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Estimating 3-Dimensional Structure of Tropical Forests from Radar Multi-baseline Interferometry: The Tapajós FLONA case

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Abstract. This paper describes the retrieval of 3-dimensional vegetation parameters from interferometric synthetic aperture radar (InSAR) using physical models and multi-baseline P-band Interferometric data A general equation, expressing the InSAR observation in terms of vegetation density, is shown as the basis for identifying and estimating forest structure parameters. Initial results are shown from a multi-baseline P-band HH polarization data acquisition mission, realized with AeroSensing airborne system flown in 2000 over Tapajós National Forest (FLONA) at five (5) horizontal baselines distant 25 m from each one. Structural parameters of two forest sites, near the Sao Jorge settment inside Tapajós FLONA, Pará State, Brazil, are presented as a result of this methodology.

Palavras-chave: remote sensing, Insar, tropical forest, biomass.

1. Introduction.

There is a growing interest in the 3rd dimension (3D) of forest structure, because it is an indicator of the state of the ecosystem, for example susceptibility to fire. 3D structure also is, potentially, a good indicator of biomass (Drake et al. 2002, Treuhaft et al. 2003) Also the knowledge of forest height provides a good estimate of the underlying topography of forests, which is very important in tropical forest studies. Radar interferometry is sensitive to the vertical dimension, the 3rd direction missing from almost all terrestrial remote sensing (Treuhaft et al. 2004). The production of vertical-profile information from InSAR results from multiple transmissions and/or multiple receptions of microwave signals. Its coverage, demonstrated by the Shuttle Radar Topography Mission's (SRTM) global coverage in 11 days, suggests InSAR has an important role to play in global or regional 3D characterization of forests. InSAR measurements can be inverted to estimate the actual vegetation density distribution as a function of height above the forest floor. This more abstract information content and the way it can be used to estimate vegetation profiles of tropical forests is the subject of this paper. The methods discussed here are part of an ongoing analysis of InSAR collected data from La Selva Biological Station in Costa Rica (Treuhaft et al, 2006) and Tapajós National Forest in Brazil. Preliminary results from the Tapajós forest will be shown.

1.1 The theoretical InSAR Observation.

The InSAR observation, called the complex cross correlation, is given by the **Equation 1,** where E_1 and E_2 are the electromagnetic fields received at the ends of the interferometer, which consists of two antennas, receiving back the radar emission emitted for, at least, one antenna distant of each other from a distance called the baseline B. (Treuhaft et al,1996)

$$\gamma \equiv \frac{\left\langle E_1 E_2^* \right\rangle}{\sqrt{\left\langle E_1^2 \right\rangle}\sqrt{\left\langle E_2^2 \right\rangle}} = \frac{\sum_{j=1}^{N} E_{1,j} E_{2,j}^*}{\sqrt{\sum_{j=1}^{N} E_{1,j}^2}\sqrt{\sum_{j=1}^{N} E_{2,j}^2}} \qquad (1)$$

The cross correlation, which is the numerator of **Equation 1**, for a vegetation volume, explicitly written as function of baseline B, wavelength λ, and incidence angle θ_0, depends on vegetation density as in **Equation 2:**

$$cross\ cor(B,\lambda,\theta_0) \propto e^{i\phi(z_0)} \int_0^{h_v} dz'\ e^{i\alpha_z(B,\lambda,\theta_0)z'}\ \rho(z')\left\langle f^2(z')\right\rangle \exp\left[\frac{-2}{\cos\vartheta_0}\int_{z'}^{h_v} dz''\ \sigma_x(z'')\right] \qquad (2)$$

This equation, from Treuhaft et al. 1996, is normalized by *cross cor*(B=0,λ,θ_0) to calculate the complex coherence of **Equation 1**. The brackets indicate an average over scatterer type—branches, leaves, trunks—signifying an average scatterer strength as a function of height above the ground. In (2), α_z is the derivative of interferometric phase with respect to height above the ground. The interferometric phase at a given height above the ground, the arctangent of the first term in the integrand of (2), is proportional to the pathlength difference of scatterers (the forest volume is composed of elementary scatterers, which bounce back the radar emissions) at that height. The next 2 terms $\rho(z) < f^2>$ determine the brightness of the vegetation at height z, with $\rho(z)$ being the number of scatterers per unit volume at z and $< f^2>$ the average brightness of a scatterer. The last exponential accounts for attenuation of the waves propagating forward or backward in the medium. $\sigma_x(z)$ is the extinction coefficient at z and is also proportional to $\rho(z)$. The main physical assumption in **Equation 2** is waves in the forest propagate similarly to those in a uniform slab of material, without multiple complex interactions between the various forest components. A heuristic description of **Equation 2** can be found in Treuhaft et al. (2006).

1.2 Estimating Forest Profiles from the InSAR Observations.

In the estimation of vegetation density profiles, which is usually taken to mean leaf area density, three assumptions are made. The first regards the quantity $\rho(z) < f^2(z)>$. We have made the assumption that 1) it is the variation in the scatterer number density with height, $\rho(z)$, that is directly proportional to vegetation density profiles. The second assumption is that 2) the brightness per scatterer $< f^2(z)>$ does not depend significantly on height. Biophysically, this assumption implies that the average type of scatterer, for example the average size of leaves, does not appreciably change as a function of height. Mathematically, this means that the brightness of the vegetation at height z can be written as $\rho(z) < f^2 >$, varying proportional only to the number of scatterers per unit volume. Finally, it is assumed that 3) the vertical dependence of the extinction coefficient, $\sigma_x(z)$, in the last exponential in (2) also depends only on $\rho(z)$. These assumptions have never been rigorously justified through calculations relating biophysical forest features to electromagnetic scatterer characteristics. Instead relative vertical profiles estimated with the above 3 assumptions have been compared to field-measured leaf area density in Central Oregon, United States (Treuhaft et al. 2002). Further assumptions of vegetation homogeneity, i.e. uniform density, have been used to estimate tree height from polarimetric interferometry (Papathanassiou and Cloude 2001).

The estimation of forest parameters follows from **Equation 2**, given the above assumptions. **Figure 1** schematically presents the estimation process which is iterative in nature. The radar system parameters, a relative shape for $\rho(z)$ and an initial set of forest parameters is initially included in the **Equation 2**. The estimation process continues, systematically altering the forest parametes and reentering them into the Equation, minimizing the difference between the theorectical and observed coherence, the magnitude of **Equation 1**.

2. Study area, methodology and data.

The area selected for this study is located at the lower Rio Tapajós region (Pará State), limited by geographical coordinates W 55° 06' to W 54° 53' and S 3° 03' to 3° 12' , along highway BR- 167 Cuiabá-Santarém and close to the São Jorge village.

In September 2000, a X (HH polarization) and P band full polarimetric system, from *AeroSensing RadarSysteme GmbH,* was flown over the cited area in a collaboration between the Brazilian Army Cartographic Service Division (DSG) and the National Institute for Space Research (INPE). AeS-1 (*AeroSensing Radar Systeme, GmbH*) radar system provides P band (λ = 72 cm) full polarimetric image data, obtained with a middle frequency of 415 MHz, 70 MHz band-width and depression angle of 45° and X band HH data with middle frequency of 9.6 GHz, 400 MHz band-width and mean flight height of 3.216 m. The P band scenes have a pixel size with range and azimuth resolutions of 1.5 and 0.7 m respectively (1 look slant range). X band imagery have a pixel of 0.5m ground range resolution. In parallel with the airborne SAR mission, a field measurement campaign was made to measure timber volume density in the primary forest and secondary succession in selected transects inside the estimated DEM. Topographic maps and Landsat-TM images were used as complementary materials for the registration procedure and selection of sample sites in the field. One third of this area was covered by 25 P-band tracks distant 25m from each one. Five (5) tracks in sequence were selected for this study forming a multi-baseline data set with baselines ranging from 25 to 125m. Different values of the baseline length enter (2) through α_z.

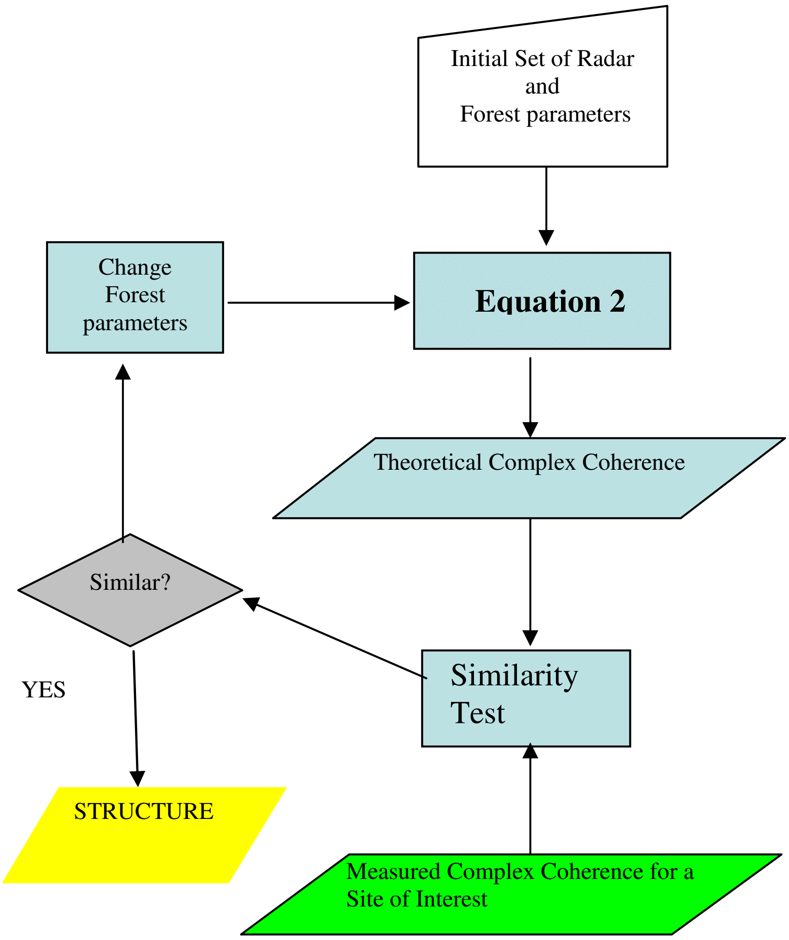

Figure 1: Schematics for 3D Forest Structure Parameter Estimation

3. Results.

Five complex coherence maps, corresponding to these baselines were calculated. All these maps have been corrected for signal to noise ratio and range decorrelation based on bare soil samples (where coherence is supposed to be 1). **Equation 2** has been rearranged in terms of how much energy is reflected from ground (w = ground/volume power ratio) and using the so called stand model where vegetation density is considered constant between a certain height, the pedestal, and the total forest height H. Two primary forest sites were tested for pedestal equal to zero; H/8; H/4 and H/2 where H is the total height estimated for that particular test site. **Figure 2** shows the dissimilarity (D) graphics for one case where the vegetation density is considered constant between H/8 and H. Dissimilarity, here, is defined as the Euclidian Distance between the vector of coherences calculated by Model, (one coherence value for each baseline) and the measured coherence data. The power ratio varied from zero to 2.5 and H varied form 20m to 44m. The minimum was attained at H=33m and w=1 when D = 0.143.

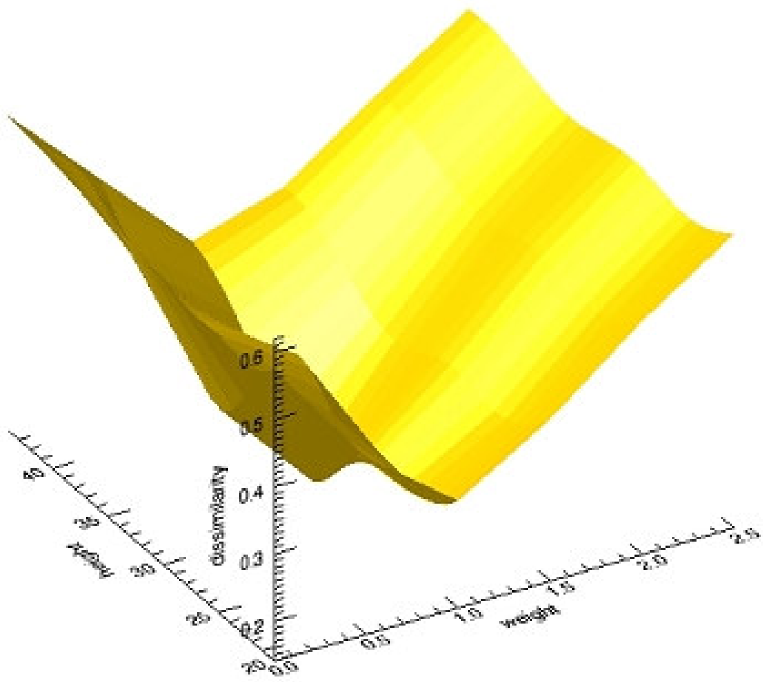

Figure 2. Dissimilarity variation for a Primary Forest area considering stand model where vegetation density is considered constant between H/8 and H. Minimum is attained for H = 33m and ground/volume power ratio w=1, when D=0.143.

Table 1 shows the minimum dissimilarity D, and corresponding forest parameters for two primary Forest sites with pedestal varying in the set {0, H/8.; H/4.; H/2}. Coherence averages for each site were taken considering the complex data, covering a minimum area of 6.617 m². In this paper the modulus of these coherences was used to compose the field data. These results shows that, from five pieces of information, (five interferometric baselines), three structural parameters were calculated which allows one to describe site A as: considering uniform vegetation density, site A has most of its biomass between 4.12 m and 33m, and half of radar incoming energy is reflected on the ground. Site B has its biomass between 9.5m and 38m and most of radar energy is reflected on the volume. No detailed ground data are available for these two sites but a field trip where photos were taken, ground data observed in similar nearby sites, and the general behavior of the modeling process allows one to observe the great potential of the methodology. Further investigations will be necessary to relate these findings to actual structural forest parameters that are important in and of themselves. Also the investigations will continue taking into account the influence of other polarizations.

Table 1. Dissimilarity between Data and Model, as a function of Forest Height, Pedestal and Power Ratio

Dissimilarity , Height, Power Ratio					
Site		Pedestal			
Area (m^2)		0	H/8	H/4	H/2
A 13.693	D	0.168	**0.143**	0.208	0.211
	H	34	33	34	33
	W	1	1	1	0.5
B 6.617	D	0.183	0.163	**0.162**	0.207
	H	37	39	38	37
	W	0.5	1	0.5	0.5

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