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Unified Phenomenological Decomposition of Radar Targets (Postprint)

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Abstract

Huynen phenomenological decomposition as the first formalized target decomposition has not been widely accepted. Huynen's preference for scattering symmetry and regularity restricts not only the application of this decomposition but also its unification with other target dichotomies such as the Barnes-Holm decomposition and Yang decomposition. The non-uniqueness issue then arises because we may have different dichotomies of radar targets, but we have no idea on how to select them. Recently, a unified Huynen dichotomy was developed by Li and Zhang to extend Huynen decomposition for a full preference for symmetry and regularity, non-symmetry, irregularity, as well as their couplings. The dichotomy covers all the existing dichotomies and provides an excellent discrimination of radar targets. This paper gives a concise review of the Huynen-type target dichotomies to investigate the existing concerns influencing the application of such decompositions and the corresponding coping methods. We hope this review will help to promote the wide acceptance of Huynen-type target dichotomies in the future.

Full Text

Unified Phenomenological Decomposition of Radar Targets

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Abstract

Huynen phenomenological decomposition, as the first formalized target decomposition technique, has not gained widespread acceptance. Huynen's emphasis on scattering symmetry and regularity not only limits the applicability of this decomposition but also impedes its unification with other target dichotomies

such as the Barnes-Holm and Yang decompositions. This limitation gives rise to a non-uniqueness issue: while multiple radar target dichotomies exist, no clear criteria exist for selecting among them. Recently, Li and Zhang developed a unified Huynen dichotomy that extends Huynen decomposition to accommodate full preferences for symmetry and regularity, non-symmetry, irregularity, and their various couplings. This unified framework encompasses all existing dichotomies and provides excellent discrimination of radar targets. This paper presents a concise review of Huynen-type target dichotomies, examining the persistent concerns that have limited their application and the corresponding solutions that have been developed. We hope this review will promote broader acceptance of Huynen-type target dichotomies in the future.

Index Terms—Huynen decomposition, radar polarimetry, target decomposition, unified target dichotomy

1. Introduction

Dr. J. R. Huynen first formalized the concept of target decomposition in his 1970 Ph.D. dissertation, “Phenomenological Theory of Radar Targets” [1]. Huynen demonstrated that radar targets, like waves, can be decomposed, and that polarimetric decomposition offers a viable method for understanding complex targets. Building upon this pioneering work, numerous decomposition techniques have been developed, attracting considerable attention over the past four decades [2].

Despite its theoretical significance, Huynen decomposition (HD) has not received widespread attention or practical application. It is often cited as one of Huynen’s main visionary concepts that remains unaccepted today. While frequently mentioned in literature as the first decomposition or a typical target dichotomy, only a minority of reviews provide detailed introductions or focused discussion. This paper aims to provide a concise review of the existing concerns regarding Huynen-type target dichotomies (HTD) and the methods developed to address them. Section 2 focuses on the non-uniqueness of HTD and the need for unification, presenting the unified Huynen dichotomy (UHD). Section 3 discusses the local unitary invariance of HTD and the scattering preference property to illustrate their physical significance. Based on the permutation and combination of UHD’s scattering preferences, Section 4 presents a scattering pyramid classification scheme for mixed scatterers, addressing concerns about the practical value of HTD. Section 5 investigates the potential consistency between UHD and Cloude decomposition (CD) to resolve the Huynen-Cloude controversy over decomposition uniqueness from 1992. Section 6 concludes the paper.

2. Decomposition Non-Uniqueness and UHD

Three main factors have limited the application of HTD. First, Barnes and Holm observed that HD is not unique, as two other dichotomies share the same roll-invariance around the radar line of sight [3]. While Barnes-Holm decompo-

sition (BHD) relaxes Huynen' s preference for symmetry and regularity (SR), it was criticized for providing little physical insight into scattering, as it creates two “exotic worlds” with imbalanced preferences for left- and right-handed helices [4]. Second, the Huynen-Cloude controversy [4], [5] highlighted that HD lacks “global” invariance—i.e., invariance under all unitary transforms. Cloude argued that removing Huynen' s roll-invariance restriction yields infinite possible target dichotomies, whereas eigenvector-based CD ensures a unique result [5]. He concluded that no target dichotomy exists—only CD provides a unique decomposition. Huynen countered that CD loses physical significance through eigendecomposition and suffers from parameter proliferation, making it “dubious,” whereas HD maintains clear physical significance by aligning with the fundamental symmetries of our world [4]. Huynen' s position received support from Pottier [6] and Holm [7], but Cloude' s concerns attracted more followers, significantly impacting HD' s adoption.

The third factor involves Yang et al.' s finding that HD cannot reliably extract desired targets due to stability issues, prompting their proposed modification [8]. However, the first two factors overshadowed this work, limiting the impact of Yang decomposition (YD).

[Figure 1: see original paper]

The non-uniqueness concerns regarding HD have remained unresolved. This issue manifests in two ways in the literature. First, while infinite mathematical decompositions of a mixed target into a single target and an N-target exist, the preference for SR reduces these to HD alone. We do not consider this form of non-uniqueness particularly noteworthy, as it exists in other decompositions as well. For example, Cloude et al. [11] noted that infinite decompositions of a mixed target into three single targets exist, but orthogonality constraints reduce these to the unique CD solution. In this sense, the uniqueness controversy between Huynen and Cloude is trivial, as they simply hold different views on treating the same problem. The second manifestation is more significant: BHD and YD provide alternative target dichotomies to HD, offering three distinct perspectives—Huynen' s preference for SR, Barnes-Holm' s concern for roll-invariance, and Yang' s focus on stability. Each dichotomy is reasonable, yet no consensus exists on selection criteria, particularly between BHD and YD. We believe this non-uniqueness fundamentally restricts HTD application.

A unified Huynen dichotomy (UHD) was recently developed to address HTD non-uniqueness [12]. In Huynen' s phenomenological theory, SR, irregularity (IR), and non-symmetry (NS) constitute the three fundamental scattering characteristics [1]. HD derives from physical realizability conditions that specify how a 3×3 complex Hermitian matrix qualifies as a target coherence matrix (for monostatic backscattering), preferring only SR scattering. From these realizability conditions, two additional dichotomies emerge that prefer IR and NS scattering, respectively. These dichotomies not only supplement HD but also simplify YD, achieving consistent decomposition results from a completely different foundation.

The N-targets from these two dichotomies are invariant to unitary ellipticity transforms and unitary absolute phase transforms, respectively, yielding four additional dichotomies. Combined with BHD, this results in nine total target dichotomies. A mechanism based on SPAN (total scattered power) was devised to unify them, ensuring each dichotomy has a fair chance of selection. This unified framework, termed UHD, encompasses all existing HTD (HD, BHD, and YD) and provides adaptive dichotomy for distributed/mixed radar targets dominated by SR, IR, NS, or their couplings [12], as illustrated in Fig. 1.

3. Local Unitary Invariance and Scattering Preference

Cloude noted that HD cannot provide “global” invariance under all unitary transforms [5]; however, such invariance is not always necessary [12]. Global invariance is a specific attribute of CD, upon which Cloude and Pottier based their H/α classifier to address Huynen’s concerns about CD’s physical significance. HTD provides only “local” invariance—i.e., invariance under specific unitary transforms. Nevertheless, this local invariance endows each HTD with a specific attribute: scattering preference, which describes how certain target scattering information is preserved in the extracted single target. Huynen qualitatively explained HD’s preference using the three phenomenological characteristics (SR, NS, IR) [1]. While practically relevant, this description offers limited utility for detailed data interpretation [13] and conveys restricted information [12]. For example, applying this description to the two BHD variants yields preferences expressed as couplings of IR and NS, but fails to distinguish between them.

A novel scattering preference description was proposed by directly relating each HTD to a canonical scattering mechanism [12], as listed in Table 1. This approach reveals that HTD inherently possess physical significance.

4. Classification Based on Permutation and Combination of UHD

An effective decomposition must both extract single targets and describe mixed targets that cannot be modeled by a dominant single target. Boerner [14] noted that HD performance deteriorates with increasing entropy, making it unsuitable for analyzing random mixed targets common in natural scenes. CD faces the same limitation, but Cloude and Pottier resolved it using the average target concept. To enhance UHD’s applicability, a scattering pyramid scheme (Fig. 2(a)) was developed [12] by adaptively permuting and combining multiple HTD with different preferences to characterize mixed target scattering. Fig. 2(c) shows the AIRSAR San Francisco classification result, with the H/α classifier and its classification provided in Figs. 2(b) and 2(d) for comparison.

The schemes show clear similarity, as both use scattering randomness to coarsely differentiate targets and partition low-randomness scenarios into three classes: surface, dihedral, and volume scattering. However, notable differences exist.

First, the forest areas (dark green) in Fig. 2(c) appear much clearer, particularly in the avenue regions (circles 1 and 2) and Sunset Reservoir Park (circle 3), due to different handling of high-entropy targets. The scattering pyramid labels these targets entirely as R (random scatterer), whereas H/α splits them into two zones. The improved separability in Fig. 2(c) suggests that further distinguishing random targets is not always necessary. Second, the beach area in rectangle 4 appears as volume scattering (green) in Fig. 2(d) but as SD (preferring surface and dihedral scattering [12]) (yellow) in Fig. 2(c). The latter better matches ground truth, as beaches typically comprise sand. Similar improvements appear in the polo field (circle 5) and golf course (circle 6). Additionally, Reservoir Park and the Golden Gate Bridge (circles 3 and 7) show volume scattering in Fig. 2(d) but DS (preferring dihedral and surface scattering [12], dark red) in Fig. 2(c). Comparison with optical imagery confirms that Fig. 2(c) provides more credible classification.

5. Consistency Analysis of HTD and CD

Beyond reviewing HTD's theoretical unification and practical application, this paper investigates potential consistency between HTD and CD. Rather than treating them as competing approaches, we seek to establish their complementary relationship. This analysis proceeds along two dimensions. First, in extracting dominant single targets, a mathematical convergence toward CD becomes evident when extending HD to canonical Huynen dichotomy (CHD, which simplifies YD [12]), and further extending BHD and CHD/YD to UHD. UHD achieves extraction results highly consistent with CD, as illustrated in Fig. 3 [Figure 3: see original paper].

Second, UHD models mixed target scattering using Cloude-Pottier's average target concept [9], enabling a scattering degree of preference (SDoP)/alpha classification that serves as a competent alternative to H/α [12], shown in Fig. 4 [Figure 4: see original paper].

6. Conclusion

HD was once considered a decomposition of limited practical value. This paper provides a concise review of existing concerns regarding HTD and the methods developed to address them. This review demonstrates that concerns about HD have been adequately resolved, that HTD performance is well-established, and that the Huynen-Cloude controversy may be effectively settled. Four decades of development in this field indicate that no unique decomposition exists—rather, an infinite family of decompositions is possible. Uniqueness emerges only when preferring specific aspects. Each decomposition offers distinct utility but cannot provide complete scattering information. Therefore, combining multiple decompositions enables integrated understanding and enriches polarimetric radar's view of the world. For detailed information on UHD, its classification applications, and consistency with CD, please refer to [12].

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Figure Captions

Fig. 1. The unified Huynen dichotomy (UHD) of radar targets. It covers all existing HTD such as HD, BHD, and YD in a unified frame.

Fig. 2. The scattering preference-based pyramid scheme and its comparison with entropy/alpha scheme on AIRSAR data of San Francisco, where (a) is the scattering preference pyramid, (b) is the entropy/alpha plane, (c) and (d) are the classification results from scattering preference pyramid and entropy/alpha, respectively.

Fig. 3. Relationships between CD and HTD (including (black) HD, BHD (chocolate) I & (blue) II, (red) CHD or YD, and (green) UHD) ((a) to (c)) on the moduli of the three components and (d) on the Frobenius norm of the extracted single target Pauli vector on AIRSAR San Francisco data. A convergence to CD is clearly shown from HD and BHD to CHD, and further to UHD. Please refer to Section IV of [12] for the detailed mathematical evaluation of UHD.

Fig. 4. (a) UHD-based scattering degree of preference (SDoP)/alpha classification scheme and (b) its classification of San Francisco scene.

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

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