Estimating Forest Vertical Structure from Multialtitude, Fixed-Baseline Radar Interferometric and Polarimetric Data

Robert N. Treuhaft[1], Beverly E. Law[2], and Paul R. Siqueira[3]

[1]Jet Propulsion Laboratory, MS 138-212, California Institute of Technology
4800 Oak Grove Drive, Pasadena, California 91109
Tel/Fax: 818-354-6216/818-393-5115 email: rnt@radar-email.jpl.nasa.gov
[2]Department of Forest Science, Peavy Hall 154 Oregon State University Corvallis, OR 97331
Tel/Fax: 541-737-2996/541-737-2540 email: lawb@ccmail.orst.edu
[3]JPL MS 300-235, Tel/Fax: 818-393-9285/818-393-5285 email: siqueira@southport.jpl.nasa.gov

1. INTRODUCTION

Parameters describing the vertical structure of forests, for example tree height, height-to-base-of-live-crown, underlying topography, and leaf area density, bear on land-surface, biogeochemical, and climate modeling efforts [1]. Single, fixed-baseline interferometric synthetic aperture radar (INSAR) normalized cross-correlations constitute two observations from which to estimate forest vertical structure parameters: Cross-correlation amplitude and phase. Multialtitude INSAR observations increase the effective number of baselines potentially enabling the estimation of a larger set of vertical-structure parameters. Polarimetry and polarimetric interferometry can further extend the observation set. This paper describes the first acquisition of multialtitude INSAR for the purpose of estimating the parameters describing a vegetated land surface. These data were collected over ponderosa pine in central Oregon near longitude and latitude -121 37 25 and 44 29 56. The JPL interferometric TOPSAR system [2] was flown at the standard 8-km altitude, and also at 4-km and 2-km altitudes, in a race track. A reference line including the above coordinates was maintained at 35° for both the north-east heading and the return south-west heading, at all altitudes. In addition to the three altitudes for interferometry, one line was flown with full zero-baseline polarimetry at the 8-km altitude. A preliminary analysis of part of the data collected suggests that they are consistent with one of two physical models describing the vegetation: 1) a single-layer, randomly oriented forest volume with a very strong ground return or 2) a multilayered randomly oriented volume; a homogeneous, single-layer model with no ground return cannot account for the multialtitude correlation amplitudes. Below the inconsistency of the data with a single-layer model is followed by analysis scenarios which include either the ground or a layered structure. The ground returns suggested by this preliminary analysis seem too strong to be plausible, but parameters describing a two-layer compare reasonably well to a field-measured probability distribution of tree heights in the area.

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2. THE DATA IN THIS ANALYSIS

At each altitude, both single-transmit and alternate-transmit (ping-pong) C-band data were collected. Ping-pong data yield a baseline effectively twice the physical baseline. The interferometric sensitivity to vertical structure is determined by the derivative of interferometric phase ϕ with respect to target altitude z holding the range r and azimuth η coordinates fixed, given by [3]

$$\frac{\partial\phi}{\partial z}\Big|_{r,\eta} \equiv \alpha_z = \frac{k_0 B \cos(\theta_0 - \delta)\cos\theta_0}{h \sin\theta_0} \quad (1)$$

where k_0 is the wave number, B is the baseline length, h is the radar altitude, θ_0 is the incidence angle, and δ is the angle of the baseline with the horizontal. Flying at h =4- and 2-km altitudes increases the effective baseline and interferometric sensitivity and yields effective baselines at 2.5m (the physical TOPSAR baseline), 5, 10, and 20 m, with the middle two baselines redundant because they are realized with single-transmit and ping-pong acquisition. In order to conduct the most complete analysis for the estimation of forest vertical structure parameters, the amplitudes and phases of all the data from all altitudes plus the polarimetry should be characterized by simply physical models depending on vegetation structure parameters [4]. At the time of publication of this paper, only the INSAR correlation amplitudes were available for the 8-km altitude return line, at a heading of 239°, and the 4-km altitude line at 59° heading, as shown in the table below:

Altitude	Heading	Transmit Mode	Incidence Angle	Amplitude
8 km	239°	Single-transmit	36.5°	0.914+/-0.012
8 km	239°	Ping-pong	36.5°	0.724+/-0.030
4 km	59°	Single-transmit	40.5°	0.784+/-0.023
4 km	59°	Ping-pong	40.5°	0.618+/-0.037

Table 1: The data subset from which vertical structure parameters were estimated in this paper.

The incidence angle in Table 1 refers to a forested area near the pine flux tower close to the above coordinates. Although it was planned for this area to be at the same incidence angle for each heading, aircraft displacements of $\approx$800 m apparently caused the slightly different incidence angles. In the analysis that follows, the difference in incidence angle is actually an asset because it diversifies the data set and allows for more accurate parameter estimation. The correlation amplitudes in the last column of Table 1 are corrected for the thermal-noise and the range-decorrelation effects [3], and reflect the amplitude due to the vertical structure of vegetation. As expected, correlation amplitude decreases with increasing α_z [3]. The errors shown are based on the internal scatter of the correlation amplitudes within the forested area, which approximately 200 m on a side. Because the data have not been fully calibrated yet, an *a posteriori* calibration was done for the forested area in the Table by requiring that the vegetation-induced correlation be equal to unity over the nearby Circle M Ranch, which is flat with very low-lying vegetation. Systematic shifts in correlation amplitude, for example between ping-pong at 8 km and single-transmit at 4 km (with nearly identical α_z), were applied to the data based on the Circle M Ranch amplitudes, but the origins of these corrections are not yet understood and constitute a possible source of error in this analysis.

3. DATA SENSITIVITY TO VERTICAL STRUCTURE

Figure 1 shows a calculation (the curved lines) of cross-correlation amplitude versus tree height, for homogeneous, single-layer, randomly-oriented volume with no ground surface. Each curved line corresponds to one of the experimental configurations (altitude, transmit mode, and incidence angle) in Table 1. Each of the horizontal lines corresponds to the data in the last column of Table 1. The calculated model would be a good fit to the data if each horizontal line intersected a curved line for *one* value of tree height. What Figure 1 therefore shows is that a single-layer randomly-oriented volume cannot explain the data at the baselines, altitudes, and incidence angles in this analysis. Figure 1 also shows the importance of multibaseline observations. If just the 8-km altitude

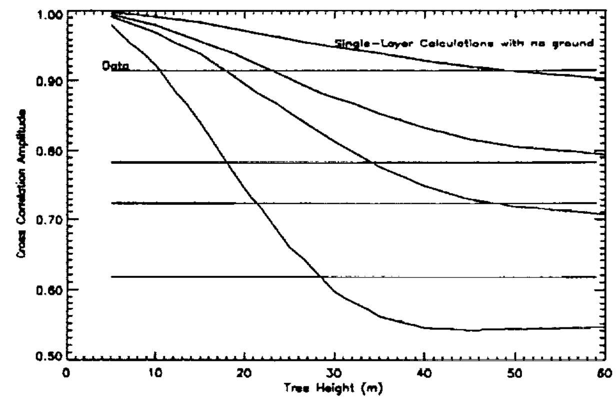

Figure 1: Calculated and measured INSAR amplitudes.

data (the first two entries of Table 1) were available, the corresponding curved lines on Figure 1 (the first and third from the top) do intersect the first and third horizontal lines for tree heights close to 50 m. The addition of the other data points at a different incidence angle and altitude shows that the single-layer volume with no ground return does *not* account for these data. In the absence of the additional altitude, these data would have erroneously been assumed to be consistent with a $\approx$ 50-m tree height.

4. ANALYSIS AND RESULTS

The analysis is prompted by the conclusion of Figure 1 that a more complicated model is needed to account for the data. A parameter estimation analysis was done using each of two physical-model scenarios: 1) a randomly oriented volume with a direct ground-surface return, and 2) a two-layer randomly oriented volume with no ground return. Schematically the first estimation scenario can be represented as (details in [4])

$$\begin{pmatrix} \text{Tree height} \\ \text{Extinction coefficient} \\ \text{Ground/volume power} \end{pmatrix} = M_1^{-1} \begin{pmatrix} \text{Amplitude 1} \\ \text{Amplitude 2} \\ \text{Amplitude 3} \\ \text{Amplitude 4} \end{pmatrix} \tag{2}$$

and the second two-layer scenario as

$$\begin{pmatrix} \text{Tree height} \\ \text{Crown extinction coef.} \\ \text{Height to base of crown} \\ \text{Subcrown ext. coef.} \end{pmatrix} = M_2^{-1} \begin{pmatrix} \text{Amplitude 1} \\ \text{Amplitude 2} \\ \text{Amplitude 3} \\ \text{Amplitude 4} \end{pmatrix} \tag{3}$$

where M_1^{-1} represents the use of a physical model describing the randomly-oriented volume + direct ground surface return for parameter estimation, and M_2^{-1} represents the physical model of the two-layer system.

Table 2 gives the parameter estimates for scenario 1:

Tree Height	Extinction Coefficient	Ground/Volume Power
29.3 m	0.24 db/m	3.2

Table 2: Estimated parameters using a physical model including a single-layer volume with a ground surface.

While the first two parameters are somewhat reasonable for what is expected from ground measurements of this terrain and analysis of Boreal forest data [4], the last parameter is not reasonable. The ground/volume power ratio should be about 10% at C-band, based on [4] and [5]. In the analysis of Boreal forest data in [4], it was found that including polarimetric data in the parameter estimation was important for constraining the ground/volume ratio, and that may be the case here too when the acquired polarimetry is incorporated. For now, the second model scenario produces more reasonable parameter estimates, as shown in Table 3:

Height-to-base-of-crown	Subcrown Extinction Coefficient	Tree Height	Crown Extinction Coefficient
7.9 m	2.9 db/m	42.2 m	0.02 db/m

Table 3: Estimated parameters using a physical model including two volume layers.

The field-measured probability density function (pdf) of tree heights in the region over which the data of Table 1 were taken is shown in Figure 2. Site data show that the forest in this area is dominated by two height classes

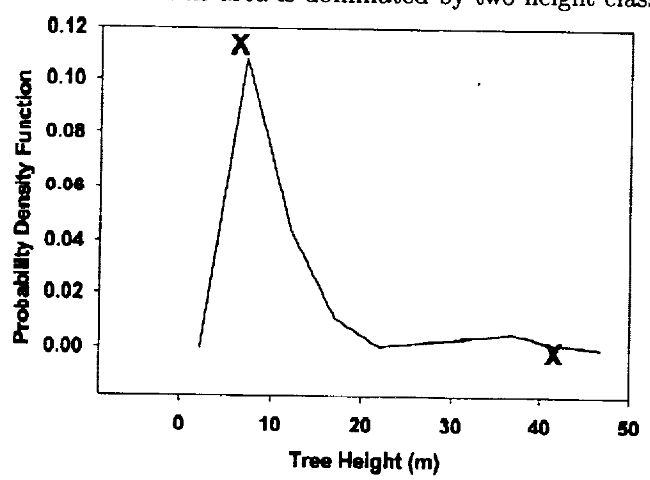

Figure 2: Field-measured probability density function of tree heights. **X**'s mark the height-to-base-of-crown and tree-height parameters from multialtitude INSAR.

of ponderosa pine, one with height 10 m and tree density of 0.056 tree/m^2, and one with height 35 m and tree density of 0.007 trees/m^2, as indicated in the pdf. The X's show the height-to-base-of-crown and tree height parameters of Table 2, with relative ordinate given by the relative values of the extinction coefficients. If the height-to-base-of-crown and tree-height parameters are interpreted as the heights of the shorter and taller trees respectively, and the ratio of the extinction coefficients as the relative densities of the two tree classes, there is qualitative agreement with the field-measured pdf of Figure 2.

5. SUMMARY AND FUTURE ESTIMATION

This paper demonstrates the feasibility of using multialtitude, fixed-baseline INSAR to estimate vertical-structure parameters of forests. Two model scenarios applied to C-band INSAR data collected at 8-km and 4-km altitudes over central Oregon with TOPSAR suggest the need for either a ground surface contribution with a single vegetation layer or a two-layer vegetation model. The two-layer model parameters seem more reasonable and qualitatively reflect the field-measured characteristics of the forest studied. The parameters produced from the single set of INSAR cross-correlations in this paper do not constitute a proof that multialtitude INSAR will reliably produce vertical structure parameters, but they do prompt future, more complete demonstrations. A complete set of amplitudes and phases will be used in parameter estimation scenarios, augmenting those shown in (2) and (3), from 2-, 4-, and 8-km altitude INSAR. Including polarimetry in the observation vector will constrain ground/volume power fractions and terrain slope parameters.

6. ACKNOWLEDGMENTS

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