Estimating 3-Dimensional Structure of Tropical Forests from Radar Interferometry

Estimativa da Estrutura 3-Dimensional das Florestas Tropicais Através de Interferometria de Radar

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Abstract

This paper describes the retrieval of 3-dimensional vegetation density profiles from interferometric synthetic aperture radar (InSAR) using physical models. InSAR's sensitivity to vertical structure is generally regarded as less direct and more difficult to understand than that of lidar. But InSAR's coverage is superior to that of lidar, suggesting InSAR is more promising as an important component of a global 3-dimensional forest monitoring technique. The goal of this paper is to introduce, simplify and demystify the use of simple physical models to understand InSAR. A general equation expressing the InSAR observation in terms of density is described heuristically, along with the approximations in its development. The information content of the equation leads to the estimation of density parameters. Preliminary results are shown from a multibaseline C-band (wavelength=0.056 m) vertical-polarization interferometer, realized with AirSAR flown at multiple altitudes over primary, secondary, and selectively logged tropical forests, as well as abandoned pastures at La Selva Biological Station in Costa Rica.

Key words: forest profile; radar interferometry; InSAR; vegetation density.

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Resumo

Este trabalho descreve o procedimento de recuperação do perfil tri-dimensional da densidade de vegetação, a partir de dados interferométricos de radar de abertura sintética (InSAR), utilizando modelos físicos. A sensibilidade da técnica InSAR para detectar estruturas verticais de vegetação é geralmente considerada menos direta e mais difícil de entender se comparado com dados de LIDAR (técnica utilizando laser). A utilização da técnica InSAR permite uma cobertura superior ao LIDAR e é potencialmente mais promissora como técnica de monitoramento global para a detecção da estrutura tri-dimensional de florestas. O objetivo deste trabalho é o de simplificar e desmistificar o uso de modelos físicos simples no entendimento da técnica InSAR. A equação geral que expressa a observação InSAR em termos de densidade é escrita heuristicamente, bem como as aproximações feitas no seu desenvolvimento. O conteúdo de informação da equação nos possibilita a estimação dos parâmetros de densidade da vegetação.

Palavras chaves : perfil de floresta; radar interferométrico; InSAR; densidade da vegetação.
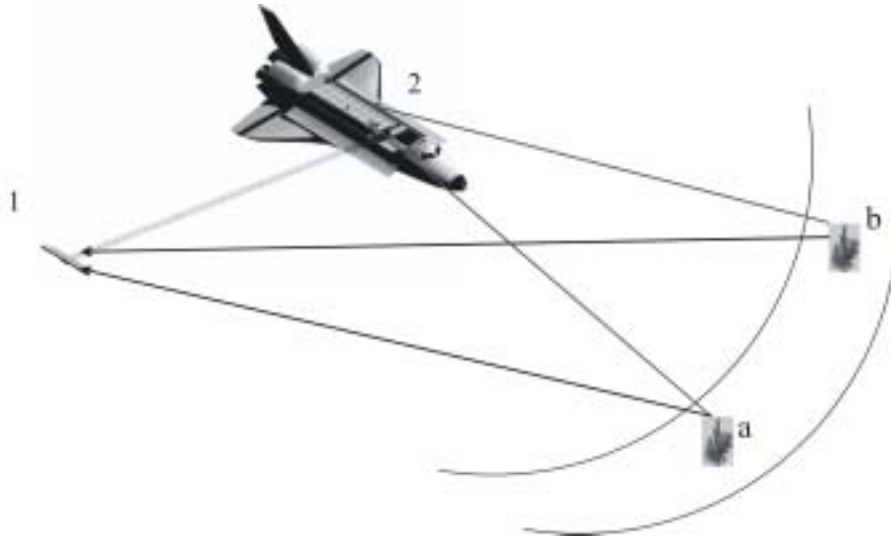
Introduction

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. Interest in 3D structure also stems from its potential to be a good indicator of biomass (DRAKE et al., 2002, TREUHAFT et al., 2003). Radar interferometry is sensitive to the vertical dimension, the 3rd direction missing from almost all terrestrial remote sensing (TREUHAFT et al., 2004). Lidar is also sensitive to the vertical dimension (LEFSKY et al., 2002). Lidar estimates the vertical structure of forests by measuring the time delay between transmission and reception of laser pulses. A single transmission with multiple receptions can be used to infer a power-return profile (e.g. DRAKE et al., 2002) or, with modeling, can be interpreted as a vegetation density profile (HARDING et al., 2001). To date, lidar's narrow beam, a direct result of its optical wavelength—and a desired one for the higher spatial resolution it enables—renders it most useful for few-100-square-kilometer research (*e.g.* DRAKE et al., 2002), and probably less useful for global monitoring (HOFTON et al., 2002) by itself. The production of vertical-profile information from InSAR results from multiple transmissions and/or multiple receptions of microwave signals. Like lidar, InSAR cannot produce profile information with a single transmission and reception, but is currently being tested for its profiling capabilities with multiple transmitted and/or received signals. InSAR's

few-meter vertical resolution may well always lag lidar's few-cm resolution, but 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's sensitivity to vertical structure is more abstract and less easy to understand than lidar's. Lidar measures the height of a forest component by the simple ball-throwing distance from the transmitter to the component in question. Each InSAR measurement is more like a measurement of the vertical granularity of the forest at a given vertical spatial scale. Many such granularity measurements at different scales can be inverted to estimate the actual 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 profiles is the subject of this paper. The methods discussed here are part of the analysis of tropical-forest data from La Selva Biological Station in Costa Rica and Tapajós National Forest in Brazil. Preliminary results from the Costa Rican forest will be shown.

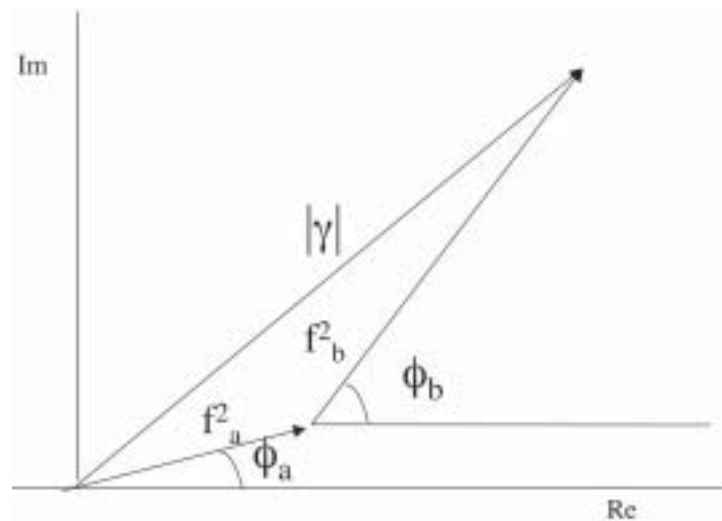## The Sensitivity of InSAR to Vertical Forest Vegetation Density

The InSAR observation, called the complex cross correlation, consists of 2 parts, a phase and a magnitude. The phase from a single scatterer, such as scatterer "a" in figure 1, is proportional to the difference in the pathlengths to the 1 and 2 ends of the interferometer—in the picture the length of the black line minus the length of the red line. For scatterer b, this distance difference is greater and the corresponding interferometric phase is greater. The phase of each contribution is therefore proportional to the height of each scatterer above the ground surface. A "scatterer" is a component of the vegetation which sends the transmitted signal back to the receiver.

Figure 1. The Shuttle Radar Topography Mission interferometer, showing the path lengths
from two scatterers, a and b, to the two ends of the interferometer. The scatterers
could be leaves, branches, parts of the trunk, or anything in the forest scene

The signals from these two hypothetical scatterers in figure 1 add vectorially if
they are in the same resolution cell, as shown in figure 2. Each signal contributes a vector
with length proportional to the backscattering strength, f^2_a and f^2_b for scatterers *a* and *b*,
respectively, with a phase, as already noted, proportional to the scatters' height.

Figure 2. Vectorial addition of the signals from scatters a and b to form the total cross correlation.
The lengths of each component vector a and b is shown next to the vector, as is the
length |g| of the total cross correlation coherence. "Re" is the real part of the InSAR
cross correlation, "Im" is the imaginary part

The real part (Re) in figure 2 is the backscattering strength x cos(InSAR phase) for each vegetation component a and b, and the imaginary part (Im) is the backscattering strength x sin(InSAR phase).

The InSAR observation arising from these two vegetation components is the complex coherence, given in terms of the electric fields E_1 and E_2 received at the ends of the interferometer as:

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

where the ensemble average brackets $\langle \rangle$ literally mean averaging over different ensemble members of statistically similar terrain. In other words, each ensemble member is a different realization of the same parent statistical population of vegetation cover. On the right side of (1), the practical realization of the ensemble averaging is shown as radar "look" averaging. A "look" is one, usually few-m x few-m, sample of the terrain. The electric fields are averaged over looks, from a few to many hundreds, to produce the InSAR cross correlation. The vector sum of figure 2 becomes an integral for a real forest's continuously varying vegetation distribution. The cross correlation, which is the numerator of (1), for a vegetation volume, explicitly written as function of baseline B, wavelength l, and incidence angle q_0, depends on vegetation density as follows:

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

This equation, from Treuhaft et al. 1996, is normalized by *cross cor*(B=0,l,q_0) to calculate the complex coherence of (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 at that height. The next 2 terms r(z) < f²> determine the brightness of the vegetation at height z, with r(z) being the number of scatterers per unit volume at z and < f²> 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 r(z). The main physical assumption in (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.

Estimating and Validating Forest Vegetation Profiles from the InSAR Cross Correlation

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 r(z) < f²(z)>. We have made the assumption that 1) it is the variation in the scatterer number density with height, r(z), that is directly proportional to vegetation density profiles. The second assumption is that 2) the brightness per scatterer < f²(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 r(z) < f²>, 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 r(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).

In order to apply (2) to the estimation of profiles in the tropical forests of La Selva Biological Station, Costa Rica, r(z) was considered to be composed of 8 layers, each with uniform density, from 0 to 50 m height. Eight values of the extinction coefficient were chosen, determining relative values of r(z), and both extinction and relative densities were inserted into (2). These 8 values of extinction and corresponding relative values of the scatterer number density are varied until the coherences and phases of (2), with many different baselines, match those of the data as closely as possible. The resulting relative values of r(z) are taken to be the relative vegetation density profile. 18 effective baselines were used at La Selva by varying the altitude of the AirSAR airborne radar. Because InSAR sensitivity is proportional to the baseline length over the radar altitude, the multialtitude approach is equivalent to a multibaseline approach. The data were taken at C-band (wavelength=0.056 m) and at vertical (V) polarization.

Field-measured vegetation density profiles were obtained as illustrated in Figure 3 to validate InSAR profile estimates. The total height of each tree along 100-m transects, within 10 m of the transect line, was measured along with the commercial height (where the

trunk first forks), yielding the length of the line "c" in the figure. The x- and y-axes of the leaf canopy were also measured, yielding the lines "a" and "b" in the figure. The total volume of the resulting ellipses for each tree lying within 1-m vertical bins, one of which is shown as a dashed line in figure 3, was taken to be the field-measured vegetation density for each bin at z. Explicitly, the vegetation density is derived from the field measurements as

$$Density(z) \propto \sum_{i=1}^{number\ of\ trees\ overlapping\ z \pm \Delta z/2} \int_{z_{lo_i}}^{z_{hi_i}} \frac{\pi}{4} a_i b_i \left(1 - \left(\frac{z - z_i}{c_i}\right)^2\right) dz \qquad (3)$$

where z_i is the center of each tree with any part inside the bin at z, and a_i and b_i are the x- and y-axes of the ellipses describing tree i. The integration limits are between the lowest and highest points for each tree within the bin Dz thick.

Figure 4 shows preliminary results for the 8 extinction coefficients, or equivalently the 8 relative values of r(z) as a function of height estimated for a primary forest stand at La Selva in black. The field-estimated density, as described above, is in green, and a lidar profile (BLAIR et al., 2004) is shown in green. There is reasonable agreement between the InSAR profile and those of the field and lidar, in that the error bars of the InSAR are close to the field and lidar profiles. Means of reducing the InSAR error bars include using all 18 baselines—only 9 were used for Figure 4—and improving the calibration of noise and range decorrelation as well as improving parameter estimation procedures. Error bars for the field and lidar measurements will also help to determine the significance of the agreement of all three profiling measurements.

Figure 3. Each ellipse corresponds to a tree canopy. The total height, commercial height, and the x- and y-extents of each tree were measured to obtain the height, c, and the ellipse axes a and b for calculation of the ellipse volume inside the dashed lines indicating one vertical bin. The height "z" of the bin is indicated by the alternate dashed line, and the top and bottom of the bin of thickness Dz bin are shown with dashed lines
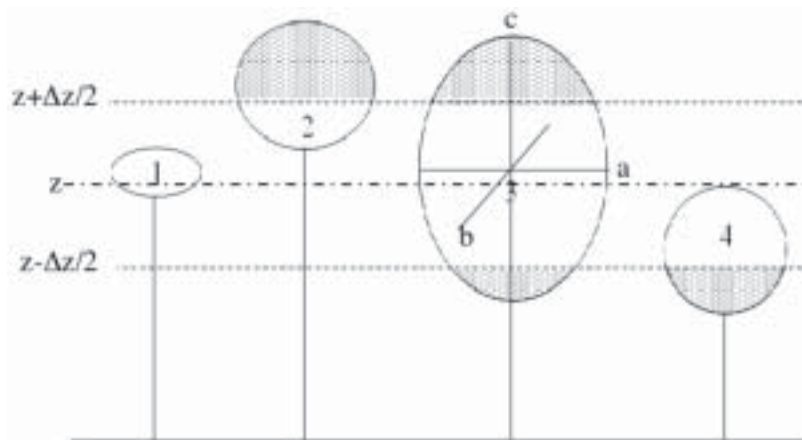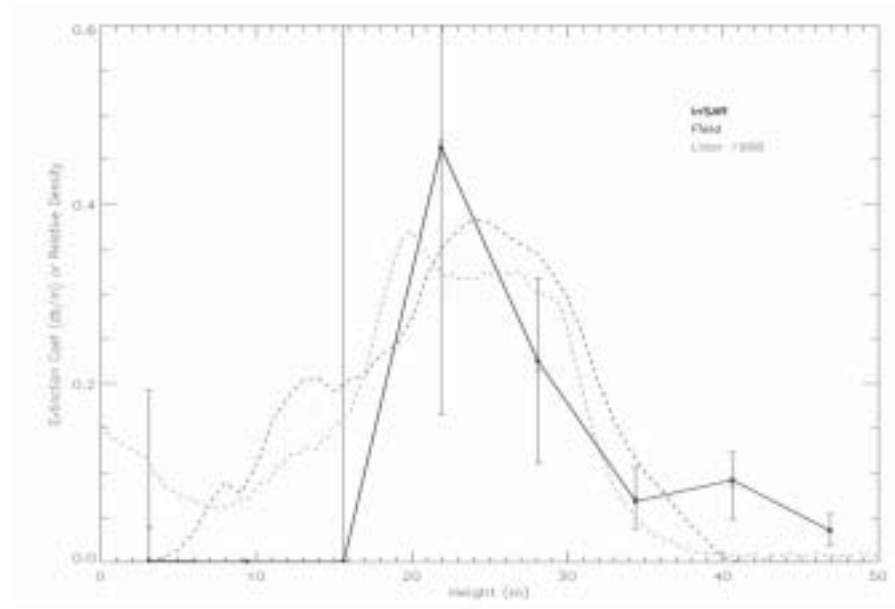
Figure 4. Extinction coefficient, or vegetation relative density, as a function of forest height for primary forest at La Selva Biological Station, Costa Rica. The black line with error bars is the InSAR determination using parameter estimation and (2). The red line is determined from the field measurements indicated in Figure 3, and the green line is a lidar power profile from Blair et al., 2004

Conclusions

InSAR has potential as a vegetation profiling remote sensing technique. A single InSAR cross correlation essentially sums the contributions of each vegetation component in a vectorial way. An integral expression formally describes this vectorial sum and depends on a quantity called the "vegetation number density" or r(z). This density, which is the number of vegetation scatterers per unit volume, is assumed to be proportional to both the vegetation density—e.g. leaf area density—and the extinction coefficient. Field measurements of density are derived from the commercial height, the total height, and the x and y axes of the canopy of each tree, assumed to be ellipsoids. First InSAR profiles from 9 baselines over La Selva Biological Station in Costa Rica have reasonable agreement with field and lidar measurements, but the formal errors (the error bars) are large. Future work will include reducing errors by using a complete set of observations, 18 baselines instead of 9, and more accurate InSAR calibration procedures. We will also produce InSAR profiles for 30 sites measured in the field, including primary, secondary and selectively logged tropical forests, along with abandoned pastures.

Acknowledgments

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