Canonical Huynen Decomposition of Radar Targets (Postprint)

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Abstract

Huynen decomposition prefers the world of basic symmetry and regularity (SR) in which we live. However, this preference restricts its applicability to ideal SR scatterer only. As for the complex non-symmetric (NS) and irregular (IR) scatterers such as forest and building, Huynen decomposition fails to analyze their scattering. The canonical Huynen dichotomy is devised to extend Huynen decomposition to the preferences for IR and NS. From the physical realizability conditions of polarimetric scattering description, two other dichotomies of polarimetric radar target are developed, which prefer scattering IR, and NS, respectively, and provide two competent supplements to Huynen decomposition. The canonical Huynen dichotomy is the combination of the two dichotomies and Huynen decomposition. In virtue of an Adaptive selection, the canonical Huynen dichotomy is used in target extraction, and the experiments on AIRSAR San Francisco data demonstrate its high efficiency and excellent discrimination of radar targets. 2015 SPIE.

Full Text

Canonical Huynen Decomposition of Radar Targets

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ABSTRACT

Huynen decomposition exhibits a fundamental preference for scattering symmetry and regularity (SR), which restricts its applicability to ideal SR scatterers only. For complex non-symmetric (NS) and irregular (IR) scatterers such as forests and buildings, Huynen decomposition fails to adequately analyze their scattering characteristics. The canonical Huynen dichotomy is devised to extend Huynen decomposition to accommodate preferences for IR and NS scattering. Based on the physical realizability conditions of polarimetric scattering description, two additional dichotomies are developed that prefer scattering IR and NS, respectively, providing competent supplements to Huynen decomposition. The canonical Huynen dichotomy combines these two dichotomies with Huynen decomposition. Through adaptive selection, the canonical Huynen dichotomy is applied to target extraction, and experiments on AIRSAR San Francisco data demonstrate its high efficiency and excellent discrimination capability for radar targets.

Keywords: Canonical Huynen dichotomy, Huynen-type target dichotomy, target decomposition, scattering preference, phenomenological theory, physical realizability conditions, polarimetric synthetic aperture radar, target extraction

1. INTRODUCTION

The concept of polarimetric target decomposition was first formalized by Huynen in his Ph.D. dissertation [1]. Since then, numerous decomposition methods have been proposed [2], and classifying terrain by extracting useful scattering information from PolSAR data via target decomposition has become a highly active research topic in geoscience and remote sensing. This methodology plays a crucial role in monitoring natural disasters such as volcanic eruptions, landslides, earthquakes, and tsunamis, as well as in assessing human activity-related environmental changes like wetland degradation and deforestation [3, 4].

Despite its theoretical importance, Huynen decomposition has not received widespread application or attention. A commonly cited reason is its non-uniqueness, as theoretically infinite target dichotomies may exist if Huynen' s restriction on roll-invariance is removed [5]. However, this paper does not focus on this particular imperfection, as it also exists in other decomposition methods [6]. Instead, we address the inability of Huynen decomposition to analyze irregular and non-symmetric targets—a limitation independently confirmed by Holm and Barnes [7], Yang et al. [8], and Paladini [9]. Holm and Barnes encountered this issue when processing a rotated diplane immersed in polarization noise [7]. Yang et al. observed similar problems with a distributed dihedral scatterer (entropy = 0.08, alpha angle = 88.93°) [8]. Paladini recently conducted a comparable experiment on a distributed ship target dominated by even-bounce scattering, concluding that "the Huynen theory about the high-frequency noise nature of the N-target and the specular nature of the signal part is failed in practice for all such cases where a dominant dihedral scattering is observed" [9].

This paper revisits Huynen decomposition and identifies its preference for scattering symmetry and regularity (SR) as the primary factor restricting its applicability. From the physical realizability conditions of scattering description, we devise two additional target dichotomies that prefer scattering irregularity (IR) and non-symmetry (NS), respectively. A canonical Huynen dichotomy is developed by combining these two dichotomies with Huynen decomposition, and its effectiveness is demonstrated through application to target extraction using real PolSAR data.

The remainder of this paper is organized as follows. Section 2 formulates the physical realizability conditions of scattering description. Based on these conditions, Huynen decomposition is presented in Section 3, and the canonical Huynen dichotomy is developed in Section 4. Section 5 applies the canonical dichotomy to target extraction, and Section 6 concludes the paper.

2. PHYSICAL REALIZABILITY CONDITIONS OF POLARIMETRIC SCATTERING DESCRIPTION

Single target and mixed target represent two distinct scenarios in radar polarimetry. In the single target scenario, the target stably scatters the incident wave without depolarization, and the scattering is described by the scattering [S] matrix, which has only five degrees of freedom (DoFs) in monostatic backscattering. For a mixed target situated in a dynamic environment or subjected to spatial/temporal variation, the target scattering is partially polarized and cannot be depicted by a fixed [S] matrix. The coherence [T] matrix is then constructed through statistical averaging:

$$[T] = \langle kk^H \rangle = \begin{bmatrix} 2A_0 & C & H \\ C^* & B_0 + B & E \\ H^* & E^* & B_0 - B \end{bmatrix}$$

where $\langle \cdot \rangle$ denotes ensemble averaging, k is the Pauli vector, and the superscript H indicates conjugate transpose. Ensemble averaging makes the nine parameters of [T] mutually independent. Consequently, a mixed target cannot be directly represented by a single target due to four additional DoFs. The nine parameters on the right side are known as Huynen parameters, as Huynen first linked them to the phenomenological characteristics of radar targets. As illustrated in [Figure 1: see original paper], $2A_0$, $B_0 + B$, and $B_0 - B$ are the generators of SR, IR, and NS, respectively, while the remaining parameters denote pairwise couplings between these generators [1].

A 3×3 complex Hermitian matrix qualifies as a target coherence matrix only if it satisfies the physical realizability conditions. For a mixed target, these conditions require [T] to be positive semidefinite, with all three second-order principal minors being nonnegative:

For mixed target:

$$\begin{cases} 2A_0(B_0 + B) - |C|^2 \geq 0 \\ 2A_0(B_0 - B) - |H|^2 \geq 0 \\ (B_0 + B)(B_0 - B) - |E|^2 \geq 0 \end{cases} \quad (-2)$$

In the single target scenario, [T] is rank-one and all second-order minors must be zero. This yields nine equations, but only four are independent because a single target has five DoFs. We can therefore extract three condition groups:

$$\begin{cases} 2A_0(B_0+B) = |C|^2 \\ 2A_0(B_0-B) = |H|^2 \\ (B_0+B)(B_0-B) = |E|^2 \end{cases} \tag{-3}$$

Each group in (3) is self-contained, yielding the following three equations, respectively:

For single target:

$$\begin{cases} B_0+B = \frac{|C|^2}{2A_0} \\ B_0-B = \frac{|H|^2}{2A_0} \\ B_0^2-B^2 = |E|^2 \end{cases} \tag{-2}$$

[Figure 1: see original paper] Phenomenological significance of the nine Huynen parameters.

3. HUYNEN DECOMPOSITION

The same four parameters (B_0, B, E, F) behave differently in the two target scenarios, analogous to the behavior of the four Stokes parameters in fully polarized and partially polarized wave scenarios. The wave dichotomy theorem states that a partially polarized wave can always be decomposed into the sum of a fully polarized wave and a fully depolarized wave [2]. By analogy, Huynen developed a target dichotomy to express a mixed target [T] as the sum of an equivalent single target [TS1] and a noisy N-target [TN1]:

$$[T] = [TS1] + [TN1]$$

Huynen insisted that the physical world prefers SR and that the related parameters $(2A_0, C, D, G, H)$ should be preserved in the single target. Therefore, he chose to decompose only parameters (B_0, B, E, F) [1]:

$$\begin{bmatrix} 2A_0 & C & H \\ C^* & B_0+B & E \\ H^* & E^* & B_0-B \end{bmatrix} = \begin{bmatrix} 2A_0 & C & H \\ C^* & B_{0S}+B_S & E_S \\ H^* & E_S^* & B_{0S}-B_S \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & B_{0N}+B_N & E_N \\ 0 & E_N^* & B_{0N}-B_N \end{bmatrix} \tag{5}$$

The subscripts S and N denote the equivalent single target and N-target, respectively. If we replace (B_0, B, E, F) with (B_{0S}, B_S, E_S, F_S), then parameters (B_{0S}, B_S, E_S, F_S) can be inverted from (3-1) based on the preserved parameters $(2A_0, C, D, G, H)$.

4. CANONICAL HUYNEN DICHOTOMY

Huynen reserved the SR-related parameters in [TS1] because it "leads to a consistent world-picture where psychological preference for symmetry" [1]. This worldview restricts Huynen decomposition' s applicability to ideal SR targets only, causing it to fail when analyzing complex IR and NS targets—a limitation validated by Holm and Barnes [7], Yang et al. [8], and Paladini [9]. In response, Huynen suggested that attention should shift from [TS1] to [TN1] in these cases [10]. However, observing (5) reveals that the IR- and NS-related parameters (B_0, B, E, F) are distributed across both [TN1] and [TS1], making exclusive focus on either component inappropriate for integrated characterization of such radar targets.

The canonical Huynen dichotomy extends Huynen decomposition to accommodate preferences for IR and NS. This extension is readily achieved because we still have two mixed target inequalities in (2) with their corresponding single target equations in (4). For parameters $(2A_0, B_0 - B, H, G)$, if we define:

$$\begin{cases} \tilde{B}_0 = B_0 - B \\ \tilde{B} = 0 \\ \tilde{E} = G \\ \tilde{F} = H \end{cases}$$

This enables us to rewrite (2-2) and (4-2) into forms similar to (2-1) and (4-1), respectively:

For single target:

$$2A_0(\tilde{B}_0 + \tilde{B}) = |\tilde{E}|^2 \tag{4-2}$$

For mixed target:

$$2A_0(\tilde{B}_0 + \tilde{B}) - |\tilde{E}|^2 \geq 0 \tag{2-2}$$

Analogous to Huynen decomposition, we then obtain:

$$\begin{bmatrix} 2A_0 & C & H \\ C^* & B_0 + B & E \\ H^* & E^* & B_0 - B \end{bmatrix} = \begin{bmatrix} 2A_{0S} & C & \tilde{E}_S \\ C^* & B_0 + B & E_S \\ \tilde{E}_S^* & E_S^* & \tilde{B}_{0S} + \tilde{B}_S \end{bmatrix} + \begin{bmatrix} 2A_{0N} & 0 & \tilde{E}_N \\ 0 & 0 & 0 \\ \tilde{E}_N^* & 0 & \tilde{B}_{0N} + \tilde{B}_N \end{bmatrix} \tag{8}$$

Dichotomy (8) prefers IR because it preserves the IR-related Huynen parameters $(B_0 + B, C, D, E, F)$ in the single target matrix. Based on these preserved parameters, the decomposed parameters $(2A_{0S}, B_{0S} - B_S, G_S, H_S)$ can be easily retrieved from (3-2).

Likewise, for parameters $(2A_0, B_0 + B, C, D)$, if we define:

$$\begin{cases} \bar{B}_0 = B_0 + B \\ \bar{B} = 0 \\ \bar{E} = C \\ \bar{F} = D \end{cases}$$

From (2-3) and (4-3) we then have:

For single target:

$$(\bar{B}_0 + \bar{B})(\bar{B}_0 - \bar{B}) = |\bar{E}|^2 \tag{4-3}$$

For mixed target:

$$(\bar{B}_0 + \bar{B})(\bar{B}_0 - \bar{B}) - |\bar{E}|^2 \geq 0 \tag{2-3}$$

Hence we also obtain the following target dichotomy:

$$\begin{bmatrix} 2A_0 & C & H \\ C^* & B_0 + B & E \\ H^* & E^* & B_0 - B \end{bmatrix} = \begin{bmatrix} 2A_{0S} & \bar{E}_S & H \\ \bar{E}_S^* & \bar{B}_{0S} + \bar{B}_S & E \\ H^* & E^* & \bar{B}_{0S} - \bar{B}_S \end{bmatrix} + \begin{bmatrix} 2A_{0N} & \bar{E}_N & 0 \\ \bar{E}_N^* & \bar{B}_{0N} + \bar{B}_N & 0 \\ 0 & 0 & \bar{B}_{0N} - \bar{B}_N \end{bmatrix} \tag{11}$$

Dichotomy (11) prefers NS because it preserves the NS-related parameters $(B_0 - B, E, F, G, H)$ in the single target coherence matrix [TS3]. Parameters $(2A_{0S}, B_{0S} + B_S, C_S, D_S)$ can then be obtained from (3-3) based on the preserved parameters.

Dichotomies (8) and (11) provide two competent supplements to Huynen decomposition. Together with Huynen decomposition, we now have three dichotomies preferring SR, IR, and NS, respectively. We term them the canonical Huynen dichotomy because Huynen himself claimed the existence of [TN2] and [TN3] in dichotomies (8) and (11). He named them type I and type II symmetrical canonical targets but abandoned them for "having no such natural appeal" like [TN1] [1].

5. EXTRACTION OF DOMINANT TARGET SCATTERING

A single target represents a deterministic scatterer whose scattering mechanism can be easily determined. However, a mixed target is a random scatterer that cannot be directly characterized like a single target. Huynen [1] and Cloude [5] proposed using an equivalent dominant single target to model mixed target scattering, but consensus has not been reached regarding the definition of a dominant single target. In Huynen decomposition, it refers to a scatterer that physically preserves the complete SR information of the mixed target. In eigenvector-based Cloude decomposition, it is a scatterer that mathematically approximates the mixed target optimally:

$$[T] = \sum_{i=1}^{3} \lambda_i u_i u_i^H = [TScd] + [TNcd]$$

where [TScd] is the extracted dominant scattering with Pauli vector kScd, related to the largest eigenvalue 1 and eigenvector u1 of [T]. The SPAN of [TScd] is the largest among all possible estimations of the dominant scattering of [T] [5].

Total power (SPAN) of the dominant single targets extracted by Cloude decomposition, the canonical Huynen dichotomy, and dichotomies (5), (8), and (11) from three selected pixel patches.

[Figure 2: see original paper] Illustration of the experimental PolSAR data. (a) Pauli display of L-band AIRSAR San Francisco data, where Patch1, Patch2, and Patch3 are three 6×6 pixel patches selected from ocean, city, and vegetation areas, respectively. These are used as numerical examples, and (b) shows their projection in the 2D entropy/alpha classification plane.

As an extension of Huynen decomposition, the canonical Huynen dichotomy enables three dichotomies preferring SR, IR, and NS, respectively. By devising a fair selection strategy giving each dichotomy an equal opportunity, the canonical dichotomy can be used for adaptive extraction of dominant scattering. Following Cloude decomposition, our selection is also based on SPAN: we use the three dichotomies to extract single targets [TS1], [TS2], and [TS3] from mixed target [T], then identify the one with maximum SPAN as the final dominant single target extraction [TSchd]:

$$[TSchd] = \arg\max_{[TSi]} \text{SPAN}([TSi]), \quad i = 1, 2, 3$$

where ci (i = 1, 2, 3) is a constant defined as:

$$c_i = \begin{cases} 1, & \text{if SPAN}([TSi]) = \max\{\text{SPAN}([TS1]), \text{SPAN}([TS2]), \text{SPAN}([TS3])\} \\ 0, & \text{otherwise} \end{cases}$$

The performance of canonical Huynen dichotomy for dominant scattering extraction is tested using NASA/JPL L-band AIRSAR data of San Francisco. [FIGURE:2(a)] shows the Pauli image of this scene, which covers various scatterers including ocean, city, and vegetation. Three 6×6 pixel patches are selected from these areas, and their projection in the 2D entropy/alpha classification plane is shown in [FIGURE:2(b)]. The three patches correspond to low-entropy Bragg scattering, medium-entropy dihedral scattering, and high-entropy volume scattering, respectively.

For each patch, we average the [T] matrices of all 36 pixels and normalize the averaged [T] matrix by its trace. Dichotomies (5), (8), and (11) are then applied to extract single target scattering from the three normalized mean patches. lists the obtained SPAN([TSi]) for each patch, with SPAN([TScd]) from Cloude decomposition provided for comparison. As expected, dichotomy (5)—Huynen decomposition—performs best on Patch1 due to its preference for SR scattering. However, on Patch2 and Patch3 where surface scattering is no longer dominant, Huynen decomposition cannot achieve satisfactory target extraction, and the majority of power is decomposed into [TN1]. This aligns with the findings of Holm and Barnes, Yang et al., and Paladini.

Nevertheless, dichotomies (8) and (11) provide competent supplements to Huynen decomposition. On Patch2, the single target extracted by dichotomy (8) retains the most power. The distributed dihedral scatterer used by Holm and Barnes, Yang et al., and Paladini to demonstrate Huynen decomposition' s failure can be successfully handled by this dichotomy. Patch3 corresponds to high-entropy volume scattering, where dichotomy (11) performs best among the three dichotomies. However, approximately 60% of power is still distributed into [TN3]. This does not indicate poor performance of dichotomy (11), as [TScd] extracted by Cloude decomposition on this patch also represents only 42.16% of power. The primary influence is scattering randomness: Patch3' s entropy is 0.9838, signifying high randomness and nearly isotropic scattering preference, making it impossible to identify a prominently strong preferred single target. The canonical dichotomy extracts [TSchd] by maximizing SPAN. As listed in , SPAN([TSchd]) shows minimal difference from SPAN([TScd]) across the three patches.

This numerical example illustrates the scattering preferences of the three dichotomies on selected patches. Dichotomies (5), (8), and (11) respectively preserve the 1st, 2nd, and 3rd columns of [T] intact into [TS1], [TS2], and [TS3]. We treat this preservation as a scattering preference and describe each dichotomy' s preference in terms of three phenomenological characters. As indicated in Sections 3 and 4, the three dichotomies prefer SR, IR, and NS, respectively, because the three columns of [T] relate to SR, IR, and NS. [FIGURE:3(a)], (b), and (c) further show the Pauli images of [TS1], [TS2], and [TS3] extracted from the entire San Francisco scene.

The dark blue in the ocean area of [FIGURE:3(a)] reveals Huynen decomposition' s preference for SR scattering. The wide distribution of red color in [FIGURE:3(b)] indicates dichotomy (8)' s preference for IR dihedral scattering, making it useful for building detection since buildings generally produce the strongest dihedral scattering in urban areas. Dichotomy (11) prefers NS volume scattering, and the green forests in [FIGURE:3(c)] clearly reflect this, suggesting its potential for forest detection. The three dichotomies thus provide three different perspectives on mixed targets.

The canonical dichotomy combines them through adaptive selection, and the extracted dominant scattering [TSchd] is shown in [FIGURE:3(d)], which appears much closer to the original mixed scattering [T] than any [TSi]. Furthermore, by adaptively filtering out unwanted noisy scatterings, the canonical dichotomy clarifies target scattering signatures. The target scattering in [FIGURE:3(d)] is strengthened because the "blur cover" in [FIGURE:2(a)] is removed, improving target identification capability. By quantifying Huynen decomposition' s contribution to dominant scattering extraction, we find that 37% of the San Francisco scene is inappropriate for Huynen decomposition, validating its restricted applicability.

The numerical example reveals minimal difference between SPAN([TSchd]) and SPAN([TScd]) on the three selected patches. [FIGURE:3(e)] further shows the Pauli image of [TScd] on the entire San Francisco scene, appearing nearly identical to [FIGURE:3(d)]. [FIGURE:3(f)] illustrates the relationship between SPAN([TSchd]) and SPAN([TScd]), with the nearly linear correlation indicating good consistency. For comparison, [FIGURE:3(f)] also shows the relationship between SPAN([TS1]) and SPAN([TScd]). Clearly, from the perspective of mathematical target extraction, Huynen decomposition is substantially improved by the canonical dichotomy. The mean relative residue between SPAN([TSchd]) and SPAN([TScd]) is only 3.61% for the San Francisco scene, but increases to 14.03% when replacing [TSchd] with [TS1]. These results demonstrate not only the superiority of canonical dichotomy over Huynen decomposition but also the potential unifiability of canonical dichotomy and Cloude decomposition.

Target extraction in (13) can be equivalently formulated in terms of Pauli vectors:

$$k_{Schd} = \sum_{i=1}^{3} c_i k_{Si}$$

where k_{Schd} and k_{Si} are the Pauli vectors of [TSchd] and [TSi]. From (5), (8), and (11), we can easily obtain:

$$k_{Si} = \frac{1}{\sqrt{2A_0}} \begin{bmatrix} T_{1i} \\ T_{2i} \\ T_{3i} \end{bmatrix}$$

The Pauli vector k_{Si} directly relates to each column of matrix [T]. Therefore, although canonical dichotomy appears less straightforward than Cloude decomposition because it requires performing three dichotomies for optimization, it can actually be implemented efficiently. Conversely, Cloude decomposition is not so straightforward because it requires conducting a series of unitary transforms on [T] for eigenvalue and eigenvector computation. While computation can be accelerated using LAPACK-based eigenanalysis tools, the resulting computational load remains heavy. To illustrate this, we executed Matlab codes for both decompositions on the entire San Francisco scene 100 times on a computer with Pentium (R) 8.00 GB memory and 3.20 GHz CPU clock. The average computational times were 0.2120s and 9.7406s, respectively, making the canonical dichotomy approximately 46 times faster than Cloude decomposition.

6. CONCLUSION

The preference for scattering symmetry and regularity restricts Huynen decomposition' s applicability. The canonical Huynen dichotomy extends Huynen decomposition to accommodate preferences for irregularity and non-symmetry. A 3×3 complex Hermitian matrix qualifies as a polarimetric coherence matrix only when satisfying physical realizability conditions, which form the foundation of the canonical dichotomy. The canonical dichotomy achieves dominant target extraction consistent with Cloude decomposition while offering superior efficiency.

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