Simulated and Observed Backscatter at P-, L-, and C-Bands from Ponderosa Pine Stands
Yong Wang, Frank W. Davis, and John M. Melack

Abstract—We compared the output of the Santa Barbara microwave canopy backscatter model to polarimetric synthetic aperture radar (SAR) data for three ponderosa pine stands (ST-2, ST-11, and SP-2) with discontinuous tree canopies near Mt. Shasta, California, at P-band (0.68-m wavelength), L-band (0.235-m wavelength), and C-band (0.656-m wavelength). Given the SAR data calibration uncertainty, the model made good predictions of the P-HH, P-VV, L-HH, C-HH, and C-HV backscatter for the three stands, and the P-HV and L-HV backscatter for ST-2 and SP-2. The model underestimated C-VV for the three stands, and P-HV, L-HV, and L-VV backscatter for ST-11. The observed and modeled VV-HH phase differences were $\approx 0^\circ$ for the three stands at C-band and L-band, and for SP-2 at P-band. At P-band, the observed and modeled VV-HH phase differences were at least $-80^\circ$ for ST-2 and ST-11, which indicates that double-bounce scattering contributes to the total backscatter for the two stands.

I. INTRODUCTION

SEVERAL analytical models have been developed to predict microwave scattering by trees and forests [1]–[6]. These models contribute to the understanding of radar backscatter over forested regions to the extent that they capture the basic interactions between microwave radiation and tree canopies, understories, and ground layers as functions of incidence angle, wavelength, and polarization. The Santa Barbara microwave canopy backscatter model for stands with discontinuous tree canopies combines a single-tree backscatter model and a gap probability model [5]–[6]. Comparison of the model predictions with synthetic aperture radar (SAR) data at L-band for Alaskan boreal forests is promising [6], but much work is needed to test the validity of the model predictions at other wavelengths, and for other types of forests. Here we test the validity of the model's predictions by comparing the modeled results with those of the Jet Propulsion Laboratory (JPL) airborne polarimetric SAR data obtained on September 6, 1989, for three ponderosa pine stands near Mt. Shasta, California, at P-, L-, and C-bands. We also use the HH/VV backscatter ratio to identify the trunk-ground scattering versus non-trunk-ground scattering for the stands.

II. STUDY AREA

The site is located to the southeast of Mt. Shasta, California (41°18' N, 122°05' W), and spans elevations from 1160 to 1220 m. Annual precipitation falls mainly as snow between November and April. The forest stands under investigation are natural, occur on level ground and are dominated by ponderosa pine (Pinus ponderosa) or pine mixed with white fir (Abies concolor). Understory vegetation is sparse and consists primarily of perennial grasses and forbes. The litter layer can reach a thickness of about 0.1 m. The soil is derived from recent alluvial deposits of volcanic ash (see [6] for more details).

A. Stand Data

Three ponderosa pine stands, SP-2, ST-2, and ST-11, have different stand densities, tree trunk diameter at breast height (dbh), and other characteristics (Table I). Based on field measurements, we assume that trees in a given stand are randomly distributed, and that tree dbh in the stand is lognormally distributed. In SP-2, trees have foliage-bearing branches extending nearly to the base of the trunk, so that crown depth is roughly equivalent to tree height. Thus, the same regression equation of the tree height on dbh is used for the crown depth on dbh. The regression equation is: tree height (m) = 25.68dbh (m) + 5.02 ($r^2 = 0.80$). The crown width (at half crown depth) is also linearly related to dbh (tree crown width (m) = 7.04dbh (m) + 3.64, $r^2 = 0.71$). In ST-2 and ST-11, tree height and crown width are linearly related to dbh. The regression equations are: tree height (m) = 47.56dbh (m) + 5.21 ($r^2 = 0.87$), and tree crown width (m) = 7.95dbh (m) + 1.20 ($r^2 = 0.79$). Crown depth is not as well predicted by dbh (tree crown depth (m) = 24.08dbh (m) + 7.1, $r^2 = 0.52$).
TABLE II
CROWN CONSTITUENT PARAMETERS OF PONDEROSA PINES

<table>
<thead>
<tr>
<th>Branch Type</th>
<th>Density (kg/m³)</th>
<th>( \mu_1 ) (m)</th>
<th>( \mu_2 ) (m)</th>
<th>( \sigma_1 ) (m)</th>
<th>( \sigma_2 ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large branch (SP-2)</td>
<td>0.14</td>
<td>2.48</td>
<td>0.79</td>
<td>0.050</td>
<td>0.042</td>
</tr>
<tr>
<td>Large branch (ST-2 and ST-11)</td>
<td>0.37</td>
<td>1.20</td>
<td>0.54</td>
<td>0.028</td>
<td>0.007</td>
</tr>
<tr>
<td>Medium branch</td>
<td>1.59</td>
<td>0.57</td>
<td>0.38</td>
<td>0.014</td>
<td>0.003</td>
</tr>
<tr>
<td>Small branch</td>
<td>12.13</td>
<td>0.24</td>
<td>0.16</td>
<td>0.006</td>
<td>0.002</td>
</tr>
<tr>
<td>Needle</td>
<td>2370</td>
<td>0.20</td>
<td>0.023</td>
<td>0.0005</td>
<td>NA</td>
</tr>
</tbody>
</table>

\( \mu_1 \) and \( \sigma_1 \), and \( \mu_2 \) and \( \sigma_2 \) are the means and standard deviations of branch lengths and radii, respectively.

Branch and needle measurements of six felled pine trees were used to characterize needle density and size, and branch density and size of ST-11 and ST-2 (Table II). For each sampled tree, two branches were sampled at the midpoint and quartiles of the crown depth. The curved branches and branchlets were divided into segments that were treated as straight cylinders. Branch segment length and diameter are moderately correlated \( (r^2 = 0.49) \). Based on the frequency distribution of branch diameters \( (d) \), we defined three branch size classes: large \( (d > 4.0 \text{ cm}) \), medium \( (2.0 \text{ cm} < d \leq 4.0 \text{ cm}) \), and small \( (d \leq 2.0 \text{ cm}) \) [6].

The crown structure of the large and isolated trees in SP-2 differed from those in ST-2 and ST-11. For SP-2, the density of large branches was estimated from ground photography, and large branch lengths and radii were measured. In the absence of direct measurements, trees in SP-2 were assumed to have the same medium branch, small branch, and needle characteristics as the sampled individuals.

B. Assumptions Made for Other Model Inputs

The azimuth angles of trunks were assumed uniformly distributed. The zenith angles of the trunks were assumed to be a Gaussian distribution, centered on the vertical and with one standard deviation of 5°. Large, medium, and small branches were assumed to be uniformly distributed in azimuth. The zenith distribution for large branches was measured. Large branches were mainly horizontally distributed. The zenith distributions for medium and small branches were assumed to be uniform. Needles were assumed to be uniformly distributed in azimuth and zenith.

Measurements of dielectric constants for trunks, branches, and needles collected in September 1989 were unreliable because of instrument instability and difficulties of measurement technique. We used the dielectric data from Sun et al. [5] who assumed the same dielectric constants for trunks, branches, and needles. The dielectric constants for C1, L, and P-bands were \((22.5, -j7.5)\), \((20.0, -j5.0)\), and \((20.0, -j4.0)\), respectively.

Because ST-2 and ST-11 had moister soil than SP-2 in September 1989, a slightly higher dielectric constant \((6.0, -j1.5)\) was assumed for ST-2 and ST-11 in comparison with \((5.0, -j1.0)\) for SP-2. For the three stands, ground surface roughness height and correlation length were assumed to be 0.011 m and 0.06 m. Based on the surface roughness parameters, at P-band and L-band we used the small perturbation model to predict surface backscatter. At C-band, the geometric optical model was used.

III. SANTA BARBARA MICROWAVE CANOPY BACKSCATTER MODELING FOR DISCONTINUOUS TREE CANOPIES

We briefly describe the Santa Barbara microwave canopy backscatter model for stands with discontinuous tree canopies [5]–[6]. This model combines a single-tree backscatter model and a gap probability model. The modeling approach determines the probability that a radar ray hits zero tree crown, one crown, two crowns, . . . , before hitting the ground surface. The model is assembled from four major model components represented by 4×4 transformation matrices [4]. The major components correspond to four major forest scattering mechanisms [5], [6]: surface backscatter \( (T_s) \), crown volume scattering \( (T_v) \), crown-ground multiple path interactions \( (T_m) \), and double-bounce trunk-ground interactions \( (T_d) \). We define a set of model subcomponents (of each major component) by permuting all the possible scattering and attenuation paths for each scattering mechanism, and compute the probability of subcomponent occurrence by apportioning the probability of a scattering mechanism event among the possible paths. The formulation and weighting of these subcomponents, and the four major model components are described in detail in [6]. Incoherent summation of the subcomponents yields the components; incoherent summation of the components results in total backscatter. Thus, the total backscatter \( (T_t) \) is [5], [6]

\[
T_t = T_s + T_v + T_m + T_d. \tag{1}
\]

Our model inputs include stand parameters, crown constituent parameters, ground surface parameters, and dielectric constants (Table I), as well as radar system parameters (wavelength, polarization, and incidence angle). Model outputs are the HH, HV, and VV backscatter, the VV-HH phase difference, and the HH and VV correlation coefficient [6]. These five kinds of outputs are directly related to the JPL polarimetric SAR system measurements [10].

The model is intended for modeling stands with discontinuous tree canopies. In contrast, other forest canopy backscatter models [1]–[4] model the canopy as a continuous uniform layer, and are suited for continuous canopies. Based on the field observation, tree canopies of the three stands are discontinuous, and crowns do not interlock. Thus, a model that treats trees as individual scatterers appears more appropriate for these stands than models with layered canopy structure.

IV. SAR DATA

Eight JPL airborne SAR data takes were acquired on September 6, 1989 after a dry summer. The SAR data were processed and calibrated by JPL, using 6 ft (1.83 m) and 8 ft (2.44 m) tridedral corner reflectors. The estimated calibration uncertainty of backscatter is \( \pm 1.0 \text{ dB} \) [7]. The estimated calibration uncertainty of the VV-HH phase difference is \( \pm 10° \) [10]. The calibration uncertainty of the HH and VV correlation coefficient for the Shasta SAR dataset is not
available. This uncertainty depends on the signal to noise ratio of the data, and the variability of scattering mechanisms within a resolution cell (pixel). However, a nominal uncertainty of ±0.1 was estimated by JPL [10]. We received the standard 4-look compressed data with pixel spacing of 12.1 m (azimuth) and 6.7 m (slant range). To compute the mean and standard deviation of SAR data for a stand, we located the stand on the SAR imagery, and the largest possible window within the stand was extracted. For each stand and each SAR data take, at least 400 image pixels were averaged. Thus, we will compare the obtained and modeled backscatter based on mean stand values rather than per pixel values.

TABLE III

<table>
<thead>
<tr>
<th>SAR DATA COVERAGE OF THE THREE STANDS AT MT. SHASTA SITE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data takes</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>ST-2</td>
</tr>
<tr>
<td>ST-11</td>
</tr>
<tr>
<td>SP-2</td>
</tr>
<tr>
<td>NC—not covered by SAR data takes.</td>
</tr>
</tbody>
</table>

B. Comparison of Modeled Backscatter (HH, HV, and VV) with SAR Data

Given the calibration uncertainty, the model makes good predictions of the P-HH and P-VV backscatter for the three stands (Figs. 2(a),(b)), and the P-HV backscatter for ST-2 and SP-2 (Fig. 2(c)). The model underestimates P-HV backscatter for ST-11. The maximum underestimate is 2.48 dB. Modeled L-HH backscatter agrees with SAR L-HH backscatter for the three stands (Fig. 3(a)), and the L-VV and L-HV backscatter for ST-2 and SP-2 (Figs. 3(b),(c)). The model underestimates the VV and HV backscatter for ST-11. The maximum underestimates are 2.42 dB for L-VV backscatter (Fig. 3(b)), and 3.74 dB for L-HV backscatter (Fig. 3(c)). At C-band, for the three stands model output agrees with observed HH and HV backscatter (Figs. 4(a) and (c)), but underestimates the VV backscatter (Fig. 4(b)).

C. Comparison of Modeled HH and VV Correlation Coefficient with SAR Data

At P-band, the model closely predicts the HH and VV correlation coefficients of SP-2 and ST-2, but overestimates the
coefficients of ST-11 (Fig. 5(a)). The maximum overprediction is 0.29 for ST-11. The overestimate may be attributed to the uncertainty of the mean SAR HH and VV correlation coefficients, because in the sampled windows (of the SAR data), the standard deviations of the correlation coefficients range from 0.62 to 0.70.

At L-band, the modeled HH and VV correlation coefficients are roughly equal to those of the SAR data for ST-2 and ST-11 (Fig. 5(b)). However, the model overestimates the correlation coefficient for SP-2 (Fig. 5(b)), the maximum overestimate is 0.34.

At C-band, the model overpredicts the correlation coefficients (Fig. 5(c)) for all stands. The maximum overestimates are 0.44 for SP-2, 0.55 for ST-2, and 0.55 for ST-11. We may attribute the overestimate to the uncertainty of the mean SAR HH and VV correlation coefficients, because in the sampled windows (of SAR data) the standard deviations of the correlation coefficients range from 0.42 to 0.60 for SP-2, from 0.62 to 0.72 for ST-2, and from 0.60 to 0.70 for ST-11.

The observed standard deviations of the correlation coefficients data for the three ponderosa pine stands are much greater than the nominal value (±0.1) suggested by JPL (see Section IV). There are large uncertainties of the mean values for the correlation coefficients used in the comparison. Therefore, caution should be exercised in interpreting the results of the comparison.

D. Comparison of Modeled VV-HH Phase Difference with SAR Data

Because the VV-HH phase difference has a period of 360°, the phase differences of 0° and 360° are the same. A VV-HH phase difference of 0° (360°) means that the scattering...
mechanism is a single scattering, whereas a VV-HH phase difference of 180° suggests that the scattering mechanism be a double-bounce scattering [8]. Because the mean of 0° and 360°, 180°, suggests a different scattering mechanism compared to the scattering mechanism shown by 0° or 360°, the simple arithmetic mean of the phase differences cannot be used to study the statistics of the phase differences. Therefore, to capture the major scattering mechanism in the stands, we compare the VV-HH phase difference at the mode of the phase difference distribution (from the sampled SAR data window) to that at the mode of the phase difference distribution from the simulated pixels. At C-, L-, and P-bands, a VV-HH phase difference \(\approx 0°\) for SP-2 was observed by the SAR, and predicted by our model (Fig. 6). Based on van Zyl's algorithm [8], the major scattering mechanism in stand SP-2 is single scattering (such as surface backscatter). Because SP-2 has a low stand density (Table I), most of the ground surface is exposed in this stand, and surface backscatter is strong.

ST-2 and ST-11 have similar VV-HH phase difference properties at P-, L-, or C-band. As one example, we select ST-2 to discuss the VV-HH phase difference. At P-band, the observed VV-HH phase differences at the mode were at least \(-80°\) (Fig. 7(a)). According to van Zyl's algorithm [8], the major scattering mechanism inside the sampled areas is either diffuse scattering or double-bounce scattering. The model predicts a VV-HH phase difference of \(\approx -160°\) for ST-2 (Fig. 7(b)), with most of the simulated pixels classified as having double-bounce scattering mechanism [8]. Thus, SAR data and modeled outputs both suggest that trunk-ground term contributes to the total backscatter. However, since this contribution is not dominant, a VV-HH phase difference \(\approx 180°\) (or \(-180°\)) is not observed or modeled. For ST-2, at L-band and C-band, a VV-HH phase difference \(\approx 0°\) is observed by the SAR, and predicted by the model (Fig. 7). Again, the classified results of the observed and simulated pixels suggests that the major scattering mechanism is diffuse scattering for some pixels and single scattering for others.

VI. DISCUSSION

A. Modeling the Major Scattering Mechanisms in Forests

Using the polarimetric SAR imagery, van Zyl [8] studied three scattering mechanisms, the single, double-bounce, and diffuse scatterings, in forests. The VV-HH phase differences (used as measures) for the single scattering and double-bounce scattering are 0° and 180°. When multiple scattering is present [9], diffuse scattering occurs. The VV-HH phase difference of the diffuse scattering changes rapidly, causing some of the individual scatterers from the multiple scattering to exhibit the single scattering property, but others to show the double-bounce scattering property [8]. Here, we use backscatter model to study scattering mechanisms, because
we know the backscatter of each model component, and the relative contribution of each model component to the total backscatter. If one scattering component dominates both the HH and VV backscatter, the main scattering mechanism of the total backscatter (sum of all model components) will respond roughly to the same scattering mechanism as the dominant one. Conversely, when one scattering component dominates HH backscatter, and another dominates VV backscatter, the scattering mechanism of the total backscatter will be the scattering mechanism of the one or the other, depending on the relative contribution of the components to the total HH and VV backscatter. This dependency is further affected by the relative magnitude of the HH and VV backscatter. For example, if the HH backscatter is stronger than that of the VV backscatter, the dominant component in HH backscatter weighs more than the dominant component in VV backscatter.

For ST-2, the trunk-ground term dominates the modeled P-HH backscatter, with some contribution from the crown volume scattering (Fig. 8(a)). For the same stand, crown volume scattering dominates the P-VV backscatter, with some contribution from the trunk-ground term (Fig. 8(b)). Because the HH backscatter is slightly greater than the VV backscatter, the scattering mechanism of the trunk-ground component is the major scattering mechanism of the total backscatter, yielding a modeled VV-HH phase difference around $-160^\circ$ at the mode of the phase difference distribution (Fig. 7(b)).

At L-band, crown volume scattering and the trunk-ground term contribute roughly equally to the total HH backscatter (Fig. 8(c)). Crown volume scattering dominates L-VV backscatter (Fig. 8(d)), yielding a modeled VV-HH phase difference around $0^\circ$ at the mode of the phase difference distribution (Fig. 7(b)).

At C-band, the crown volume scattering dominates the HH and VV backscatter. Thus, the scattering mechanism of the crown volume scattering is the major scattering mechanism of the total backscatter, with a modeled VV-HH phase difference around $0^\circ$ at the mode of the phase difference distribution (Fig. 7(b)).

**B. HH/VV Backscatter Ratio as a Measure of Trunk-Ground Term**

For a coniferous tree, the tree trunk contains a large portion of the total tree biomass. Because most of the tree trunks are vertical, direct trunk backscatter is too weak to be used to link backscatter to trunk biomass. However, if one can identify the scattering mechanism related to the trunk, one may be able to develop methods to quantitatively estimate tree biomass. In canopy backscatter modeling [1], [3]–[6], the total radar backscatter is divided into four major components, surface backscatter, crown volume scattering, crown-ground multiple path interactions, and double-bounce trunk-ground interactions. For the four components (see also Fig. 8), we
have found:

- Surface backscatter is only important when \( \theta_a \) is small, and when the surface is wet and rough. Surface VV backscatter is \( \geq \) surface HH backscatter.
- The crown volume scattering has a roughly equal HH and VV backscatter.
- The crown-ground multiple path term is never a dominant component.
- Backscatter from the trunk-ground term is much greater for HH backscatter than for VV backscatter.

Therefore, based on our canopy backscatter modeling on pine stands, and supported by SAR observations of the stands, HH backscatter can only exceed VV backscatter when the trunk-ground term is important, and the HH/VV backscatter ratio can serve as a measure of the trunk-ground term. For natural forests, we hypothesize that 1) if the HH/VV ratio is less than or roughly equal to 0 dB, the trunk-ground term is not dominant, and 2) if the HH/VV is much greater than 0 dB, the trunk-ground term is a major scattering source.

For SP-2, the SAR and modeled HH/VV backscatter ratios were slightly less than or equal to 0 dB at C-band, and slightly less than 0 dB at L-band (Fig. 9). Because the stand is sparse, most of the ground surface is exposed to the radar. The trees have foliage-bearing branches extending to the base of the trunk. Therefore, surface backscatter, as well as crown volume scattering should be the major scattering components. At P-band, the SAR data and the modeled results show that the HH backscatter is greater than the VV backscatter (Fig. 9). Based on our hypotheses, the HH backscatter greater than the VV backscatter suggests that there is some contribution from the trunk-ground interactions to the total backscatter. This can be explained as follows. The surface is smoother at P-band than at L-band and C-band, resulting in less surface backscatter. Increased specular reflection from the surface produces more trunk-ground backscatter. Because of the long wavelength, the crown volume scattering is less, and more incident microwave rays can penetrate the crown to hit trunks. However, taking into account the calibration uncertainty (\( \pm 1.0 \) dB), the HH backscatter may not be significantly greater than the VV backscatter. Therefore, at P-, L-, and C-bands, the trunk-ground term is not a dominant scattering source for SP-2 (see also Fig. 6).

At P-, L-, and C-bands, the HH/VV ratios of ST-2 and ST-11 are similar. SAR data and model prediction show that HH/VV ratio increases as wavelength increases, with the largest ratio at P-band (Fig. 10). The SAR and modeled HH/VV ratios are greater than 3 dB at P-band. SAR data and model prediction suggest that the trunk-ground scattering increases its contribution to the total backscatter as wavelength increases (Fig. 11). (See also Fig. 8 for the contributions from all model components to the total HH and VV backscatter for stand ST-2 at P-, L-, and C-bands.) For a given wavelength, the modeled trunk-ground HH backscatter is at least 5 dB greater than VV backscatter (Fig. 11). These results suggest that the larger the HH/VV backscatter ratio, the more dominant the trunk-ground backscatter. At P-, L-, and C-bands, the HH/VV ratio is consistent with those derived from the VV-HH phase differences in showing the relative importance of trunk-ground scattering (see also Fig. 7).

VII. CONCLUSIONS

Given the JPL airborne SAR data calibration uncertainty, the model makes good predictions of the P-HH, P-VV, L-HH, C-HH, and C-HV backscatter for the three stands, and the P-HV and L-HV backscatter for ST-2 and SP-2. The model underestimates C-VV for the three stands, and P-HV, L-HV, and L-VV backscatter for ST-11.

The observed and modeled VV-HH phase differences are \( \pm 0^\circ \) for the three stands at C-band and L-band, and for SP-2 at P-band. The major scattering mechanism is diffuse scattering for ST-2 and ST-11, and single scattering for SP-2. At P-band, the observed and modeled VV-HH phase differences are at least \( -80^\circ \) for ST-2 and ST-11, which shows that double-bounce scattering contributes to the total backscatter for the two stands.

Based on the canopy backscatter modeling, we have used the HH/VV backscatter ratio to distinguish double-bounce scattering from non-double-bounce scattering in SAR data. The results using the HH/VV ratio are consistent with those derived from the polarimetric SAR data at P-, L-, and C-bands. The HH/VV ratio does not depend on polarimetric SAR data, and thus, provides a means of estimating the importance of double-bounce scattering in SAR systems that only measure
the magnitude of the HH and VV backscatter. To the extent that most forest biomass is stored in standing trunks, this ratio may also provide a means of estimating biomass in coniferous stands, although this hypothesis needs further testing.

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REFERENCES


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