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

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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.

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 \( \phi \) with respect to target altitude \( z \) holding the range \( r \) and azimuth \( \eta \) coordinates fixed, given by [3]

\[
\frac{\partial \phi}{\partial z} |_{r, \eta} = \alpha_z = \frac{k_0 B \cos(\theta_0 - \delta) \cos \theta_0}{h \sin \theta_0}
\]

where \( k_0 \) is the wave number, \( B \) is the baseline length, \( h \) is the radar altitude, \( \theta_0 \) is the incidence angle, and \( \delta \) 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:

<table>
<thead>
<tr>
<th>Altitude</th>
<th>Heading</th>
<th>Transmit Mode</th>
<th>Incidence Angle</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 km</td>
<td>239°</td>
<td>Single-transmit</td>
<td>36.5°</td>
<td>0.914+/-0.012</td>
</tr>
<tr>
<td>8 km</td>
<td>239°</td>
<td>Ping-pong</td>
<td>36.5°</td>
<td>0.724+/-0.030</td>
</tr>
<tr>
<td>4 km</td>
<td>59°</td>
<td>Single-transmit</td>
<td>40.5°</td>
<td>0.784+/-0.023</td>
</tr>
<tr>
<td>4 km</td>
<td>59°</td>
<td>Ping-pong</td>
<td>40.5°</td>
<td>0.618+/-0.027</td>
</tr>
</tbody>
</table>

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 ≈800 m apparently caused the slightly different inci-
dence 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 esti-
mation. 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, cor-
relation amplitude decreases with increasing αz [3]. The
errors shown are based on the internal scatter of the corre-
lation amplitudes within the forested area, which approx-
imately 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 αz), 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 ex-
perimental 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 ex-
plain 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
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 alti-
itude 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 ≈ 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])

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

and the second two-layer scenario as

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

where $M_1^{-1}$ represents the use of a physical model describ-
ing 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:

<table>
<thead>
<tr>
<th>Tree Height</th>
<th>Extinction Coefficient</th>
<th>Ground/Volume Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.3 m</td>
<td>0.24 db/m</td>
<td>3.2</td>
</tr>
</tbody>
</table>

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:

<table>
<thead>
<tr>
<th>Height-to-base-of-crown</th>
<th>Subcrown Extinction Coefficient</th>
<th>Tree Height</th>
<th>Crown Extinction Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5 m</td>
<td>2.9 db/m</td>
<td>42.2 m</td>
<td>0.02 db/m</td>
</tr>
</tbody>
</table>

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 of ponderosa pine, one with height 10 m and tree density of 0.056 tree/m², and one with height 35 m and tree density of 0.007 trees/m², 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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7. REFERENCES