A unified model for decomposition of coherent and partially coherent target scattering using polarimetric SARs

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Abstract—
The target scattering vector model (TSVM) introduced in [1] is reconsidered for a unified decomposition of coherent and partially coherent target scattering. The model, which is robust under change of antenna polarization basis, permits a unique representation of target coherent scattering in term of five parameters that are target characteristics. The TSVM is integrated in Cloude's incoherent decomposition method (ICTD) to derive the TSVM-ICTD, which permits a unique and basis invariant decomposition of natural extended target scattering. It is shown that both phase and magnitude of the complex scattering type should be used for an unambiguous description of symmetric scattering type. The use of the TSVM helicity angle is important for the characterization of the symmetric nature of target scattering. This parameter permits solving for certain scattering type ambiguities that might occur with Cloude α parameter with targets of non-symmetric scattering. Speckle effect on the TSVM parameter estimation is also discussed. It is shown that the TSVM parameters, and in particular the symmetric scattering type, can be significantly biased. The statistics of the coherence are used to determine the minimum window size required for an unbiased estimation of the TSVM decomposition parameters.

I. Introduction

The objective of target decomposition theory is to express the average scattering mechanism as the sum of independent elements in order to associate a physical mechanism with each component [2], [3], [4]. Cloude's ICTD [5] is presently the most used method for decomposition of natural extended target scattering. The characteristic decomposition of the Hermitian target coherency matrix allowed Cloude and Pottier to derive key parameters, such as the scattering type α and the entropy H [4], which have become the standard tools for target scattering classification and for geophysical parameter extraction from polarimetric SAR data [6], [7].

We have shown [1] that Cloude-Pottier's $\alpha\beta$-model, which is used for parameterization of the eigenvectors, might lead to parameters that vary with orientation angle for non-symmetric target scattering. Theses parameters, noted as β, Φ_1, Φ_2, and Φ_3 in [1], vary with the rotation of the incidence plane about the radar LOS, and as such are not antenna polarization basis invariant. Corr and Rodrigues [8] have applied Cloude's ICTD in an alternative orthonormal basis formed with a sphere and a pair of left and right handed helices. The use of the alternative sphere-helix basis (in stead of the Pauli matrix) leads to different β and Φ_i $(i = 1, 3)$ parameters, which permit solving for certain scattering ambiguities related to α scattering type description that were brought out in [8]. Therefore, one might conclude that the use of the $\alpha\beta$-model for parameterization of the coherency eigenvectors might lead to a scattering decomposition that does depend on the antenna polarization basis for non-symmetric targets. The integration in the ICTD of the target coherent scattering model (TSVM) [1] should lead to a unique target scattering decomposition in terms of target characteristic parameters, which satisfy the general requirement stated by S. Cloude regarding target scattering decomposition; "robust under a change of wave polarization base [5]".

In this study, the model introduced for decomposition of coherent target scattering, the TSVM [1], is presented. The TSVM is used for parameterization of target coherency eigenvectors, and this leads to an incoherent target scattering decomposition, the TSVM-ICTD, which is suitable for decomposition of targets of partially polarized scattering. Speckle effect on the TSVM parameter estimation is then discussed, and the constraint on the processing window size for an unbiased TSVM parameter estimation is determined in terms of independent looks. The new decomposition method is validated using convair-580 polarimetric SAR data.

II. Parameterization of target coherency eigenvector: the TSVM

If the absolute target phase is ignored, the TSVM might be expressed as [1]:

$$\vec{e}_T^{\,TSVM} = m \cdot \begin{matrix} \cos\alpha_s \cos 2\tau_m \\ j\cos\alpha_s \sin 2\psi \sin 2\tau_m + \cos 2\psi \sin\alpha_s e^{j\Phi_{\alpha_s}} \\ -j\cos\alpha_s \cos 2\psi \sin 2\tau_m + \sin 2\psi \sin\alpha_s e^{j\Phi_{\alpha_s}} \end{matrix} \quad (1)$$

where ψ, τ_m, and m are Huynen's maximum polarization parameters [2]. ψ provide an intrinsic measure of target orientation angle, the helicity τ_m is used to assess target

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symmetry, and m is the amplitude of the maximum polarization. α_s and Φ_{α_s} are the polar coordinates of the symmetric scattering type, $\alpha_s^c = \alpha_s \cdot \exp j\Phi_{\alpha_s}$, which is presented here as a complex parameter. α_s, which is identical to the η parameter introduced in [9], corresponds to the angle of the symmetric scattering vector direction in the trihedral-dihedral basis. For a symmetric target of entropy H close to zero, α_s is identical to Cloude's scattering type angle α. Φ_{α_s} is the phase difference between the vector components in the trihedral-dihedral basis (named η in [9]). Notice that the representation of the TSVM in the Pauli basis permits solving for Huynen's skip angle ambiguity [10], and as a result, the TSVM provides a unique and non ambiguous representation of target scattering phase [11].

A. *TSVM incoherent target decomposition*

The TSVM is used for the parameterization of the coherency eigenvectors that result from the coherency characteristic decomposition. Each single scatterer is represented with one eigenvector and the corresponding eigenvalue, which provides a measure of the relative importance of the single scatterer. The TSVM-ICTD characterizes each single scattering component of target scattering with the normalized eigenvalue and the orientation invariant parameters α_s, Φ_{α_s}, and τ_m. The analysis of these parameters for all of the three coherency eigenvectors should permit an in-depth analysis of the eigenvalue spectrum. For a global analysis of the scattering, averaged parameters (weighted by the eigenvalues) can be derived from the separate eigenvector parameters, as done in [4], with the risk of loss of useful information for target of relatively high entropy.

III. Speckle effect on the TSVM-ICTD: Minimum processing window size for an unbiased estimation of the TSVM parameters

The TSVM parameters are derived after diagonalization of the coherency matrix. The "complex" Jacobi method is currently the most used method for diagonalization of Hermitian covariance matrices. A sequence of plane complex rotations is applied to annihilate the off-diagonal matrix elements. Successive transformations make the off-diagonal elements smaller and smaller, until the matrix is diagonal to machine precision. It can be shown [11] that the elements of each pq-transformation are functions of the pq-channel sample coherence magnitude and phase, given in [12], [13]. The fact that the various pq-channel sample coherence magnitudes and phases are generally biased [12], [13], leads to biased eigenvalues and eigenvectors. These biases can be cancelled if unbiased estimates of the coherence magnitude and phase were used during the diagonalization process. The statistics of the sample coherence magnitude can be used [13] to determine the minimum number of independent samples requested for unbiased coherence estimation within areas for which the coherence magnitude is larger than a given threshold. A number L of independent-looks $L \simeq 60$ per processing window should affect only the coherence lower than 0.1 [13]. This leads to almost unbiased TSVM parameters, as illustrated in the following using Convair-580 SAR data.

Figure 1 presents the variations with the processing window size of the dominant scattering type α_s estimate for a forested area. The curve noted as "alpha1-W", represents as a function of the half window size W the TSVM parameter estimate derived from the 1-look coherency matrix sample. Since the coherency matrix sample is asymptotically unbiased, the estimate converges towards a finite value $\alpha_s \simeq 17°$, under stationarity and ergodicity conditions. The multi-look α_s estimate is significantly biased for small processing window, with a significant bias (more than 20° for a 5x5 processing window, as seen in Figure 1. The bias decreases with increasing number of L to become almost insignificant for a 15x15 window ($L \simeq 60$).

IV. Illustrations using Convair-580 SAR data: Results and discussions

In the following, a processing window of about 60 independent looks is used for an unbiased estimation of the TSVM-ICTD parameters. The Ottawa scene of Figure 2 includes farm fields, forest and urban areas. The dominant scattering orientation invariant target parameters α_{s1}, $\phi_{\alpha_s 1}$, and τ_1 are presented in Figure 3. Most of the areas in the scene are of symmetric scattering with an helicity τ_1 within $\pm\pi/12$, at the exception of few isolated non-symmetric scatterers in the urban areas. τ_1, which also represents the degree to which Cloude scattering type α_1 deviates from α_{s1}, allow us to conclude that the TSVM-ICTD and Cloude ICTD are generally similar for the scene under study, which is dominated by target of symmetric scattering; $\tau_1 \simeq 0$ and $\alpha_1 \simeq \alpha_{s1}$.

Comparison of the dominant scattering type magnitude α_{s1} (or α_1) with the HH polarization reveals some weakness related to the scattering type description; whereas α_{s1} cannot discriminate the farm fields from forested areas, the HH polarization does, as seen in Figure 2. Such weakness is recovered when the phase information provided by the scattering type phase $\phi_{\alpha_s 1}$ is used, as seen in Figure 3. The key role of the scattering type phase information for a complete characterization of target scattering type has been confirmed in another study we are conducting on wetland classification [11].

The medium single scattering (corresponding to λ_2, with $\lambda_3 < \lambda_2 < \lambda_1$) is considered here to illustrate certain scattering ambiguities related to Cloude's alpha description. The medium scattering type helicity τ_2, and symmetric scattering type parameters α_2, and α_{s2} are presented in Figure 4. The medium scattering component behave generally as a non-symmetric scattering at the exception of farm fields, as seen Figure 4. The use of the TSVM-ICTD helicity information permits solving for scattering type ambiguities that occur with α_2. All the non-symmetric scatterers, which have the same α_2 value than symmetric scatterers, are removed from the α_2 image in a separate image τ_2 (with $\tau_2. \neq .0$). As a result, ambiguous symmetric and non-symmetric scatterers of the same α_2 value, such as the helical and dihedral scattering of ($\alpha_2 = 90°$), are now well separated in τ_2 and α_{s2}, as seen in Figure 4. Notice that the moving cars on the top right of Figure 4 of $\alpha_2 = 90°$ are now assigned to symmetric dihedral scattering according to α_2 and τ_2 images of Figure 4.

V. Conclusion

The TSVM introduced in [1] permits a unified decomposition of coherent and partially coherent target scattering. The TSVM-CTD, which is applied on one look scattering matrix, represent coherent scatterering in term of five parameters that are antenna polarization basis invariant. The TSVM-ICTD uses the TSVM for the parameterization of each of the three coherency eigenvectors, and the normalized eigenvalues for measurement of the relative importance of each single scattering component. For symmetric scattering, the TSVM-ICTD and Cloude-Pottier's $\alpha\beta$-ICTD lead to identical scattering decomposition. The use of the scattering type phase information Φ_{α_s}, in addition to the one provided by the scattering type magnitude α_s, is essential for an unambiguous description of target scattering. Cloude-Pottier's α scattering type description might be ambiguous at the presence of non-symmetric scattering, as noted in [8], [1]. Such ambiguities are solved with the TSVM-ICTD, which uses the helicity in addition to the symmetric scattering type parameters α_s, and Φ_{α_s} for a complete and unique representation of target scattering. We have previously recommended a mixed use of high-resolution CTD and coarse resolution-ICTD for optimum analysis of coherent and partially scattering that might occur in the same SAR scene [9], [7]. The unified decompositions TSVM-CTD and TSVM-ICTD should permit a high and coarse-resolution target scattering decomposition in terms of unique TSVM parameters that ar antenna polarization basis invariants, and as such, targe characteristics.

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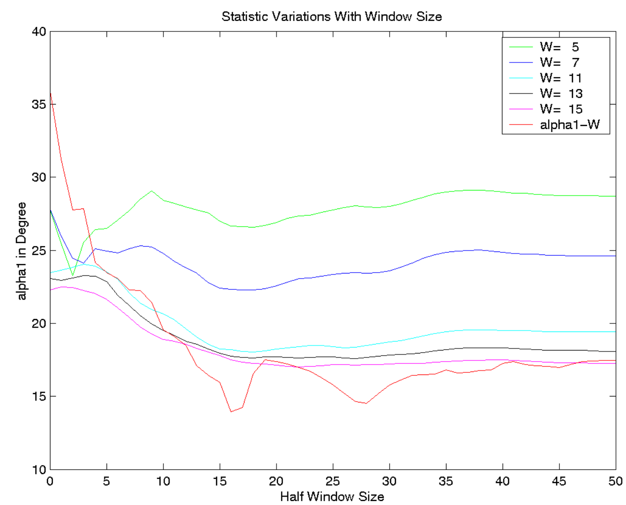

Fig. 1. *Dominant scattering α_s bias variation as a function of the multi-look window half size W*

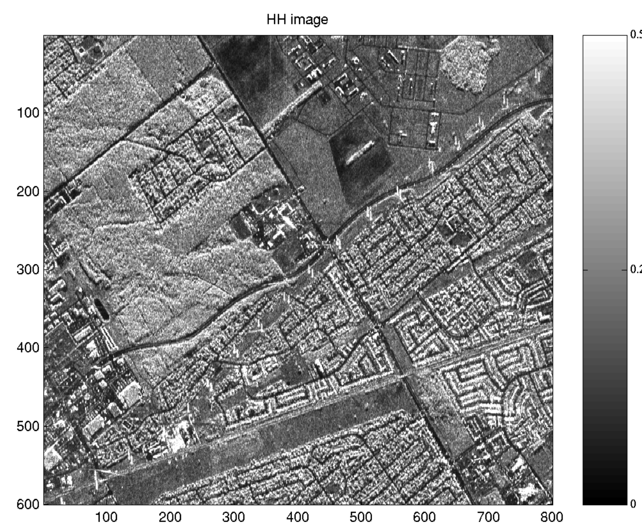

Fig. 2. *Convair-580 HH 4-Look SAR Image (Ottawa)*

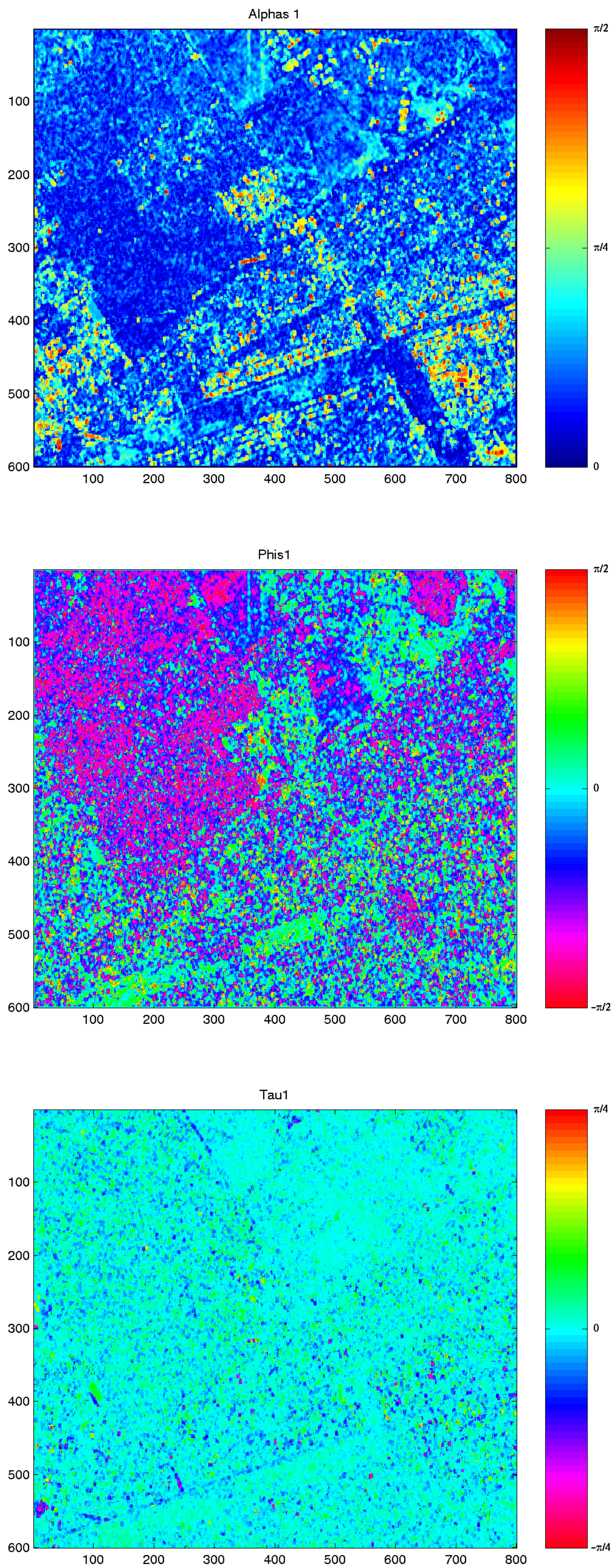

Fig. 3. *Dominant Scattering Type and Helicity*

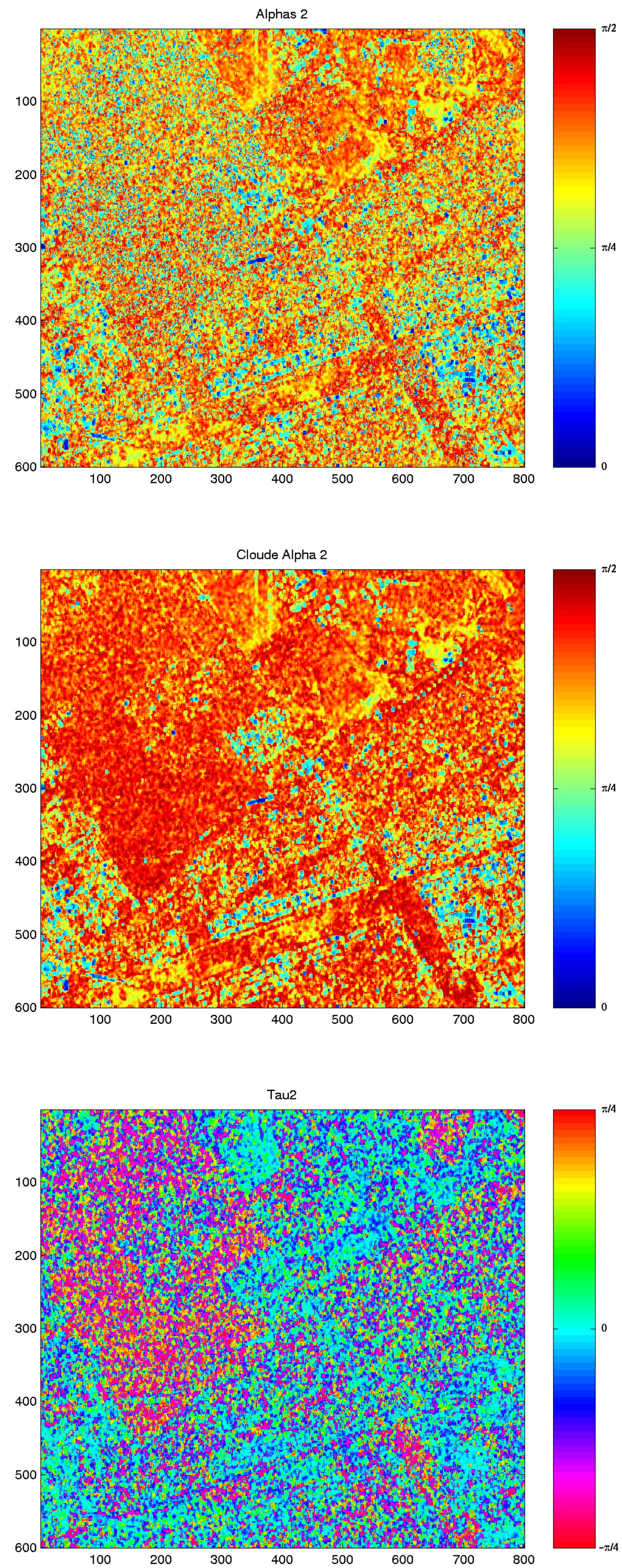

Fig. 4. *Medium Scattering Type Magnitude and Helicity*