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Model-based decomposition with adaptive selection of unitary transformations (Postprint)

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Abstract

In this paper a three component model-based decomposition with adaptive selection of unitary transformations for polarimetric synthetic aperture radar (POLSAR) data processing is proposed. Singh et al implemented two unitary transformations on the coherency matrix to minimize the power of cross-polarization, and as a result the T23element of the coherency matrix becomes zero. Another two unitary transformations are proposed by us to carry out on the coherency matrix also to minimize the power of crosspolarization, and the T13element of the coherency matrix becomes zero. Here, we first implement Singh' s two unitary transformations and the proposed two unitary transformations on the coherency matrix separately. Then we select the one which leads to the smaller T33. At last, we carry out the three component model-based decomposition proposed by Freeman and Durden based on the obtained coherency matrix. The smaller T33is obtained, the better the over-estimation of volume scattering in model-based decomposition can be suppressed. The RADARSAT-2 POLSAR data of San Francisco area is used to validate the improvement of the proposed method over the three component decomposition only with Singh' s two unitary transformations.

Full Text

Preamble

MODEL-BASED DECOMPOSITION WITH ADAPTIVE SELECTION OF UNITARY TRANSFORMATIONS

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Abstract

In this paper, we propose a three-component model-based decomposition with adaptive selection of unitary transformations for polarimetric synthetic aperture radar (POLSAR) data processing. Singh et al. implemented two unitary transformations on the coherency matrix to minimize the power of cross-polarization, which resulted in the T_{33} element becoming zero. We propose an alternative set of two unitary transformations that also minimize cross-polarization power, making the T_{33} element zero. In our method, we first apply Singh' s two unitary transformations and our proposed two unitary transformations separately to the coherency matrix. We then select the transformation pair that yields the smaller T_{33} element. Finally, we perform the three-component model-based decomposition proposed by Freeman and Durden on the resulting coherency matrix. The smaller the obtained T_{33} element, the better the suppression of volume scattering over-estimation in model-based decomposition. RADARSAT-2 POLSAR data of the San Francisco area is used to validate the improvement of the proposed method over three-component decomposition using only Singh' s two unitary transformations.

1 Introduction

Model-based decomposition has long been a prominent research topic in polarimetric synthetic aperture radar (POLSAR) target decomposition. The pioneering work is the three-component decomposition proposed by Freeman and Durden [1], which decomposes the covariance matrix of POLSAR data into surface scattering, double-bounce scattering, and volume scattering components. Surface scattering occurs on Bragg surfaces, double-bounce scattering arises from ground-wall or ground-trunk dihedral structures, and volume scattering occurs from canopy targets. However, cross-polarization occurs when targets are azimuthally modulated [2] or when dihedrals are not aligned with the flight track [3,4]. Since azimuth-modulated surfaces and oriented dihedrals introduce additional cross-polarization, volume scattering estimated from cross-polarization is often over-estimated.

Yamaguchi et al. proposed a four-component decomposition that adds a helix term to alleviate this over-estimation [5]. Orientation angle compensation (OAC) has also been applied to POLSAR data to reduce cross-polarization power [2,3,4]. Beyond OAC, Singh et al. implemented another unitary transformation on the coherency matrix to minimize the power of the cross-polarization (T_{33} element) [6]. After this transformation, seven degrees of freedom remain out of nine in the coherency matrix, enabling a four-component decomposition where five of the seven degrees of freedom are accounted for. The two unaccounted degrees of freedom correspond to the real and imaginary parts of the T_{13} element. As noted in [6], parts of these two degrees of freedom remain unaccounted for in all known model-based decompositions.

In fact, besides orientation angle, the helix angle also contributes to cross-polarization power, as can be verified through the helix term in four-component decomposition. The helix term in Yamaguchi et al.' s decomposition is:

$$T_{\text{helix}} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & \pm j \\ 0 & \pm j & 1 \end{bmatrix}$$

Although Yamaguchi et al. included this term in their decomposition, it was not displayed in the resulting color-coded images. Inspired by applying OAC to the coherency matrix, we propose a helix compensation operation for the coherency matrix, accomplished through a unitary transformation that minimizes the T_{33} element. Subsequently, another unitary transformation minimizes the T_{13} element for the coherency matrix following the first transformation (helix compensation). After these two transformations, the T_{33} element becomes zero. We implement Singh' s two unitary transformations and our proposed two unitary transformations separately on the coherency matrix, then preferentially select the transformation pair yielding the smaller T_{33} element. Finally, FDD is performed on the coherency matrix obtained after the selected unitary transformations. The proposed method provides improved alleviation of volume scattering over-estimation compared to applying FDD with only Singh' s two unitary transformations.

3 Singh' s Two Unitary Transformations

The first unitary transformation is rotation about the radar line of sight, also known as OAC in [2,3,4]:

$$T(\theta) = R(\theta) T R^{\dagger}(\theta)$$

where † denotes complex conjugate transposition, $T(\theta)$ is the coherency matrix after OAC, and the rotation matrix is:

$$R(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(2\theta) & \sin(2\theta) \\ 0 & -\sin(2\theta) & \cos(2\theta) \end{bmatrix}$$

By minimizing the $T_{33}(\theta)$ element (the third row and third column element of $T(\theta)$), the angle θ can be derived as:

$$\theta = \frac{1}{4}\tan^{-1}\left(\frac{2\mathrm{Re}(T_{23})}{T_{22}-T_{33}}\right)$$

After the rotation of (8), T_{33} becomes zero, and T_{13} remains unchanged.

The second unitary transformation carried out following the first is:

$$F(T(\theta)) = U(\varphi)T(\theta)U^{\dagger}(\varphi)$$

where † denotes complex conjugate transposition, and:

$$U(\varphi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(2\varphi) & j\sin(2\varphi) \\ 0 & j\sin(2\varphi) & \cos(2\varphi) \end{bmatrix}$$

The coherency matrix can also be expressed using Huynen' s nine parameters [7] as:

$$T = \begin{bmatrix} A_0+B_0 & C-jD & H+jG \\ C+jD & A_0+B & E+jF \\ H-jG & E-jF & A_0-B \end{bmatrix}$$

where $F(T(\theta))$ is the matrix obtained after this unitary transformation, and:

$$F(T(\theta)) = \begin{bmatrix} A_0+B_0 & C'-jD' & H'+jG' \\ C'+jD' & A_0+B' & E'+jF' \\ H'-jG' & E'-jF' & A_0-B' \end{bmatrix}$$

Similar to OAC above, the angle φ can be derived by minimizing the T_{33} element:

$$\varphi = \frac{1}{4}\tan^{-1}\left(\frac{2\mathrm{Im}(T_{23}(\theta))}{T_{22}(\theta)-T_{33}(\theta)}\right)$$

After the unitary transformation of (11), T_{33} becomes zero, and T_{13} remains unchanged.

The coherency matrix of a target under reflection symmetry assumption can be decomposed into three components as [1,3]:

$$T = P_sT_s + P_dT_d + P_vT_v$$

The models of the three components can be expressed as:

$$T_s = \begin{bmatrix} 1 & \beta^* & 0 \\ \beta & |\beta|^2 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad T_d = \begin{bmatrix} |\alpha|^2 & \alpha & 0 \\ \alpha^* & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad T_v = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1/2 & 0 \\ 0 & 0 & 1/4 \end{bmatrix}$$

Because P_s, P_d, and P_v are the powers of surface scattering, double-bounce scattering, and volume scattering, respectively, these three coefficients should not be negative. However, as discussed above, over-estimation of volume scattering often occurs, which leads to negative P_d. When T_{33} equals zero, the T_{13} and T_{23} elements are both zero. Thus, the degrees of freedom of the coherency matrix reduce from nine to seven after these two unitary transformations. Although the physical meaning of the second unitary transformation is somewhat obscure, it indeed makes the T_{33} element smaller, which helps alleviate the over-estimation of volume scattering.

4.1 The Proposed Two Unitary Transformations

As mentioned above, both orientation angle and helix angle contribute to cross-polarization. Similar to OAC, we propose helix angle compensation for the target:

$$G(T) = U(\tau) T U^\dagger(\tau)$$

where τ is the helix angle, and the unitary transformation matrix is:

$$U(\tau) = \begin{bmatrix} \cos(2\tau) & 0 & j\sin(2\tau) \\ 0 & 1 & 0 \\ j\sin(2\tau) & 0 & \cos(2\tau) \end{bmatrix}$$

The angle τ can be derived by minimizing the T_{33} element:

$$\tau = \frac{1}{4} \tan^{-1}\left(\frac{2\mathrm{Im}(T_{13})}{T_{11} - T_{33}}\right)$$

After the unitary transformation of (14), T_{33} becomes zero, and T_{13} remains unchanged.

The second unitary transformation is proposed as:

$$H(G(T)) = U(\omega) G(T) U^\dagger(\omega)$$

where the unitary transformation angle is ω, and:

$$U(\omega) = \begin{bmatrix} \cos(2\omega) & 0 & \sin(2\omega) \\ 0 & 1 & 0 \\ -\sin(2\omega) & 0 & \cos(2\omega) \end{bmatrix}$$

The angle ω is derived by minimizing the T_{13} element:

$$\omega = \frac{1}{4}\tan^{-1}\left(\frac{2\mathrm{Re}(T_{13}(\tau))}{T_{11}(\tau) - T_{33}(\tau)}\right)$$

After the unitary transformation of (17), T_{13} becomes zero, and T_{33} remains unchanged.

Both the real and imaginary parts of T_{13} become zero after applying these two unitary transformations. As far as we know, this is the first time that helix unitary transformation has been directly implemented on the coherency matrix, and that two unitary transformations are utilized to make the T_{13} element zero. The difference between Singh' s unitary transformations and ours is that Singh' s first transformation is OAC, while our first transformation is helix compensation. In addition, T_{13} is one of the results of Singh' s transformations, whereas T_{33} is the counterpart of our transformations.

4.2 The Proposed Decomposition

We first apply Singh' s two unitary transformations ((8) and (11)) and the proposed two unitary transformations ((14) and (17)) separately to the same coherency matrix. We then adaptively select the transformation pair that yields the smaller T_{33} element and perform FDD on the resulting coherency matrix. The goal of adaptive selection is to best fit the ground truth, as orientation angle may be the main factor in cross-polarization generation for some targets, while helix angle may be dominant for others. The flowchart of the proposed decomposition is presented in [Figure 1: see original paper].

5 Experimental Results and Analysis

RADARSAT-2 C-band data of the San Francisco area [8], acquired on April 9, 2008 in fine-beam quad-polarization mode, is used to validate the improvement of the proposed method. The data has been 6-look processed in range and azimuth directions with dimensions of 470 × 2402 pixels. The helix angle τ calculated by (16) is presented in [Figure 2: see original paper]. It should be noted that the scene in Figure 2 is only part of the San Francisco area data, with the corresponding Google Earth optical image shown in [Figure 5: see original paper]. The τ value is around zero in ocean areas. For comparison, the θ_h (helix angle of the dominant eigenvector) from [9] is shown in [Figure 3: see original paper]. The two are generally consistent, confirming that the physically meaningful τ from (16) contains useful information.

The proposed method is then applied, with the resulting color-coded decomposition image shown in [Figure 4: see original paper]. In this image, blue indicates dominant surface scattering, red indicates dominant double-bounce scattering, and green indicates dominant volume scattering. The experimental results show that 67.60% of pixels select Singh' s two unitary transformations, while the remaining pixels select our two transformations. The average ratio of volume scattering power to total scattering power is 27.16% using only Singh' s transformations, which improves to 26.48% with the proposed decomposition. Thus, the average volume scattering power of the proposed decomposition is lower, demonstrating that the proposed method with adaptive selection of unitary transformations is more effective in alleviating volume scattering over-estimation than using only Singh' s transformations.

To more specifically demonstrate the improvement, we selected four patches for further validation, with their Google Earth optical image shown in [Figure 5: see original paper]. Patch 1 is ocean area, patch 2 is oriented built-up area, and patches 3 and 4 are park areas. The decomposition results are presented in . For patch 1 (ocean), the results of FDD with only Singh' s transformations and the proposed decomposition are similar because both orientation and helix angles of the ocean surface are small, introducing little cross-polarization. For patch 2 (built-up area), the proposed method shows a small improvement with 18.54% volume scattering compared to 19.11% using only Singh' s transformations. For patch 3, volume scattering contribution is 49.13% with the proposed decomposition versus 50.93% with only Singh's transformations. For patch 4, the values are 49.06% versus 50.89%, respectively. For patches 3 and 4, the proposed transformations are more suitable for compensating the coherency matrix because orientation angle is very small (no oriented buildings or azimuth-modulated surfaces), and the helix angle of scatterers mainly contributes to cross-polarization. The proposed decomposition is more reasonable as it accounts for different target types where either orientation angle or helix angle may be the dominant factor in cross-polarization generation.

6 Conclusion

A three-component model-based decomposition with adaptive selection of unitary transformations is proposed in this paper. Two new unitary transformations on the coherency matrix are introduced, including helix compensation. The T_{33} element becomes zero after applying these two transformations. Experimental results demonstrate the improvement of the proposed decomposition method.

Acknowledgments

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