THE TOUZI DECOMPOSITION FOR A UNIQUE TARGET SCATTERING CHARACTERIZATION USING POLARIMETRIC SAR

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Abstract

The most popular model-based decompositions (MBD) are reconsidered in the context of the estimation theory. It is shown that a large processing window is required to reduce the bias on the individual scattering contribution due the target scattering Reflection symmetry assumption. This limits the MBD efficiency in areas of non stationarity radar backscattering, such as urban areas. Eigenvector-based decompositions (EVBD) are also reconsidered. The effect of polarization basis change on target scattering description is investigated using the Cloude-Pottier ICTD, and the Touzi decomposition. The latter, which is an extension of the Kennaugh-Huynen method to partially coherent scattering, was originally developed to correct for the Cloude-Pottier scattering decomposition ambiguities. It is shown that the Touzi decomposition is the EVBD that permits the decomposition of both coherent and partially coherent scattering in terms of unique and polarization basis-invariant parameters.

I. Introduction

The objectives of target decomposition theory is to express the average scattering mechanism as the sum of independent elements and to associate a physical mechanism with each component [1], [2], [3], [4], [5], [6]. Several techniques have been proposed during the past two decades for incoherent target scattering decomposition (ICTD). These techniques can be assigned to two main categories. The first category [2], [7], [8], [9], [10], [11] is based on the eigenvector-based decomposition introduced separately by Barnes and Cloude and in the context of radar imaging [1], [12]. The latter breaks, in the monostatic case, the average coherency (or covariance) matrix into the weighted sum of three coherency matrices representing three different single scatterers. The second ICTD category regroups model-based decompositions (MBD), which has firstly been introduced by Freeman and Durden in 1998 [13]. MBD supposes that target observed scattering can be modeled as the linear sum of scattering that can be represented by models of the physical scattering process [13]. The Freeman-Durden decomposition (FDD) [13] assumes that target scattering can be modeled as the linear sum of surface, double-bounce and volume scattering. Yamaguchi et al [14] added helix as a fourth component to include in addition terrain reflection asymmetry as a fourth component to include in addition reflection asymmetry that can be introduced by terrain slopes or urban feature orientation. Recently, Van Zyl [15] suggested the integration of EVBD in the MBD to minimize the FDD negative power component under the assumption of reflection symmetry.

Even though all the ICTD above have been widely validated and show very interesting results in various applications, there is an immediate requirement for a thorough analysis of these techniques to determine their strength and eventual weakness in the characterization of target scattering [16]. In the following, the effect of speckle on MBD is assessed. It is shown that large processing window is required for unbiased estimation of target individual scattering contribution. In Section III, EGVB decompositions are reconsidered for a unique description of target scattering in terms of polarization basis-invariant parmeters. It is shown that the use of "symmetric" scattering type parameters is required for polarization basis invariant description of target scattering. Huynen's helicity permits removing the scattering type ambiguity that affects Cloude-Pottier ICTD parameters, and the Cloude α in particular. The adoption of α by EGVB expressed at the circular polarization (CP) basis [8], [11] leads to ambiguous scattering type ambiguities. Finally, the Touzi decomposition is expressed at CP to confirm the polarization basis invariance of the EVBD for target scattering description.

II. MBD: Impact of processing window size on the measurement of scattering contribution

MBD was introduced by Freeman and Durden as a technique for fitting a physical based three-component scattering mechanism model to the polarimetric SAR data itself "without utilizing any ground truth data measurement [13]". The FDD assumes that target scattering can be modeled as the linear sum of surface, double-bounce and volume scattering [13]. Freeman and Durden consider the case of a medium with reflection symmetry, and the terms of cross-correlations of hh-hv and vv-vh were ignored to derive the contribution of each individual scattering. Van Zyl has introduced a new approach, the nonnegative eigenvalue decomposition (NNED)to minimize the negative power component that was observed with the FDD. The EVBD is integrated in the FDD to provide the double bounce and surface scattering parameters (α and β) without artificially having to set the magnitude of one of them equal to one. However, the NNED still assumes reflection symmetry with the related restrictions discussed in the following. Yamaguchi [14] added the helix as a fourth component to include in addition reflection asymmetry that can be introduced by terrain slopes or urban feature orientation. The helix scattering contribution f_c was measured using the like-cross pol correlations: $f_c = 4.|Im(< hh.hv^* > + < vv.hv^* >)/2$ [14]. The latter is then subtracted from FDD target scattering equations to derive the remaining contribution of the double bounce, surface and volume scattering under the assumption of reflection symmetry (RefSym) .

The RefSym comes with major limitations in terms of the minimum window size required for accurate decomposition of target scattering using MBD. In fact, RefSym has been widely used in SAR calibration [17], [18]. Large windows are used so the products of copolarized and cross-polarized terms can be ignored. We have recently studied [16] the RefSym error generated on the Freeman and Yamguchi MBDs [13], [14], as a function of the processing window size. The probability density function of the coherence derived in [19] is used to show that large window (with a minimum of 150-200 independent samples) is required to cancel the scattering contribution bias generated by RefSym. Since all the most popular MBDs are currently applied with small processing window size (7x7 or 9x9 on 1-look image) [13], [14], [15], [20], the results obtained with MBD should be used with big care. In particular, the MBD decomposition of non stationary scattering, such as the one backscattered by urban features, might be a serious issue. Small processing window is required to apply MBD under local stationary conditions, and this leads to seriously biased MBD estimation of individual scattering contribution. The MBD scattering bias cannot be corrected by the NNED [15], and MBD can only be applied in stationary areas with large number of independent samples to minimize the error related to RefSym. Such issue does not present a problem with the eigenvector based decompositions (EVBD) that can be adapted to both CTD and ICTD for accurate decomposition of stationary and non stationary target scattering, as discussed in the following.

III. Target scattering decomposition in terms of polarization-basis invariant target parameters using EVBD

A. Introduction

Cloude and Pottier has applied the EVBD of the coherency matrix [12], in the Pauli-polarization basis, to develop the Cloude-Pottier ICTD [2], [7]. The latter has been the most popular ICTD used for decomposition and classification of target scattering [5], [6]. Recently, concerns have been raised regarding the ambiguity of Cloude-Pottier ICTD parameters [21], [8], and the Touzi decomposition [10] was introduced in the Pauli polarization basis, to solve for the Cloude-Pottier ICTD ambiguities. Van Zyl [9] has applied the EVBD in the H-V polarization basis for the decomposition of the covariance matrix of scattering generated by target with RefSym. EVBD was also applied at CP-basis [8], [11] leading to different ICTD parameters. Recently, Van Zyl [22] has questioned the invariance of EGVB with the polarization basis (H-V, Pauli, or CP) used for the scattering covariance matrix diagonalization. We will show in the following, that the description of target scattering in terms of symmetric scattering type parameters, firstly introduced in [10] and questioned in [6], is the EGVB that permits an invariant polarization basis scattering decomposition.

B. The Touzi decomposition for a unique and unambiguous description of target scattering

B.1 Eigen vector decomposition

The Touzi decomposition [10] was introduced as an extension of Kennaugh-Huynen CTD for decomposition of both coherent and partially coherent scattering. The ICTD was also inspired from the Cloude-Pottier EVBD-ICTD [23], [2], and the characteristic decomposition of the Hermitian positive semi-definite target coherency matrix $[T]$ is used to represent $[T]$ as a unique incoherent sum of up to three coherency matrices (under reciprocity assumption), $[T]_i$ representing three different single scatterers, each weighted by its appropriate positive real (non complex) eigenvalue λ_i [23]: $[T] = \sum_{i=1,3} \lambda_i [T]_i$. Each single scattering i (i=1,3) is represented by the coherency eigenvector matrices $[T]_i$ of rank 1, and the corresponding normalized positive real eigenvalue $\lambda_i/(\lambda_1 + \lambda_2 + \lambda_3)$, which is a measure of the relative energy carried by the eigenvector $\vec{k}_i$.

B.2 the Touzi scattering vector model (TSVM)

To solve for the Cloude-Pottier ICTD ambiguities, the Touzi scattering vector model (TSVM) was introduced and used for the parametrization of the coherency eigenvectors $\vec{k}_i$ ($i = 1, 3$) [10]. The TSVM was derived using the projection of the Kennaugh-Huynen scattering matrix con-diagonalization [24], [25] into the Pauli basis [10]. This projection permits solving for the Huynen skip angle ambiguity [26], and leads to an unambiguous and unique description of target scattering type phase [10], [27]. The TSVM introduces a complex entity, named the symmetric scattering type [10], for an unambiguous description of target scattering type. The polar coordinates of the symmetric scattering type, α_s and Φ_{α_s}, are given by ([10], [27]):

$$\tan(\alpha_s) \cdot e^{j\Phi_{\alpha_s}} = \frac{\mu_1 - \mu_2}{\mu_1 + \mu_2} \tag{1}$$

where μ_1 and μ_2 are the con-eigenvalues of the target scattering matrix $[S]$. For a symmetric target, α_s is identical to the Cloude α, and α_s and Φ_{α_s} are identical to the Touzi SSCM [28] parameters η and $\phi_{Sb} - \phi_{Sa}$. The symmetric scattering type parameters α_s and Φ_{α_s} are then combined with the Huynen helicity (τ_m) and maximum polarization (m) [25] to derive the expression of the TSVM. Each single target scattering $\vec{k}_i$ is represented as [10], [27]:

$$\vec{k} \quad = \quad m \cdot ([R(\psi)] \otimes [R(\psi)]) \cdot \begin{bmatrix} \cos\alpha_s \cos 2\tau_m \\ \sin\alpha_s e^{j\Phi_{\alpha_s}} \\ -j\cos\alpha_s \sin 2\tau_m \end{bmatrix}$$

where $[R(\psi)]$ is the rotation transformation matrix by the angle ψ. The Touzi decomposition is conducted through an in-depth analysis of each of the three single scattering eigenvectors (i=1,3). Each scattering i is represented in term of 5 independent parameters: $(\eta_i, m_i, \alpha_{si}, \phi_{\alpha_{si}}, \tau_i)$. Where $\eta_i = span.\lambda_i$, λ_i is the normalized eigenvalue that measures the relative energy carried by the single scattering i.

C. Why symmetric scattering type for description of target scattering?

A symmetric target is a target having an axis of symmetry in the plane orthogonal to the radar line of sight direction (LOS) [24], [25]. A symmetric target has zero helicity $\tau_m = 0$ [24], [25], and as a result, its scattering matrix can be diagonalized by a rigid rotation about the LOS, and its maximum polarization is a linear polarization, which is either aligned with the target symmetry axis or orthogonal to it [24], [25]. The description of target scattering in terms of symmetric scattering type parmeters (α_s, Φ_{α_s}), permits a unique and polarization -basis invariant description of target scattering [10], [27]. The kennaugh-Huynen con-diagonalization leads to a diagonal matrix with con-eigenvalues, (μ_1, μ_2), that are independent of the basis of polarization. α_s and Φ_{α_s} expressed in term of these unique con-eigenvalues permit a unique description of target scattering, which is independent of the basis of polarization (H-V, Pauli, CP, or others). We have defined α_s and Φ_{α_s} in the Pauli basis so the TSVM can take benefit of the widely international demonstration of the Cloude-Pottier $\alpha|H$ decomposition in various applications applications. Most of these demonstrations were conducted with natural target of symmetric scattering ($\tau_m = 0$), for which the TSVM and the Cloude-Pottier $\alpha - \beta$ models are identical (with the exception of Φ_{α_s} which was not exploited by the $\alpha - \beta$ model). Kennaugh-Huynen [24], [25] have described target scattering at the H-V polarization in terms of γ (the characteristic angle), and ν (the target skip angle). The EVBD-TSVM projection into the Pauli polarization basis, which solves for Huynen's skip angle ambiguity and extends Kennaugh-Huynen CTD to partially coherent scattering, could also be expressed in terms of γ and ν. The fact the γ and ν are linearly related with α_s and Φ_{α_s} proves the scattering type invariance with the polarization basis transformation (H-V to Pauli). The scattering type description remains also identical at the CP basis, as shown in the following Section IV.

D. Eigenvector parameters: helicity and orientation angle

EGVB leads to the characteristic decomposition of scattering covariance matrix in term of three eigenvectors that do depend on the polarization basis. Each eigenvector is expressed in term of the orientation angle ψ and the helicity τ_m. The Huynen helicity τ_m, integrated in the TSVM of (2) permits solving for the Cloude-Pottier $\alpha - \beta$ model ambiguities, as firstly shown in [10] and admitted by Cloude in [6]. In particular, the use of the Huynen helicity, introduced by Kennaugh-Huynen at the H-V polarization, permits correcting for the Cloude α ambiguity firstly raised in [8]. The target Poincaré sphere was introduced in [10] and used to show the importance of the use of τ_m, in addition the scattering type Φ_{α_s}, for a unique description of target scattering. For example, the right and left helix, which have the same symmetric scattering type $\alpha_s = \pi/4$, are mapped on two different sphere locations thanks to the helicity information; $\tau_m = -\pi/4$ and $\tau_m = \pi/4$ for the right and left helix, respectively.

For non-symmetric targets (i.e $\tau_m \neq 0$), the Cloude-Pottier α-β and TSVM models lead to different parameters, and the comparative study of the two models leads to the following conclusions [10]:

1. α and α_s are related through τ_m by; $cos\alpha = cos\alpha_s cos(2\tau_m)$. In contrast to α_s, the roll invariant Cloude α does depend on the basis of polarization for $\tau_m \neq 0$. The variations of τ_m, which in incorporated in α, with the polarization basis leads to a roll invariant but basis variant scattering description with α.

2. The projection of the Cloude-Pottier α-β in a different polarizations-basis, such as the CP basis [8], [11], cannot permits the generation of a polarization-basis invariant EGVD. Even though the CP rotation applied preserves the roll invariant α, the variation of α with τ_m makes it not suitable for an invariant description of target scattering (in another basis of polarization of non zero helicity). The CP basis transformation cannot also correct for α ambiguities that occur at the presence of asymmetric scattering.

However, the rotation angle required for the diagonalization of the covariance matrix does depend on the polarization basis. The rotation angle derived at the circular polarization (for example) provides different information with reference to the Huynen orientation angle ψ. In fact, the different and complementary information provided by the two different polarization-basis angles is important for enhanced characterization of target geophysical parameters. This mainly works with "complex" natural targets for which the simplified Huynen geometrical presentation (under which ψ_{CP} is linearly related to the ψ_{HV}) does not hold. The following presentation of the TSVM at circular polarization basis should confirm the points mentioned above.

E. Presentation of the TSVM at circular polarization

The TSVM can be expressed at the LL-LR circular polarization. Each single target scattering $\vec{k}_{CP}$ can be represented in the (RL, RR, LL)-basis as:

$$\vec{k_{CP}} = m \cdot \begin{bmatrix} j\cos\alpha_s \cos 2\tau_m \\ \exp^{-2j\psi} \cdot (\sin\alpha_s e^{j\Phi_{\alpha_s}} + \cos\alpha_s \sin 2\tau_m) \\ \exp^{2j\psi} \cdot (-\sin\alpha_s e^{j\Phi_{\alpha_s}} + \cos\alpha_s \sin 2\tau_m) \end{bmatrix}$$

For a symmetric scatterer, $\tau_m = 0$, and equation (2) is equivalent to the models derived at circular polarization basis in [8], [11] with scattering type magnitude and phase linearly related with the TSVM polarization basis invariant parameters α_s and Φ_{α_s}. For asymmetric scattering, ($\tau_m \neq 0$) and the Cloude α used in [8], [11] leads to an ambiguous description of target scattering, as discussed in [10], [27]. As seen in (2), the huynen helicity τ_m, introduced by Kennaugh-Huynen at H-V polarization and assigned physically to the geometrical symmetry of the scatterer, can still be used to characterize the symmetric-asymmetric nature of objects at CP basis.

It is worth noting that the Huynen helicity was originally developed by Kennaugh-Huynen for characterization of coherent scattering. The EGVB-Touzi decomposition [10], [27] permits the extension of the use of so named Huynen-Touzi helicity [11] for characterization of the symmetric-asymmetric nature of both coherent and partially coherent scattering. Recently, an ambiguity issue with the calculation of τ_m has been raised [29], [11]. Unfortunately, both of them have missed the point that the TSVM solves for this helicity ambiguity too, as explained in [27]. The use of the the Graves diagonalization method [30] leads to an unambiguous description of τ_m, as discussed in [27].

In summary, the Touzi decomposition [10], [27], which is the synthesis of more than 50 years of advanced methodology development in the complex field of polarimetry [30], [24], [25], [3], [12], [9], [2], is the EGVD that leads to a unique and polarization basis invariant decomposition of target scattering. We have extended the application of the Touzi decomposition to both coherent and partially coherent decomposition using a multi-resolution technique [31]. The latter permits the adaptation of the window size to target non stationarity for optimum application of the Touzi decomposition under coherent and partially coherent scattering conditions. In contrast to MBDs that require the use of large processing window to satisfy the a priori scattering model assumption, the multi-resolution EVBD Touzi decomposition introduced an an extension of Kennaugh-Huynen CTD, allows the optimum and unique description of both coherent and partially coherent scattering in terms of unique and polarization basis-invariant scattering parameters. The Touzi decomposition has become very popular and permit the promotion of the unique information provided by polarimetric SAR in various key applications, such as urban mapping, wetland and rice monitoring, forest biomass measurement, and shoreline mapping [32], [33], [34], [35], [36], [37], [38], [39].

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