrieval accuracy were possible by reducing the uncertainty of the reference biomass estimates, the SAR metrics' signal-to-noise ratio and the co-registration errors between the reference biomass maps and the SAR images. Such enhancements are possible by simply reducing the spatial resolution of input datasets which is equivalent to increasing the radius of the plots used for data extraction from both the lidar-based reference map and the geocoded SAR metrics. By increasing the minimum mapping unit area (i.e., plot size) to approximately 3 ha the forest variability decreased significantly (by approximately 20%) which in turn facilitates a more accurate AGB estimation although the resulting more accurate estimates are only applicable to larger areas – i.e., at the coarser spatial resolution. The increase in estimation accuracy was between 13% and 25% depending on the SAR metric and acquisition date.

6. CONCLUSIONS

Polarimetric target decomposition-based retrieval showed similar sensitivity to biomass levels as the backscatter intensities. This suggests there is little incentive in using such complex processing methods within current modelling approaches. The specific characteristics of the airborne flights did not allow for testing of polarimetric interferometric methods which could provide the necessary boost in performance for biomass retrieval. Decreasing the spatial resolution reduced the uncertainty of the reference biomass estimates, the signal-to-noise ratio of the radar data, the co-registration errors among datasets and, most importantly, the forest spatial variability which in turn allowed for higher biomass retrieval accuracies. This study indicates that future L-band missions will not significantly improve the accuracy of the biomass estimation using current modelling approaches. To take full advantage of their capabilities, new methods such as polarimetric interferometry will have to be developed and evaluated over a wide range of conditions.

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