Scattering preference pyramid classification of PolSAR data based on canonical huynen dichotomy postprint

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Date: 2017-01-04T00:00:00+00:00

Abstract

Huynen decomposition prefers the world of basic symmetry and regularity (SR) in which we live. However, it is just this preference prevents Huynen decomposition from analyzing the non-symmetric (NS) and irregular (IR) targets. The canonical Huynen dichotomy is proposed to provide two competent supplements to Huynen decomposition by developing two other target dichotomies with the scattering preferences for IR and NS. In virtue of an adaptive combination and permutation of the scattering preferences of the canonical dichotomy, a scattering preference pyramid description of the mixed scattering is developed in this paper. The pyramid is composed of three layers to reflect three different degrees of scattering randomness. Each layer is further composed of several blocks to totally indicate ten different scattering mechanisms. The excellent performance of this scheme is demonstrated by comparing it with the widely-used entropy/alpha classification, and a better discrimination of radar targets is obtained. VDE VERLAG GMBH Berlin Offenbach.

Full Text

Preamble

Scattering Preference Pyramid Classification of PolSAR Data Based on Canonical Huynen Dichotomy

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Abstract

Huynen decomposition exhibits a preference for the world of basic symmetry and regularity (SR) in which we live. However, it is precisely this preference that prevents Huynen decomposition from analyzing non-symmetric (NS) and irregular (IR) targets. This paper proposes the canonical Huynen dichotomy to address this limitation by developing two additional target dichotomies with scattering preferences for IR and NS. Through an adaptive combination and permutation of the scattering preferences from the canonical dichotomy, we develop a scattering preference pyramid description of mixed scattering. The pyramid comprises three layers reflecting three different degrees of scattering randomness, with each layer further divided into several blocks to indicate ten distinct scattering mechanisms. We demonstrate the excellent performance of this scheme by comparing it with the widely-used entropy/alpha classification, achieving superior discrimination of radar targets.

Introduction

Polarization plays an essential role in wave-target interaction. For a single target that stably scatters waves without depolarization, its polarimetric scattering is typically described by a stationary scattering matrix $\mathbf{S}$. However, for distributed targets or mixed scatterers subject to spatial and/or temporal variations, we cannot model their scattering using a fixed $\mathbf{S}$ matrix, and the coherence matrix $\mathbf{T}$ is formed instead. Understanding of the target can be achieved by processing these two matrices, with polarimetric target decomposition being among the most popular approaches. A comprehensive review of existing target decomposition techniques was presented in [**?**].

Huynen decomposition, also known as Huynen target dichotomy, represents the first formalized target decomposition technique. This decomposition possesses clear physical significance due to its preference for the world of basic symmetry and regularity (SR) in which we live [**?**]. However, it is precisely this preference that restricts the applicability of Huynen decomposition to ideal SR scatterers only. For complex non-symmetric (NS) and irregular (IR) scatterers such as forests and buildings, Huynen decomposition fails to analyze their scattering characteristics. To address this limitation, a canonical Huynen dichotomy was devised in [**?**] to extend Huynen decomposition to accommodate preferences for IR and NS.

Based on the physical realizability conditions of polarimetric scattering description, two additional dichotomies of mixed targets were developed, which prefer scattering IR and NS, respectively. The canonical dichotomy combines these two dichotomies with Huynen decomposition, thereby extending Huynen decomposition to exhibit preferences for SR, IR, and NS, respectively. Scattering preference constitutes a main feature of target dichotomy [**?**]. Based on this feature, the canonical Huynen dichotomy has been applied to target extraction in [**?**] and fast visualization of PolSAR data in [**?**]. Experiments on real PolSAR data demonstrate its high efficiency and excellent characterization of radar targets. For details regarding the canonical dichotomy, its applications, and its relationship with other dichotomies such as Barnes-Holm decomposition and Yang decomposition, please refer to [**?**].

This paper is dedicated to further exploring the applicability of the canonical dichotomy for target classification. An excellent decomposition should not only be able to extract single targets but also describe mixed targets. By virtue of an adaptive combination and permutation of scattering preferences, we develop a scattering pyramid description of mixed scattering in Section 3. Its excellent performance is demonstrated through comparison with the entropy/alpha classification on NASA/JPL AIRSAR data of San Francisco.

2 Canonical Huynen Dichotomy and Scattering Preference

The coherence matrix $\mathbf{T}$ of a mixed target in monostatic backscattering is usually expressed as

$$\mathbf{T} = \langle \mathbf{k}\mathbf{k}^H \rangle$$

where $\mathbf{k}$ is the Pauli vector, superscript H denotes the conjugate transpose operation, and $\langle \cdot \rangle$ denotes ensemble averaging (which can be removed for single targets). As a special case, we can write a single target $\mathbf{T}_S$ as $\mathbf{T}_S = \mathbf{k}_S\mathbf{k}_S^H$.

As an extension of Huynen decomposition, the canonical Huynen dichotomy also attempts to decompose a mixed target into the sum of an equivalent single target $\mathbf{T}_S$ and a noisy N-target $\mathbf{T}_N$, as shown on the right side of (1). However, unlike Huynen decomposition, the canonical dichotomy can provide two additional target dichotomies, resulting in a total of three different single targets $\mathbf{k}_{Si}$ ($i = 1, 2, 3$) being extracted.

Hence, each column of $\mathbf{T}$ is simply one of the single target Pauli vectors $\mathbf{k}_{Si}$ extracted by the three sub-dichotomies in the canonical dichotomy, meaning that certain target information is preserved intactly in the single target by each dichotomy. We term this reservation “scattering preference.” From a phenomenological perspective, the three sub-dichotomies (corresponding to Pauli vectors $\mathbf{k}_{S1}$, $\mathbf{k}_{S2}$, and $\mathbf{k}_{S3}$) prefer scattering SR, IR, and NS, respectively. From the viewpoint of canonical scattering, they respectively prefer canonical surface, dihedral, and volume scatterings. Please refer to [**?**] for detailed scattering preference analysis of the canonical Huynen dichotomy.

In addition to these qualitative descriptions, we further define a scattering degree of preference (SDoP) parameter to quantitatively evaluate the preference degree of each sub-dichotomy for canonical surface (SDoP$_s$), dihedral (SDoP$_d$), and volume (SDoP$_v$) scattering as follows:

$$\mathrm{SDoP}_i = \frac{\|\mathbf{k}_{Si}\|_F^2}{\mathrm{SPAN}} \quad (i = s, d, v)$$

where SPAN denotes the power of the mixed target to be decomposed, $\|\cdot\|_F$ denotes the Frobenius norm operation, and $\|\mathbf{k}_{Si}\|_F^2$ is precisely the power of the extracted single target $\mathbf{k}_{Si}$. SDoP thus measures the relative power between the extracted single target and the original mixed target. As a key feature of Huynen-type target dichotomy, SDoP will be used to construct a novel radar target classification in the next section.

3 Target Classification Based on Permutation and Combination of Scattering Preference

The motivation for further exploring the applicability of canonical Huynen dichotomy stems precisely from its preferences for surface, dihedral, and volume scatterings. These scatterings are typically contributed by canonical scatterers such as land/ocean, buildings, and forests, and they dominate nearly all PolSAR scenes. A simple PolSAR data classification scheme can thus be achieved by comparing SDoP_s, SDoP_d, and SDoP_v to identify the most preferable scattering as the dominant scattering mechanism of the target. For instance, the target would be labeled as "more preferable to surface" if SDoP_s is the largest among the three.

However, this scheme is based on the radical assumption that there is always a dominant scattering preference in mixed scattering. Consequently, it only works well for low-randomness targets and is no longer tenable for medium- and high-randomness targets, which may possess several comparable preferences from which we cannot extract a significantly stronger one. To apply the canonical dichotomy to the classification of such random targets, we need to devise an advanced scheme.

3.1 Scattering Preference Pyramid

Instead of simply comparing SDoP_s, SDoP_d, and SDoP_v, we attempt to adaptively permute and combine these parameters for joint characterization of mixed target scattering. This motivates our scattering pyramid scheme, as shown in Fig. 1 Figure 1: see original paper. The pyramid comprises three layers to reflect different degrees of scattering randomness, with each layer further composed of several blocks to indicate different scattering classes expressed through permutations or combinations of SDoP_s, SDoP_d, and SDoP_v. A special characteristic of this scheme is that both the layers and blocks are determined by the scattering preferences of the canonical dichotomy—scattering preferences can model both the scattering mechanism and the randomness. The number of blocks in each layer differs because each layer is designed to denote a different scattering scenario.

Scenario I, located in the 3rd layer, concerns only the significantly strong preference. This results in three potential permutations of SDoP_s, SDoP_d, and SDoP_v. By identifying which of the three is strongest, we obtain three classes (blocks) that prefer surface (simplified as S), dihedral (simplified as D), and volume scattering (simplified as V), respectively. Scenario II in the 2nd layer appears when the contribution of the second strongest preference is also prominent. Six permutations then arise to signify six different scattering mechanisms. The target is indexed as "more preferable to surface and dihedral" if $\mathrm{SDoP}_s \geq \mathrm{SDoP}_d > \mathrm{SDoP}_v$ (simplified as SD). The other five classes—SV, DS, DV, VS, and VD—can be likewise inferred. Scenario III in the 1st layer represents a chaotic state where the three preferences are comparable, yielding only one combination, and the target is wholly labeled as "random scatterer" (simplified as R).

Nevertheless, confusion emerges when $\mathrm{SDoP}_s = \mathrm{SDoP}_d = \mathrm{SDoP}_v$. When the target is fully deterministic, the three SDoP parameters in (3) equal 1 because the **T** matrix of a single target cannot be decomposed further [**?**]. Conversely, when the target is fully random, the three SDoP parameters also equal each other but change to 1/3. Therefore, both fully deterministic and fully random targets are labeled as R in the permutation of SDoP_s, SDoP_d, and SDoP_v. A solution can be obtained by forming the following average SDoP (SDoP_3):

$$\mathrm{SDoP}_3 = \frac{\mathrm{SDoP}_s + \mathrm{SDoP}_d + \mathrm{SDoP}_v}{3}$$

SDoP_3 equals 1 for single targets, 1/3 for noisy targets, and resides between 1/3 and 1 for other targets. Hence it can measure target randomness and be utilized to distinguish the three scattering scenarios. Targets with high SDoP_3 have low randomness, and a dominantly preferable scattering can represent them—this corresponds to Scenario I. Targets with medium SDoP_3 exhibit medium randomness, and the second strongest preference is added, as depicted in Scenario II. The target approaches complete randomness when SDoP_3 is close to 1/3, at which point Scenario III appears. By statistically counting different scatterers on widely-used PolSAR data such as AIRSAR data of San Francisco and ESAR data of Oberpfaffenhofen, the values of 2/5 and 2/3 were determined as the boundaries of the three scenarios, yielding a total of ten classes, as illustrated in Fig. 1(a) and summarized in Table 1 . Fig. 1(c) illustrates the classification result for the San Francisco scene. Before performing target decomposition, the refined Lee filter with a 7×7 aligned window was utilized to suppress speckle, and deorientation was conducted to remove the influence of target orientation. One can observe that typical targets such as the ocean, buildings, forest, avenues, beach, polo field, golf course, mountainous area, Golden Gate Bridge, Sunset Reservoir Park, and Alcatraz Island are all well identified.

3.2 Comparison with Entropy/Alpha Classification

Cloude and Pottier described mixed target scattering using the concept of average target [**?**]. They interpreted the eigendecomposition of mixed target **T** as three single target scatterings (corresponding to the three eigenvectors of $\mathbf{T}$) occurring with probabilities proportional to the three eigenvalues of $\mathbf{T}$. An entropy parameter H was used to describe target randomness, attributing mixed scattering into three scenarios: low entropy, medium entropy, and high entropy. By further parameterizing the three eigenvector-related single target scatterings with a revised Bragg α-β scattering model [**?**], an average target scattering was obtained to indicate the scattering mechanism. Particularly, the α angle of the average scattering could directly reflect the physical property of the target and was utilized to subdivide the three H-scenarios into eight effective zones, indexed by Z_i $(i = 1, 2, \ldots, 8)$ in Fig. 1(b) [Figure 1: see original paper]. The H/α classification of the San Francisco scene is shown in Fig. 1(d) [Figure 1: see original paper], which we compare with our classification in Fig. 1(c) [Figure 1: see original paper].

Our intuitive impression is one of consistency, arising from the fact that both schemes use scattering randomness to coarsely differentiate targets and further divide the low-randomness scenario into three classes for surface, dihedral, and volume scatterings. Nevertheless, their differences are also obvious, with two major distinctions observed. First, the forest (dark green) in Fig. 1(c) is much clearer, particularly in the avenue areas (circles 1 and 2) and Sunset Reservoir Park (circle 3), owing to different treatments of high-entropy targets. The target is wholly labeled as R in the scattering pyramid but is split into two zones in H/α. The good separability in Fig. 1(c) reveals that it is not always necessary to further distinguish random targets. Second, the beach area in rectangle 4 appears as volume scattering (green) in Fig. 1(d) but turns to SD (yellow) in Fig. 1(c). We believe the latter is more consistent with ground truth, as beaches generally comprise sand. Similar situations are also observed in the polo field (circle 5) and golf course (circle 6). Moreover, the Reservoir Park and Golden Gate Bridge in circles 3 and 7 also appear as volume scattering in Fig. 1(d) but turn to DS (dark red) in Fig. 1(c). The classification in Fig. 1(c) is found more credible upon further reference to optical imagery and even the Wishart H/α classification [**?**] of the San Francisco data. The inferiority of H/α arises from its statistical average modeling of mixed scattering. While average scattering can well represent mixed scattering in a total sense, it introduces certain obscurity. For example, both SD and DS (which have comparable SDoP_s and SDoP_d, as listed in Table 1) are identified as volume scattering (since α is close to 45°) by H/α. However, SD and DS are clearly different from volume scattering because they prefer dihedral and surface scatterings more than volume scattering.

Conclusions

Canonical Huynen dichotomy encompasses three different target sub-dichotomies preferring scattering SR, NS, and IR, respectively. Scattering preference is a key feature of the canonical dichotomy that describes how certain target information is preserved in the extracted single target by each sub-dichotomy. Targets vary from pixel to pixel, and the sub-dichotomy used to analyze them should also be adaptive. If we can devise an appropriate scheme, the application of scattering preference will be promising. The scattering pyramid is precisely such a scheme, which employs an adaptive combination and permutation of the scattering preferences from the canonical dichotomy to better describe mixed scattering. Comparative experiments with entropy/alpha demonstrate its excellent target discrimination capability.

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Note: Figure translations are in progress. See original paper for figures.