Forest Biomass Modelling by Polarimetric and Interferometric SAR Data: the Brazilian Scientific Missions

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Abstract. This work presents two practical examples of polarimetric and/or interferometric attributes of microwave data to improve the knowledge of structural aspects of forest typologies. Firstly, we discuss the role of polarimetric and interferometric airborne SAR data (OrbiSAR-1 system using bands of X_{HH} and $P_{HH,\ HV,\ VH\ \text{and}\ VV}$) for aboveground biomass estimation of *Eucalyptus* sp. stands to subsidize the operational forest management activities for cellulose production. Secondly, it is a contribution of polarimetric attributes of ALOS/PALSAR (L-band) for the aboveground biomass modelling of primary and secondary tropical forest from Brazilian Amazonia (Tapajós region). To perform both studies, a multivariate regression technique is carried out using variables obtained from both SAR attributes and biophysical parameters collected during field surveys. All SAR data from each mission are calibrated both radiometrically and geometrically to extract information during the digital processing. In summary, the results showed that (a) the variables combination of "Interferometry Height" (H_{Int}^2) and "Canopy Scattering Index" (CSI) are important for *Eucalyptus* biomass model; (b) the most significant variables for tropical forest biomass modelling were the $\sigma°_{HH}$ coefficient, the volume scattering component of Freeman's decomposition, the Touzi's magnitude of the second component, the phase of the second and third components and the helicity mean angle. To validate the results obtained by both models, a set of independent data from the forest inventory were generated, which indicated a prediction average error of ~ 10% to estimate the stock density of *Eucalyptus* stands and of tropical forest by SAR data.

Keywords. Biomass modelling, forest inventory, SAR data, tropical forest, Eucalyptus stand, remote sensing.

1. Introduction

The procedure derived from the multi-polarimetric and/or interferometric SAR data, rather than using single frequency radar, allows detailed information to be obtained about three-dimensional forest structure of scattering targets under study [1], [2].

Several authors [3], [4] studied multi-polarimetric SAR backscatter for the discrimination of forest types, discussing those aspects of scattering and attenuation of SAR signals at different frequencies interacting with structural vegetation parameters. [2], [5], [6], [7] discuss the contribution of the interferometric mode to estimate biophysical parameters in forest areas. [8] developed indices based on ratios and normalized differences of multi-polarimetric data, which can be related to certain characteristics of vegetation cover, such as e.g. biomass index [BMI = $(\sigma^o_{HH} + \sigma^o_{VV}) / 2$], canopy structure index [CSI = $\sigma^o_{VV} / (\sigma^o_{VV} + \sigma^o_{HH})$], volume scattering index [VSI = $\sigma^o_{HV} / (\sigma^o_{HV} + \text{BMI})$], applied to tropical forests in Central America. [9], [10], [11], [12], [13], [14] explain the contributions of coherent and incoherent SAR attributes related to the complexity structure of high density of tropical forests, when there is a need to model the forest biomass and /or volume.

The National Institute for Space Research - INPE (Brazilian Ministry for Science, Technology and Innovation – MCT) is to develop new remote sensing methodologies to help the policy and control of the forest resources from Brazil. In this context, some studies on radar applications were conducted to support the tasks of forest inventory and monitoring. At this frame, the work aims to shows the results derived from two scientific experiments in forest areas, as described below:

- to generate a model to estimate the forest biomass of *Eucalyptus sp.* stands, using the multivariate analysis for the associating coherent and incoherent polarimetric attributes in P-band, as well as the interferometric height (H_{Int}^2) from DEM of X- and P-bands from airborne SAR imagery;
- to generate a model to estimate of aboveground biomass of Amazon tropical forest, based on the combination of multi-polarimetric attributes (considered by literature as incoherent and coherent), based on the radar measurement of power and its phase information of the backscattered signal from ALOS/PALSAR data.

2. Study area and SAR data acquisition

The first study was carried out in the Rio Paraíba Valley region (W 45° 23'to 45° 25'and S 22° 54' to 22° 55'), São Paulo State, provided airborne SAR data over reforested area with *Eucalyptus sp.* (plantation with ~6 years of age), collected by the OrbiSAR-1 system (OrbiSat da Amazônia S.A.). Data acquisition was carried out in X- band with HH polarization (1 m of resolution) and in fully polarimetric P-band (range and azimuth resolution of 2 m), both with ~ 45° boresight angle.

The second study was conducted around the Tapajós region (NE Pará State, Brazil), located in S 3º 01' 59.85" - S 3º 10' 39.33" and WGr 54º 59' 53.08" - WGr 54º 52' 44.96", a region dominated by Dense Ombrophylous Forests tropical and sections of Open Ombrophilous Forests, with an land use related to subsistence agriculture, few cash crops, cattle raising and selective logging activities. In this study, fully polarimetric data was used from ALOS/PALSAR images (PLR format), ascending mode, with a spatial resolution of 4.50m in range and 9.50m in azimuth, with incidence angle of 24.333º.

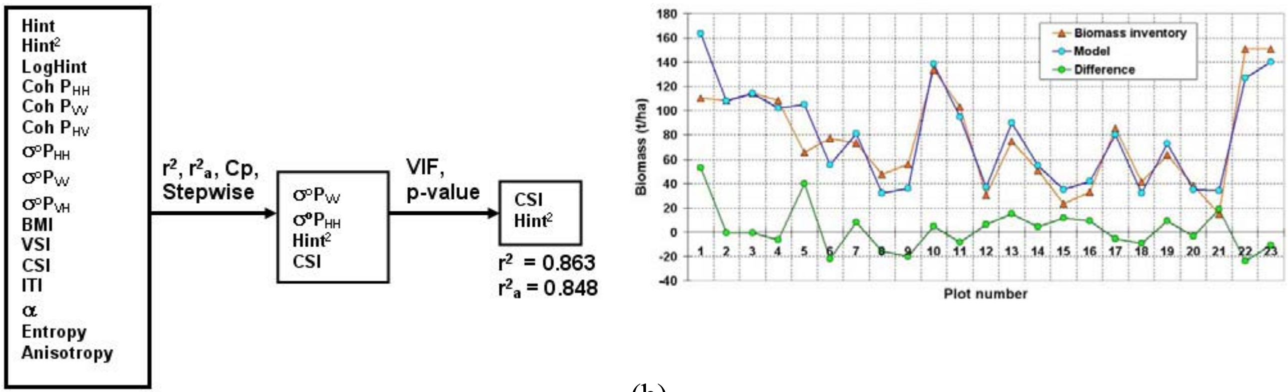
Field campaigns included the forest inventory in several geo-referenced plots of Tapajós tropical forests domain, as well as in the *Eucalyptus* reforested areas, which were carried out simultaneously to the both independent SAR data acquisitions.

3. The interferometric and polarimetric airborne SAR data for biomass modelling of the *Eucalyptus sp.* stands

The airborne OrbiSAR-1 data (X- and P-bands) was radiometrically calibrated using corner reflectors. The antenna pattern correction was performed using homogeneous target area. The polarimetric calibration was also performed to minimize the distortions imposed by the PolSAR system in the scattering matrix (cross-talk and channel imbalance), using the method proposed by [15].

The *Eucalyptus* biomass model was estimated by linear regression modelling between the field inventory data and the interferometric and polarimetric airborne SAR data. Field inventory data was acquired based on the measurement of DBH and tree the height values in the 23 independent plots of ~400m^2 each. The aboveground biomass estimation was obtained by a destructive method, where one individual of *Eucalyptus*, whose DBH value was similar to the mean of each plot, was cut-down and weighted to represent the whole stand. Simultaneously, some topographic profiles were carried out using an Infrared Total Station in the same stands, for the P-band interferometric quality DEM analysis, whose results mentioned that a better correlation was obtained in the P_{HH} polarization, if compared with the other polarizations to describe the ground height [16].

To select the SAR coherent and incoherent variables (Figure 1a) to the regression model the Stepwise, Cp, R^2 and R^2_a criteria were used, as well as the Cook's distance to find the outliers cases. The Levene's method was used to verify the homoscedastic behaviour of regression residues. Based on this approach, the variables Hint (difference values between interferometric DEM in X- and P-bands) and CSI (measure of the relative importance of vertical versus horizontal structure in the forest cover) presented a linear behaviour, whose final model is: Biomass = – 114.505 + 0.137 H_{int}^2 + 316.058 CSI, in which the biomass configuration have a good similarity as compared as the inventory data (Figure 1b). The biomass variations of all plots obtained during the ground survey are related to the different local site index where the stands are also located, the particular genetic differences (seminal and clones) of these plantations.



(a) (b)

Figure 1: Diagram of SAR attributes tested to construct the model (a); and comparative behaviour of biomass modeling of the reforested areas with *Eucalyptus* sp. (b). Source: adapted from [16].

The criteria PRESS (Prediction Sum of Squares) and SSE (Sum of Squares Errors) whose values were used for the model validation, allow the use of MSE (Mean Squared Errors) to predict errors. [17], [18] shows that this biomass model generated presents 20.49% of prediction error if compared with the mean stand biomass, whereas 10.38% if compared with maximum stand biomass.

4. The multi-polarized SAR data for modelling of biomass estimation in tropical forest

The geometric and radiometric calibrations of the ALOS/PALSAR images were performed according to [19]. These corrections were necessary to obtain the real values referring to each polarization being analysed. The amplitude and phase information, that explore different polarimetric characteristics of the targets investigated, were extracted from PALSAR images in representative selected samples and used for the forest inventory carried out during the field campaign. The attributes used to describe the targets and to generate the forest biomass model are classified in coherent and incoherent categories.

a) Incoherent attributes

The incoherent attribute types are based on information from the real part of each pixel, which are represented by: backscatter coefficient (σ°), described by [20]; the ratio of parallel polarization (Rp) and the ratio of cross polarization (Rc), outlined by [3]. Besides that, there is also the total power (PT), reported by [20], [21]; and the indices formulated by [8] in forest environments, called as a biomass index (BMI), Canopy Structure Index (CSI) and Volume Scattering Index (VSI).

b) Coherent attributes

These attributes use the SAR phase information, which were evaluated by polarimetric coherence of HH-VV (γ) and phase difference of HH-VV ($\Delta\varphi$), described by [3]. Furthermore, we analysed the parameters resulting from the decomposition by coherence matrix [T], called as entropy (H), anisotropy (A) and the mean alpha angle($\Delta\overline{\alpha}$) [21], [22]; the magnitude (αs) and Touzi phase ($\Phi\alpha$s), also derived from the same former decomposition were analysed. Beside that, we considered the orientation angle (ψ) and heliticity (τ_m), derived from two stages: (1) the Graves matrix [G]; (2) the Kennaugh-Huynen matrix, described in [23], [24]. Moreover, the volume scattering components (*Pv*), double bounce (Pd) and surface (Ps), resulting from the decomposition matrix [C] [25].

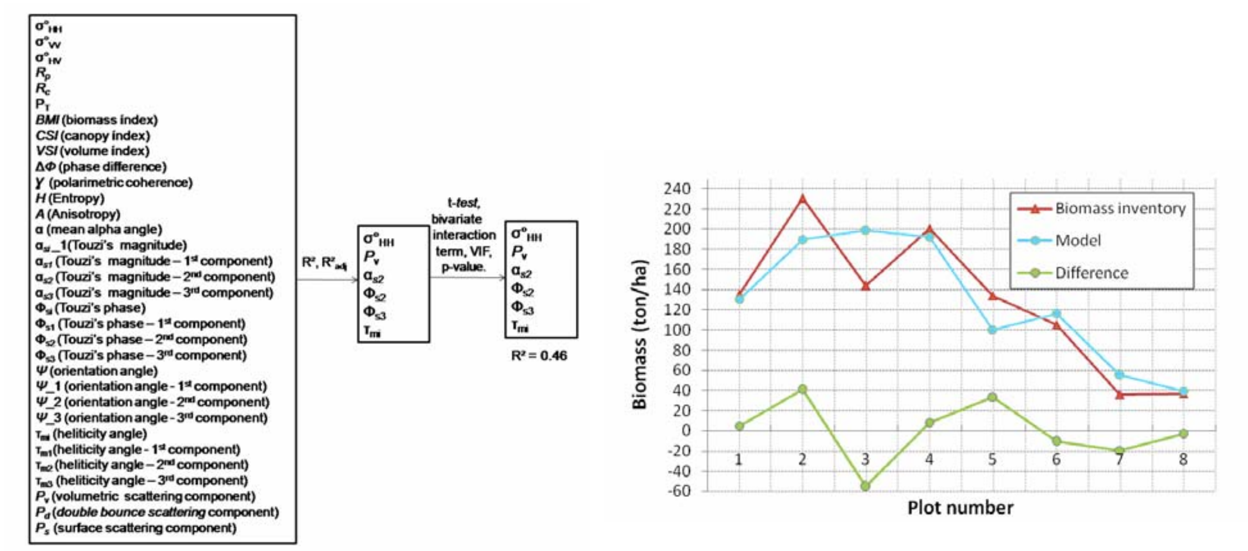
To select the SAR coherent and incoherent variables (Figure 2a) to the regression model the Cp Mallow, R^2 and R^2_a criteria were used, as well as some statistical procedures such as the presence of interaction effects (by bivariate interaction terms) and the diagnosis of multi-colinearity (by calculus of Variance Inflation Factor - VIF, according to [26], analysis of outliers (Cook´s distance) and residuals [17], [18], [27] are part of the methodological approach, at the interaction analysis of SAR and field survey data).

In this case, 41 plots were selected for forest inventory with 33 samples for model generation and 8 plots for model validation, as mentioned by [28], encompassing the total area of 14.5 ha, covering five classes: Primary Forest with or without timber exploitation; Advanced, Intermediate and Initial Secondary Succession. Aboveground biomass for these areas with primary and secondary forest was estimated based on alometric equations according to [29], [30], respectively, using DBH and total height (HT) measure in the field survey:

$$Y(t.ha^{-1}) = 0.044\ ((DBH)^2 \times HT)^{0.9719}$$

$$Y(t.ha^{-1}) = e^{(-2,17+(1,02*(\ln(DBH)^2)+(0,39*(\ln(HT))}$$

Based on these criteria the final model was selected (R^2 = 0,46 and QMR = 3245,60): [Biomass = – 12221.37 – 70.31 ($\sigma°_{HH}$) + 1064.65 (P_V) + 6.28 (α_{S2}) – 2,42 (Φ_{S2}) + 3.44 (Φ_{S3}) + 6.05 (τ_m)], with selected explanatory variables: the backscatter coefficient at HH polarization, the volume scattering component of Freeman’s decomposition, the Touzi’s magnitude of medium scattering, the Touzi’s phase of the medium and low scattering and the heliticity mean angle. The backscatter at VV polarization and the orientation angle of Touzi have shown the higher correlation coefficients with individual biomass values. But, they were not included in the subset of explanatory variables based on the analysis of subsequent tests. Another important aspect to the composition of the final model is that the majority of SAR selected attributes were consistent, demonstrating the importance of phase information to estimate the biomass of primary and secondary forests. During the predictive capacity of the biomass model, the average estimation error was 7.45%, based on the set of 8 independent plots used for the validation (Figure 2b).



(a) (b)

Figure 2: Diagram of ALOS/PALSAR attributes tested to construct the model (a); and comparative behavior of biomass values derived from the regression model and field measured in the independent sampling blocks of tropical forest typologies used for the validation (b). Source: adapted from [28].

5. Conclusions

Based on the two scientific technical works, we concluded that:

- the biomass estimates from *Eucalyptus* stands, when incorporating interferometric height and backscatter attributes, provide a higher accuracy to the model. This interferometric SAR attribute have a strong relationship with the *Eucalyptus* biomass content, because the reforested area is clear in the understory strata, and the species under study has a small canopy despite its great height;

- the Touzi attributes (αS2, ΦS2, ΦS3, τ_m) are innovative variables in the calculation of aboveground biomass of tropical forests, which are associated with the backscatter coefficient in HH polarization and volume scattering component of the Freeman decomposition. These attributes indicate the consistency for this estimation prediction using L-band PALSAR data, whose performance was demonstrated by independent sampling.

Advances in analysis of available radar products (TerraSAR TanDEM-X mode, COSMO Skymed), focusing in models of stand architecture, stocking density and visualization forest growth, will be very helpful to support the inventory and monitoring tasks of forest resources in the Brazilian territory.

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