L-band SAR backscatter sensitivity to forest structure in semi-arid environments: biomass retrieval error analysis at plot level.

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Abstract highlights:

- The utility of L-band synthetic aperture radar (SAR) backscatter data for estimating above ground biomass (ABG) in low biomass conditions (<100 t ha^{-1}) and for different species composition was studied.
- A water cloud type model was used to assess the relationships between field measured biomass and observed backscatter. Moreover, the retrieval errors were studied by biomass intervals using common empirical and semi-empirical models.
- Strong relationships were found between aboveground biomass and SAR backscatter at all sites. For areas with biomass levels below 30 t ha^{-1} the retrieval errors were as much as 250% of ground measured values due to the significant influence of surface backscatter. The estimation error decreased with biomass, being as low as 30% for the 50-100 t ha^{-1} intervals.
- This study shows that retrieval accuracy of forest biomass from L-band SAR backscatter is highly variable within the range of forest biomass considered. In particular, larger errors were observed at both ends of the sensitivity interval. Low biomass levels (< 30 t ha^{-1}) covered most of the dynamic range of the observed backscatter, indicating retrieval limitations when surface backscatter contributions are not accounted for.

Extended Abstract:

Many authors have studied the relationships between above ground biomass (AGB) and radar backscatter (Lucas et al. 2010; Luckman 1998; Santoro et al. 2006). However, only few studies provided detailed information on the accuracy of biomass retrieval that can be achieved through inversion of current empirical and/or physical models. Frequently no information on the retrieval accuracy is given, or only an average estimation error is provided for the entire biomass range. Most of the time the retrieved ABG intervals are much larger when compared to the range of ABG where L-band observations exhibit sufficient sensitivity (0-100 t/ha). In addition, very limited information on the retrieval accuracy by biomass interval is available. Such information could have significant impacts when modeling carbon storage for regions characterized by different biomass levels. This paper assesses the backscatter relationships for semi-arid forests characterized by average biomass levels well below the L-band saturation point (100 t/ha). The main objective was to evaluate the retrieval errors by biomass intervals

within the optimum L-band sensitivity interval making use of the most common existing models.

Field data at plot level were available for two study areas corresponding to local and regional forest inventories. At the local level 70 inventory plots were analyzed, located within a 1600 ha forest in New South Wales, Australia where the dominant forest species is white cypress pine (*Calitris glucophylla*). At regional level, 145 inventory plots were available for semi-arid pine forests located in the central sector of the Iberian range, Spain. The ABG levels for the sites used in this study ranged from 1.6 to more than 200 t ha^{-1}. However, most of the plots (90%), had an ABG below the saturation limit of L-band radar observations (100 t/ha). Two dual polarized (HH and HV polarizations) ALOS PALSAR scenes were available for each study area.

To understand the relationships between radar backscatter and biomass, and estimate the saturation point with increasing ABG values, a radiative transfer model of wave propagation trough horizontal scattering and attenuating layers was used.

$$\sigma^\circ_{for} = \sigma^\circ_{gr} e^{-\beta ABG} + \sigma^\circ_{veg}(1 - e^{-\beta ABG})$$ (1) (Santoro et al. 2006)

This model has the advantage of allowing a straightforward inversion to estimate forest parameters from SAR observations. The forest backscatter (σ°_{for}) is given by the sum of direct ground (σ°_{gr}) and attenuated (by the vegetation layer) scattering and the direct scattering of the vegetation (σ°_{veg}). The two–way forest microwave transmissivity is expressed as $e^{-\beta ABG}$ where β is an empirically defined coefficient and the model is calibrated by estimating σ°_{veg}, σ°_{gr} and β using non-linear least-squares minimization. The backscatter-biomass saturation point can be approximated by the σ°_{veg} parameters which represents the asymptote of the function. Backscatter dynamic range was computed as the difference between σ°_{veg} and σ°_{gr}.

Biomass retrieval errors were also assessed using the most common empirical and semi-empirical backscatter models (equations 1 to 6), parameterized for each available area and SAR image. Models (2) and (3) are loosely based on the water cloud model (Attema andUlaby 1978) while (4) to (6) use linear or non linear functions to model biomass as a function of radar backscatter.

$$\sigma^\circ = a - e^{-(bABG+c)}$$ (2) (Luckman 1998)

$$\sigma^\circ_{(dB)} = a + \left(\sigma^\circ_{gr\,(dB)} - a\right) * e^{-(bABG)}$$ (3) (Lucas et al. 2006)

$$\log(ABG) = a + b\sigma^\circ_{(dB)} + c\sigma^{\circ 2}_{(dB)}$$ (4) (Saatchi et al. 2007)

$$ABG^{\lambda} = a + b\sigma^\circ_{(dB)}$$ (5) (Sandberg et al. 2011)

$$ABG = ae^{b\sigma^\circ}$$ (6) (Moreau andLe Toan 2003)

where: σ° - backscatter coefficient (linear units)
σ°(dB) - backscatter coefficient (dB)

a,b,c – model coefficients
σ°gr(dB) – mean backscatter of a non forested area (fixed value for each image/polarization combination)
λ – parameter estimated from data (λ=1/2)

Model parameterization was performed using 75% of the sample data, whit the remaining 25% retained to calculate the retrieval error. For each image/polarization, 25 repetitions were conducted by randomly assigning plots to the training and the test datasets, respectively. The relative estimation error for each inventory plot was as:

$$\text{Relative error (\%)} = 100 * |ABG_{observed} - ABG_{predicted}| \,/\, ABG_{observed} \qquad (7)$$

We used a relative value to account for the smaller relevance of the same absolute error when the level of biomass increases. The average estimation error for the entire dataset and by biomass interval was subsequently calculated by average of the individual plot errors.

For both study areas, the backscatter coefficient increased asymptotically with increasing AGB from the minimum values associated with sparsely vegetated areas. At plot level, the dynamic range of L-band cross-polarized backscatter was within 8 to 10 dB. When looking at individual biomass intervals, however, the dynamic range was significantly lower. The results show a dynamic range of around 6 dB between bare ground and AGB of 100 t/ha. Moreover, almost two thirds of this dynamic range (3.5-4 dB) was covered by just the two lowest biomass intervals used (0-10 t/ha and 10-30 t/ha). The correlation between co-polarized backscatter and ABG, as well as the recorded dynamic range (4 dB), was lower than for cross-polarized. The inclusion of very low biomass plots (<10 t/ha) provided an anchor effect that significantly increased the coefficients of determination for the fitted models.

Across the entire range the estimation errors were around 50-70% of the observed biomass. However, when analyzed by biomass intervals, consistent results were observed between study areas. The highest estimation error was usually associated with the lowest biomass interval (0-10 t/ha) despite its highest backscatter dynamic range. With increasing biomass the errors decreased significantly until reaching the saturation limit, after which the trend reversed (Fig. 1). The high errors at low biomass are likely the result of high signal variability (seen also in the increased dynamic range) due to surface conditions. At such low biomass levels most of the backscatter contributions come from soil (surface scattering) with only a minor volume scattering component. To better understand this effect, the surface backscatter component was modeled using a surface-only backscatter model together with input surface moisture and surface geometrical roughness recorded at some of the Australian plots. This showed a backscatter variability of up to 3-4 dB when changing model inputs within the full range of soil moisture and surface roughness measured on the ground (0.05-0.15 m^3/m^3 and 0.5-1.2 cm rms). This value is very close to the HH backscatter variance for the 0-10 t/ha interval (3 dB).

This study has showed that the retrieval accuracy of forest biomass from L-band radar backscatter observations is highly variable within the range of forest biomass considered. In particular, larger errors were observed at both ends of the sensitivity interval, i.e., when approaching 0 and 100 t/ha. At lower biomass levels (<30 t/ha) information on soil roughness and surface moisture must be incorporated into the empirical/semi-empirical retrieval algorithms in order to increase the accuracy of the biomass estimates. At higher biomass levels (>100 t/ha) signal saturation dominates and the estimation accuracy starts degrading. However, for mid-range biomass intervals, satisfactory retrieval accuracy was achieved (25-40%) when using empirical models. Overall biomass retrieval errors were significantly lower when empirical models were used (50%) compared to more physically based models (70%).

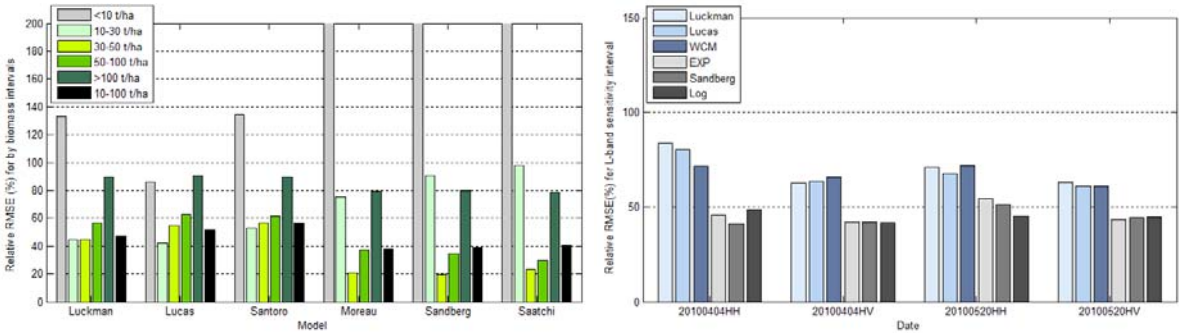

Fig. 1 Relative biomass retrieval error by biomass interval (left) and the average retrieval error for each model and date/polarization (right). L-band ALOS PALSAR, Australian site.

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