Decomposition of polarimetric synthetic aperture radar backscatter from upland and flooded forests

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(Received 22 August 1995; in final form 24 June 1996)

Abstract. The goal of this research was to decompose polarimetric Synthetic Aperture Radar (SAR) imagery of upland and flooded forests into three backscatter types: single reflection, double reflection, and cross-polarized backscatter. We used a decomposition method that exploits the covariance matrix of backscatter terms. First we applied this method to SAR imagery of dihedral and trihedral corner reflectors positioned on a smooth, dry lake bed, and verified that it accurately isolated the different backscatter types. We then applied the method to decompose multi-frequency Jet Propulsion Laboratory (JPL) airborne SAR (AIRSAR) backscatter from upland and flooded forests to explain scattering components in SAR imagery from forested surfaces. For upland ponderosa pine forest in California, as SAR wavelength increased from C-band to P-band, scattering with an odd number of reflections decreased and scattering with an even number of reflections increased. There was no obvious trend with wavelength for cross-polarized scattering. For a bald cypress-tupelo floodplain forest in Georgia, scattering with an odd number of reflections dominated at C-band. Scattering power with an even number of reflections from the flooded forest was strong at L-band and strongest at P-band. Cross-polarized scattering may not be a major component of total backscatter at all three wavelengths. Various forest structural classes and land cover types were readily distinguishable in the imagery derived by the decomposition method. More importantly, the decomposition method provided a means of unraveling complex interactions between radar signals and vegetated surfaces in terms of scattering mechanisms from targets. The decomposed scattering components were additions to the traditional HH and VV backscatter. One cautionary note: the method was not well suited to targets with low backscatter and a low signal-to-noise ratio.

1. Introduction

Recently Cloude (1992) and van Zyl (1994) showed that polarimetric SAR backscatter can be decomposed into three scattering types: a scattering power with an odd number of reflections, a scattering power with an even number of reflections, and a cross-polarized scattering power. Decomposition is based on the covariance matrix of the scattering terms from a single target.

A single SAR image pixel is typically comprised of many scatterers. The backscatter covariance matrix can be thought of as the average of the covariance matrices of individual scatterers within the pixel. In principle, decomposing this covariance
matrix into constituent reflection types should simplify the backscatter data and render them in a form where they can be more readily related to surface features. Cloude (1992) and van Zyl (1994) laid the theoretical foundation for decomposing a polarimetric SAR image. Here we make an addition to the model put forward by van Zyl (1994). The addition is the development of criteria to identify the scattering mechanisms of the decomposed components. We then implement the revised model, and decompose SAR imagery of upland and flooded forested environments. First we do an empirical test of the target decomposition method by applying it to SAR imagery of dihedral and trihedral corner reflectors positioned on a smooth, dry lake bed. Based on the good results obtained there, we proceed with analyses of the JPL AIRSAR imagery of upland ponderosa pine forests in California and floodplain bald cypress-tupelo forest in Georgia.

2. Method of radar target decomposition

2.1. Decomposition of covariance matrix for azimuthly symmetric and reciprocal targets

Using measurements of a monostatic polarimetric SAR system (e.g., AIRSAR), one can define the covariance matrix \( \mathbf{U} \) for azimuthly symmetric and reciprocal targets as

\[
\mathbf{U} = \begin{bmatrix}
\langle S_{hh} S_{hh} \rangle & 0 & \langle S_{hh} S_{hv} \rangle \\
0 & 2\langle S_{hv} S_{hv} \rangle & 0 \\
\langle S_{hv} S_{hh} \rangle & 0 & \langle S_{vv} S_{vv} \rangle
\end{bmatrix}
\]

\( s_{pq} \) \((p,q = h,v)\) are the scattering elements of \( pq \) polarizations, \( * \) is a conjugate operator for a complex number. Because within each resolution cell of an SAR there are usually many targets scattering the incoming microwave energy, the scattering measured by the SAR is an average (\( \langle \cdot \rangle \)) of all targets within the cell.

To understand the scattering mechanism within the covariance matrix, Cloude (1992) and van Zyl (1994) decomposed \( \mathbf{U} \), as

\[
\mathbf{U} = \lambda_1 \mathbf{K}_1 (\mathbf{K}_1^*)' + \lambda_2 \mathbf{K}_2 (\mathbf{K}_2^*)' + \lambda_3 \mathbf{K}_3 (\mathbf{K}_3^*)'
\]

where \( ' \) is a transpose operator for a vector. \( \lambda_i(i = 1, 2, \text{ and } 3) \) are eigenvalues of \( \mathbf{U} \), \( \mathbf{K}_i(i = 1, 2, \text{ and } 3) \) are eigenvectors of \( \mathbf{U} \), and

\[
\mathbf{K}_1 = \begin{bmatrix} k_{1hh} & k_{1hv} & k_{1vv} \\ k_{1hh} & 0 & k_{1vv} \end{bmatrix}'
\]

\( = \begin{bmatrix} k_{1hh} \ 0 \ k_{1vv} \end{bmatrix}' \)  \hspace{1cm} (3)

\[
\mathbf{K}_2 = \begin{bmatrix} k_{2hh} & k_{2hv} & k_{2vv} \\ k_{2hh} & 0 & k_{2vv} \end{bmatrix}'
\]

\( = \begin{bmatrix} k_{2hh} \ 0 \ k_{2vv} \end{bmatrix}' \)  \hspace{1cm} (4)

\[
\mathbf{K}_3 = \begin{bmatrix} k_{3hh} & k_{3hv} & k_{3vv} \\ 0 & 1 & 0 \end{bmatrix}'
\]

\( = \begin{bmatrix} 0 \ 1 \ 0 \end{bmatrix}' \)  \hspace{1cm} (5)

Detailed expressions for the eigenvalues and the elements of the eigenvectors can be found in van Zyl (1994). It is easy to show that \( \mathbf{K}_i(i = 1, 2, \text{ and } 3) \) are unit vectors, and are orthogonal to each other.
2.2. Identification of scattering mechanisms of decomposed components

To identify the scattering mechanisms of the decomposed components from $\mathbf{U}$, we rewrite equation (2), with incorporation of equations (3), (4), and (5), as

$$
\mathbf{U} = \lambda_1 \begin{bmatrix}
  k_{1hh}^* k_{1hh} & 0 & k_{1hh}^* \\
  0 & 0 & 0 \\
  k_{1vv}^* k_{1vv} & 0 & k_{1vv}^*
\end{bmatrix} + \lambda_2 \begin{bmatrix}
  0 & k_{2hh}^* k_{2hh} & k_{2hh}^* \\
  k_{2hh}^* & 0 & 0 \\
  k_{2vv}^* k_{2vv} & 0 & k_{2vv}^*
\end{bmatrix} + \lambda_3 \begin{bmatrix}
  0 & 0 & 0 \\
  0 & 0 & 0 \\
  k_{1vv}^* k_{1vv} & 0 & k_{1vv}^*
\end{bmatrix}
$$

(6)

Based on expressions of $k_{1hh}$, $k_{1vv}$, $k_{2hh}$, and $k_{2vv}$ (van Zyl 1994), we can show $(k_{1hh}^* k_{1vv}^*)/(k_{2hh}^* k_{2vv}^*)$ ratio is always negative. Because of the negative ratio, the difference between the $hh$-$vv$ phase difference of the $k_{1hh}^*$ and the $hh$-$vv$ phase difference of the $k_{2hh}^*$ is $180^\circ$. Thus, the $\lambda_1 k_1^*$ and $\lambda_2 k_2^*$ represent scattering mechanisms with an $180^\circ$ phase shift. In other words, if $\lambda_1 k_1^*$ represents scattering component with an odd number of reflections, then $\lambda_2 k_2^*$ is scattering component with an even number of reflections, and vice versa. To identify what scattering mechanisms $\lambda_1 k_1^*$ and $\lambda_2 k_2^*$ represent, we discuss the following.

In a complex plane, a positive real number has a phase angle of 0°, and a negative real number has a phase angle of 180°. For a simple target such as a trihedral or dihedral corner reflector, $k_{1hh}^*$ or $k_{2hh}^*$ is always a real number. However, because of the complex nature of scattering mechanisms from general targets such as forests, as well as the noise effect of an SAR system, $k_{1hh}^*$ and $k_{2hh}^*$ may not be real numbers; they could be complex numbers. Thus, we, approximately, use the real parts of $k_{1hh}^*$ and $k_{2hh}^*$ to identify the scattering mechanisms of the $\lambda_1 k_1^*$ and $\lambda_2 k_2^*$:

(i) if the real part of $k_{1hh}^*$ is positive (with a phase angle of 0° on the complex plane) and the real part of $k_{2hh}^*$ is negative (with a phase angle of 180° on the complex plane), then $\lambda_1 k_1^*$ represents scattering power with an odd number of reflections (with a 0° of $HH -VV$ phase difference), and $\lambda_2 k_2^*$ represents scattering power with an even number of reflections (with an 180° of $HH -VV$ phase difference).

(ii) if the real part of $k_{1vv}^*$ is negative and the real part of $k_{2hh}^*$ is positive, then $\lambda_1 k_1^*$ represents scattering power with an even number of reflections, and $\lambda_2 k_2^*$ represents scattering power with an odd number of reflections.

(iii) $\lambda_3 k_3^*$ represents total cross-polarized scattering power.

Using equation (6) and conditions (i), (ii), and (iii), we can decompose polarimetric SAR backscatter data into a scattering power with an odd number of reflections (shortened as SP-O), an even number of reflections (shortened as SP-E), and total cross-polarized scattering power (shortened as SP-C).

3. Study areas and AIRSAR data

To test the decomposition method we analysed two AIRSAR images of Goldstone Lake, California, a dry lake bed 60 km north of Barstow. The study site was selected by scientists from the JPL to test SAR calibration methods, and they deployed a number of calibration devices including trihedral and dihedral corner reflectors. The
corner reflectors were arranged on the lake bed, which is a level surface of low reflectance at C-, L-, and P-bands (Freeman et al. 1990). SAR images were acquired on 23 May 1988 and 26 July 1989. We applied the decomposition method to both images with similar results, and so present only the May 1988 imagery here.

The second study site is located at the base of Mt. Shasta, California. Since 1989 this site has been the focus of several SAR studies (e.g., Sun et al. 1991, Wang et al. 1993). Topography is level and the soil is a coarse sandy loam with veneer of pine needles and duff of 1–5 cm depth. Land cover is a mosaic of ponderosa pine (Pinus ponderosa) and ponderosa pine-white fir (Abies concolor) stands ranging from recent clear-cuts to dense plantations and mid-seral forests with 600–800 trees ha\(^{-1}\) to mature, open pine woodlands with large, scattered trees and densities of less than 30 trees ha\(^{-1}\). For this study we examined five stands that span forest structures from open pine woodland to mid- and late-seral forests of medium to dense stocking (see Table 1 for a summary of five ponderosa pine stands). We analysed eight images of the Shasta site that were acquired over the course of the day on 6 September 1989. The data were processed and calibrated by JPL, as described by Sun et al. (1991) and Wang et al. (1993). Because similar results were obtained from the eight data takes, we confine this discussion to one data take at C-, L-, and P-bands.

The flooded forest site is located in the Altamaha River floodplain in coastal Georgia (Hess and Melack, 1994). The floodplain supports emergent freshwater marshes and swamp forest. The flooded forest is dominated by tupelo gum (Nyssa aquatica), black gum (N. biflora), and bald cypress (Taxodium distichum). The understory consists of Fraxinus spp. and Acer rubrum saplings and a variety of shrubs (Myrica cerifera, Lyonia lucida, Clethra alnifolia.) We analysed a single AIRSAR scene acquired on 28 March 1990 during high water conditions when much of the bottomland forest was flooded to depths of 0.5–2 m.

4. Results
4.1. Decomposed backscatter from trihedral and dihedral corner reflectors

The trihedral corner reflectors deployed on the Goldstone Lake bed were used by JPL in calibrating the imagery and thus do not provide an independent test of the decomposition method. These reflectors were oriented horizontally (parallel to the soil surface) and pointed towards the AIRSAR, and thus should have produced high SP-O backscatter, and low SP-E and SP-C backscatter at C-band. As predicted, they are bright, conspicuous features in the decomposed image of SP-O backscatter and are not apparent in images of SP-E and SP-C backscatter (figure 1). These results do not validate the decomposition method but do confirm that our implementation of the decomposition method is performing as expected.

<table>
<thead>
<tr>
<th>Stand</th>
<th>Sp2</th>
<th>St2</th>
<th>St11</th>
<th>St10</th>
<th>St4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean dbh (m)</td>
<td>0.78</td>
<td>0.37</td>
<td>0.46</td>
<td>0.34</td>
<td>0.28</td>
</tr>
<tr>
<td>One standard deviation of dbh (m)</td>
<td>0.31</td>
<td>0.18</td>
<td>0.29</td>
<td>0.23</td>
<td>0.21</td>
</tr>
<tr>
<td>Min. dbh (m)</td>
<td>0.13</td>
<td>0.07</td>
<td>0.06</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Mean tree height (m)</td>
<td>25.1</td>
<td>22.8</td>
<td>27.1</td>
<td>21.4</td>
<td>18.5</td>
</tr>
<tr>
<td>Stand density (# of trees ha(^{-1}))</td>
<td>24</td>
<td>309</td>
<td>233</td>
<td>566</td>
<td>775</td>
</tr>
<tr>
<td>Basal area (m(^2) ha(^{-1}))</td>
<td>13.4</td>
<td>41.2</td>
<td>54.3</td>
<td>75.6</td>
<td>75.5</td>
</tr>
</tbody>
</table>
Figure 1. Scattering powers decomposed from the JPL AIRSAR C-band data, Goldstone, CA (23 May 1988). (a) SP-O, (b) SP-E, and (c) SP-C.

The three dihedral corner reflectors that appear in figure 1 (b) were not used to calibrate the imagery and thus provide a stronger test of the decomposition method. Because they were oriented parallel to the ground surface and pointed towards the sensor, one would predict from theory that they should have produced a high SP-E return but contributed little SP-O or SP-C backscatter. The decomposed C-band imagery is certainly consistent with theory (figure 1 (b)), as are the results at L- and P-bands (table 2). Typically, 70–90 per cent of total backscatter from each of the dihedral corner reflectors was modelled as SP-E backscatter (table 2).

If a dihedral corner reflector is oriented 45° off a horizontal ground surface and aimed at the SAR, the reflector should in theory return only cross-polarized backscatter. Three such corner reflectors at the Goldstone site are conspicuous in figure 1 (c), again providing another strong evidence that the decomposition method effectively separates the three scattering types. The reflectors are shown as white spots, pointed by an arrow, in the decomposed C-band cross-polarized scattering image (figure 1 (c)). This result is another verification of the decomposition method. Table 3 quantifies three scattering types, averaged from a 3 by 3 window near the reflectors, of these dihedral corner reflectors; cross-polarized scattering is dominant at C-, L-, and P-bands.
Table 2. Percentage of scattering powers of SP-O, SP-E, and SP-C normalized by total power from three dihedral corner reflectors (Dcr) oriented 0° (horizontally) on ground surface. AIRSAR data, Goldstone, CA (23 May 1988).

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Dcr 1</th>
<th></th>
<th></th>
<th>Dcr 2</th>
<th></th>
<th></th>
<th>Dcr 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.03</td>
<td>0.87</td>
<td>0.10</td>
<td>0.27</td>
<td>0.71</td>
<td>0.02</td>
<td>0.07</td>
<td>0.93</td>
</tr>
<tr>
<td>L</td>
<td>0.01</td>
<td>0.88</td>
<td>0.11</td>
<td>0.03</td>
<td>0.88</td>
<td>0.09</td>
<td>0.03</td>
<td>0.92</td>
</tr>
<tr>
<td>P</td>
<td>0.03</td>
<td>0.83</td>
<td>0.14</td>
<td>0.05</td>
<td>0.86</td>
<td>0.09</td>
<td>0.02</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Table 3. Percentage of scattering powers of SP-O, SP-E, and SP-C normalized by total power from three dihedral corner reflectors (Dcr) oriented 45° from ground surface. AIRSAR data, Goldstone, CA (23 May 1988).

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Dcr 4</th>
<th></th>
<th></th>
<th>Dcr 5</th>
<th></th>
<th></th>
<th>Dcr 6</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.08</td>
<td>0.07</td>
<td>0.85</td>
<td>0.13</td>
<td>0.06</td>
<td>0.81</td>
<td>0.17</td>
<td>0.02</td>
</tr>
<tr>
<td>L</td>
<td>0.24</td>
<td>0.13</td>
<td>0.63</td>
<td>0.19</td>
<td>0.09</td>
<td>0.72</td>
<td>0.20</td>
<td>0.10</td>
</tr>
<tr>
<td>P</td>
<td>0.39</td>
<td>0.14</td>
<td>0.47</td>
<td>0.30</td>
<td>0.24</td>
<td>0.46</td>
<td>0.33</td>
<td>0.15</td>
</tr>
</tbody>
</table>

4.2. Decomposed backscatter from ponderosa pine forest

Figure 2 is a C-band total power (black and white grey scaled) image covering our Mt. Shasta study area. The white shows high backscatter, grey intermediate backscatter, and black low backscatter. The scattered dark areas are open fields and clear-cut areas, and the grey areas are ponderosa pine forest. The colour composite of scattering powers decomposed from the SAR data at C-, L-, and P-band is shown in figure 3. The colours are coded as red standing for SP-O, green SP-E, and blue SP-C.

Open fields and clear-cut areas are bright red showing strong SP-O return. The forested areas are also dominated by red color, showing strong SP-O return. There

Figure 2. C-band total power of AIRSAR data covering the study area Mt. Shasta, CA (6 September 1989).
Decomposed SAR scattering components in forests

Figure 3. Colour composite of scattering powers decomposed from multi-frequency AIRSAR data, Mt. Shasta, CA (6 September 1989). SP-O (Red), SP-E (Green), and SP-C (Blue). (a) C-band (top), (b) L-band (middle), and (c) P-band (bottom).
are some green areas (SP-E) and blue areas (SP-C) scattered within the forested areas, but these two types of scatterings are small. These results show that at C-band the SP-O dominates in the ponderosa pine forest (figure 3(a)).

At L-band, the whole image may be still dominated by the SP-O or red colour (figure 3(b)). However, in the forested areas there is more green at L-band than at C-band. The increase of the green colour or SP-E may be explained as a result of the increase of trunk-ground interactions at L-band. As the wavelength increases to P-band (figure 3(c)), there are even more greens within the forests than at L-band; more trunk-ground interactions within the forests at P-band than at L-band. These results are consistent with those from the analysis of HH–VV phase differences of the SAR backscatter and modeled backscatter from the ponderosa pine forest (Wang et al. 1993).

To quantify above analysis, we have selected five ponderosa pine stands where ground data were collected (see table 1 for a summary of the stand data). As the basal area of a stand increases, the total power of the backscatter at C-, L-, and P-bands increases (figure 4(a)). The total power at L-band and P-band may be similar, and may be saturated once the basal area is over 54 cm$^2$ m$^{-2}$ (table 1).

At C- and L-bands the SP-O increases as the basal area increases. The SP-O at P-band is smaller than that at C-band or L-band for stands with basal areas over 40 cm$^2$ m$^{-2}$ (figure 4(b)). This may be explained as less canopy scattering at P-band than at C- and L-bands.

As the wavelength increases from C-band to P-band, there is more SP-E in the stands with large basal areas (figure 4(c)). This may be a result of more trunk-ground interactions at a long wavelength than at a short wavelength. Also, at P-band, as the stands changes from Sp2 (with a basal area of 13.4 cm$^2$ m$^{-2}$) to St11 (with a basal area of 54.3 cm$^2$ m$^{-2}$), the increase of the SP-E is about 9 dB (figure 4(c)) whereas the increase of the total power of backscatter is around 5 dB (figure 4(a)). This enlarged dynamic range of the SAR data may provide a better potential in applications such as the retrieving of the biophysical parameters of forests because the decomposed data may be more sensitive to the change of the parameters.

Because the total cross-polarized scattering derived from the decomposition method is simply twice of HV or VH backscatter (equations (1) and (6)), no new results are anticipated. We show the plot of the cross-polarized scattering only for the completion of the presentation (figure 4(d)).

As noticed in figure 4, the scattering power varies not only among stands, but among wavelengths. These variations make it difficult to generalize our findings. We have normalized the powers of the three scattering types by the total power of backscatter at C-, L-, and P-bands, respectively. In general, for the ponderosa pine forest, as SAR wavelength increases from C-band to P-band, (1) the normalized SP-O decreases (figure 5(a)), (2) the normalized SP-E increases (figure 5(b)), and (3) there may be no obvious trend for the normalized SP-C (figure 5(c)).

4.3. Decomposed scattering powers from floodplain forest

Figure 6, an L-band AIRSAR total power image with a black and white grey scale, shows the Altamaha River floodplain study area. A black straight-line on the right is a highway. Black curved features are rivers. Grey and light grey areas are flooded forests. Decomposed powers of three scattering types at C-, L-, and P-bands are shown in figure 7 as a colour composite. The colours in figure 7 are coded as red for SP-O, green for SP-E, and blue for SP-C.
Red and magenta (red and blue mixed) dominates decomposed image at C-band (figure 7(a)). Some green areas are scattered over the image; these areas are flooded forests. The curved river channels are noticeable. Parts of river channels are bright red showing strong SP-O. However, there are some green scattered on the river channels showing the existence of the SP-E. A possible explanation is that the backscatter from the channels is small (dark in figure 6), and may be close to the noise level of the SAR data. The noise affects the decomposition.

There is more green at L-band (figure 7(b)) than at C-band (figure 7(a)). Most of the green areas are flooded forests. Thus, there is a strong SP-E in the flooded forest. As wavelength increases from C-band to L-band, attenuation from tree canopy becomes less; more microwave energy can penetrate the canopy and hit the ground water surface. Because the flooded forests are dense and trees in the forests are tall and large (Hess and Melack 1994), and the water surface is a perfect reflection medium, the interactions of double-bounce trunk-ground or the SP-E can be strong.
Figure 5. Percentage of scattering powers of three scattering types normalized by total power at C-band (c), L-band (l), and P-band (p) from five ponderosa pine stands, Mt. Shasta, CA.

Figure 6. L-band total power of AIRSAR image, Altamaha River, GA (28 March 1990).
Figure 7. Colour composite of scattering powers decomposed from multi-frequency AIRSAR data, Altamaha River, GA (28 March 1990). SP-O (Red), SP-E (Green), and SP-C (Blue). (a) C-band (top), (b) L-band (middle), and (c) P-band (bottom).
The result is consistent with the findings in flooded forest by other researchers (e.g., Richards et al. 1987, Hess et al. 1995). Visually, there may not be much difference between the decomposed scattering power images at $L$-band and $P$-band (figure 7(b,c)). However, one, examining carefully, may argue that the green in the flooded forests are slightly purer (or with less mixtures of red and blue) at $P$-band than at $L$-band. The purity of the green colour at $P$-band further shows that there is more double-bounce trunk-ground scattering than other types of scattering such as the direct canopy volume scattering. It should also be noted that the noise affects the decomposition, especially at $P$-band. The scattering power decomposed from some portions of the river channels (in middle on the left, figure 7(c)) is SP-E (green).

5. Conclusions and remarks

We have used multi-frequency JPL AIRSAR data of Goldstone (CA) to verify a radar target decomposition method. By using this method, we decomposed the AIRSAR backscatter data into the scattering power with an odd number of reflections (SP-O), the scattering power with an even number of reflections (SP-E), and the total cross-polarized scattering (SP-C). Dihedral corner reflectors oriented 0° (horizontally) on a flat ground, and 45° off the ground were used in the verification of this method.

We then applied the method to decompose the multi-frequency AIRSAR backscatter data from two types of forests to help understand scattering mechanism in forested environment, and to evaluate potential application of the decomposition method in forests. For ponderosa pine forest (Mt. Shasta, CA), as the wavelength increased from $C$-band to $P$-band, the SP-O return decreased, the SP-E return increased, and there was likely no obvious trend for the cross-polarized scattering.

For floodplain forest (Altamaha River, GA), the SP-O return dominated the decomposed image at $C$-band. The SP-E return from the flooded forests was strong at $L$-band, and stronger at $P$-band. This increase of the SP-E return could be explained as a result of the increase of the trunk-ground interactions at long wavelengths. The cross-polarized scattering from flooded forest was not strong at $C$-, $L$-, and $P$-bands, and its strength became less and less as the wavelength increased from $C$-band to $P$-band.

In the imagery derived by the decomposition method, various forest structural classes and land cover types were easily distinguishable. More importantly, the decomposition method provided a means of unraveling complex interactions between radar signals and vegetated surfaces in terms of the scattering mechanisms from targets, but not in terms of the $HH$ and $VV$ polarizations from a radar system configuration. As shown in this paper, this decomposition method helped understand the scattering mechanisms of polarimetric SAR data.

Sum of $k_{1bh} k_{bh}^*$ and $k_{2bh} k_{2bh}^*$ was the total $HH$ backscatter, and $k_{1vv} k_{vv}^*$ plus $k_{2vv} k_{2vv}^*$ was the total $VV$ backscatter (equations (1) and (6)). Thus, in addition to traditional $HH$ and $VV$ backscatter from a polarimetric SAR system, one more independent backscattering component ($k_{1bh} k_{bh}^*$ or $k_{2bh} k_{2bh}^*$) for $HH$, and one more component ($k_{1vv} k_{vv}^*$ or $k_{2vv} k_{2vv}^*$) for $VV$ have been derived. These two components might provide additional potential in applications of polarimetric SAR backscatter data.

By studying the decomposed scattering powers from ponderosa pine forest, we have noted that at $P$-band, as the stand density changed from sparse to dense, the increase of the SP-E return was about 9 dB, but the increase of the total power was
around 5 dB. This enlarged dynamic range of the SAR data could provide a better potential in applications (e.g., the retrieving of the biophysical parameters of forests) because the decomposed data may be more sensitive to the change of the parameters. This is a task we will pursue in the near future.

In the analysis, we also noticed that the noise of SAR data could affect the decomposition. There may be falsely decomposed scattering components with an even number of reflections because of the noise effect, whereas the correct ones may be the scattering power with an odd number of reflections. This false decomposition was likely to occur when the backscatter from targets (e.g., river channels) was small or close to the noise level. Because most natural targets with low backscatter were flat and smooth (to slightly rough) surfaces (such as open fields, and water and river surfaces), scattering from these surfaces should be the scattering power with an odd number of reflections. To prevent or eliminate this false decomposition, one method used in our decomposition was to set a threshold for the noise level. If the total power of targets within an image pixel was less than the threshold, the larger value of decomposed scattering powers (SP-O and SP-E) would be assigned to the SP-O return, and the smaller one to the SP-E return. We tested thresholds ranging from $-50$ dB to $-25$ dB. For the Altamaha SAR data, as the thresholds increased from $-50$ dB to $-25$ dB, the SP-E (green) from the river channels became less and less, and finally disappeared. The threshold used for figure 7 was $-40$ dB; we left the scattered green areas within the river channels for showing the noise effect on the decomposition. It should be noted that, normally, one might not know what was the noise level of SAR data or what threshold value should be used. Several iterations by using different threshold values might, empirically, lead to a satisfactory result.

Acknowledgments

We thank Annie Richardson at the Radar Data Center (JPL) for providing AIRSAR data of the Goldstone area (CA), and thank Laura Hess at the University of California, Santa Barbara (UCSB) for offering AIRSAR data of the Altamaha River floodplain (GA). The AIRSAR data of Mt. Shasta (CA) was obtained from the UCSB SIR-C/X-SAR project funded by NASA through JPL (contract # 958468), and this research was also funded by the SIR-C/X-SAR project.

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