EXPLOITING INVERSE SAR IMAGES AND DUAL-POL DECOMPOSITION FOR THE ESTIMATION OF TREE SCATTERING PROPERTIES

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ABSTRACT

The Inverse Synthetic Aperture Radar (ISAR) provides images of objects that are rotating with respect to the radar. An efficient image focusing algorithm is required to generate ISAR imagery from the echoes of raw data. On the other hand, the dual-polarization decomposition technique enables precise retrieval of scattering mechanisms (H-α), allowing for various applications. In this paper, we propose a novel study case of 2D ISAR imaging of partial polarimetric data of natural targets. First, a stack of 2D complex-valued raw data with VV and VH polarizations is calibrated, and then the image focusing is applied using a match-filter and spherical-wave front compensation (SWFC) method. The eigenvector descriptors based decomposition is employed, and the scattering mechanism is identified using the Lee and Pottier H-α plane. To the best of the authors' knowledge, ISAR images are used for the first time for this study. Given that decomposition enhances target characterization for studying scattering mechanisms, the application of the Radar Vegetation Index (RVI) demonstrates how dual-polarized ISAR images can be used for vegetation identification.

Index Terms— SAR, ISAR, polarimetry, RVI, H-α.

1. INTRODUCTION

Recently, geoscience and remote sensing have made significant progress toward their goal of monitoring the natural environment. Therefore, there is an increasing demand for 2D SAR systems for the appropriate imaging of desired targets. It is a big challenge for researchers to obtain the scattering mechanism of complex radar targets for their use in natural environments [1]. By using calibrated polarimetric data, one can obtain meaningful information such as exact scattering information and target characterization. 2D SAR and ISAR imaging have been extensively used for target scattering classification, analysis, and identification. Coherent image formation with meaningful information is a task of signal processing; therefore, efficient imaging is required that focuses data with respect to the scattering center with fewer side-lobes [2]. Furthermore, eigen-decomposition (H-α) in the form of a coherency matrix is the most common approach used for natural target scattering estimation leveraging SAR data. Consequently, this configuration uses scattering models with dielectric surfaces to estimate the actual capability of the dual-pol decomposition system [3]. As a result, partial polarimetric SAR or ISAR data can provide the accurate and dependable information to extract plant biophysical parameters. The RVI is an indicator that uses polarimetric radar backscatterings to describe phenology and vegetation volume information. The aim of RVI estimation is to identify the optimal radar polarization combination that can result in a strong correlation with the two existing parameters used for RVI estimation, thus achieving accurate results.

In this paper, we propose a novel case study using trees as targets with an ISAR setup. The measurements are conducted with the experimental radar COBRA on the turntable on Fraunhofer terrain. First, we perform ISAR experiments using natural targets with different combinations of tree types and sizes. The traditional ISAR imaging method SWFC is implemented to obtain complex ISAR images [5]. To study the scattering mechanism of the trees, dual-pol decomposition is computed based on the coherency matrix by using partial polarimetric data [6]. This decomposition is studied for the first time using ISAR images with natural targets. We estimate plant vegetation indices for real-time applications using dual-pol backscattering for quantitative analysis [7].

2. METHODOLOGY

2.1. Inverse SAR Imaging Method.

The mathematical expression of the received scatterings in the form of frequency samples (f), and turntable angles (θ), together $E_s(f,\theta)$ for 2D ISAR can be represented with respect to the scattering function as follows,

$$S(f,\theta) = E_s(f,\theta)\exp\left(-j\frac{2\pi\Delta f t}{c}\right)_{\times N_\theta} \tag{1}$$

where Δf, c, t, and N_θ are the range shift in the frequency domain, speed of light, sampling time, and vector of rotation angles, respectively, with repeated action ('*repmat*') on the cross-range direction. To retain the potential scatterers' sample, a linear matched filter (MF) is computed via FFT and IFFT processing. The reconstructed signal is sampled and digitized by exploiting the discrete Fourier transform, and some of the down-range samples are discarded using the matched filter transfer function. Finally, IFFT is applied to store the replica of the original received signal $S^{'}(f, \theta)$. Then a 2D hamming window $H(f, \theta)$ is applied on the range and cross-range directions in order to mitigate the external scatter beside the target, yields in a much smoother ISAR image.

$$S_w(f, \theta) = S^{'}(f, \theta)\ H(f, \theta) \tag{2}$$

The 2D ISAR image reconstruction is attained by using the spherical wavefront compensation (SWFC) method. All the turntable angles for one rotation are gathered to reconstruct a 2D image. The derivation of SWFC is given below:

$$S_\psi = \sqrt{(R\text{cos}\phi\text{cos}\theta + X)^2 + (R\text{cos}\phi\text{sin}\theta + Y)^2} - R \tag{3}$$

$$\text{ISAR}_{(VV/VH)} = \int_{-\pi}^{+\pi} S_w(f, \theta)\ \exp(\frac{4j\pi f_{\text{vec}}}{c} \times S_\psi) d\theta \tag{4}$$

where ϕ is the depression angle between the received antenna and the target, R defines the distance from the center of the target and radar. Provided that X, and Y, are 2D coordinates of the equispaced imaging grid. f_{vec} is the frequency vector for a given range of bandwidth. By using both polarization, one can obtain the focused ISAR images with the dual-polarimetric elements including S_{VV} and S_{VH}.

2.2. Eigen Descriptors for dual-pol H-α: General Theory

The coherent decomposition of dual-pol is supported by the eigenvalues and eigenvectors of the coherence matrix. The scattering vector for dual-polarized ISAR data are represented as $\mathbf{k_{Dp}} = \begin{bmatrix} S_{VV} & S_{VH} \end{bmatrix}^{\mathbf{T}}$. The 2×2 coherence matrix allows us to obtain the entropy (H), alpha (α), and span (λ) images for trees, as enunciated.

$$\begin{aligned} \mathbf{T_2} &= \langle \mathbf{k_{Dp}} \cdot \mathbf{k_{Dp}^{*T}} \rangle = \begin{bmatrix} \langle S_{VV} S_{VV}^* \rangle & \langle S_{VV} S_{VH}^* \rangle \\ \langle S_{VH} S_{VV}^* \rangle & \langle S_{VH} S_{VH}^* \rangle \end{bmatrix} \text{ or} \\ \mathbf{T_2} &= \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = U \begin{bmatrix} \lambda_1 & \\ & \lambda_2 \end{bmatrix} U^H = \sum_{i=1}^{2} \lambda_i \mathbf{u}_i \mathbf{u}_i^H \end{aligned} \tag{5}$$

'H' in superscript denotes the hermitian operator, which is conjugate transpose. so U^H is equal to U^{*T}. Once the eigenvalues λ_i, and eigenvectors $\mathbf{u}_i$ of the coherency matrix are obtained. We can compute the entropy. $H - \alpha$ decomposition can be expressed by exploiting the non-negative eigenvalues ($\lambda_i, i = 1, 2$) and the corresponding eigenvectors, and entropy is expressed as:

$$H = -\sum_{i=1}^{2} (p_i) \log_2(p_i), \text{where, } p_i = \frac{\lambda_i}{\lambda_1 + \lambda_2} \tag{6}$$

where the mean scattering angle (α) and span or mean magnitude of the mechanism (λ) are given as:

$$\alpha = \sum_{i=1}^{2} p_i \alpha_i, \text{and } \lambda = \sum_{i=1}^{2} p_i \lambda_i \tag{7}$$

while α, and λ provide the nature of scattering and the span or size of the target, respectively.

2.3. RVI Estimation using Dual-pol ISAR data.

Partial polarimetric ISAR data provide reliable information typically required to extract biophysical plant parameters. Radar scatters are greatly influenced by vegetation type, structure, moisture, and phenology; thus, we defined the RVI, which takes these parameters into account and is very useful in vegetation monitoring at a large scale. The modified version of RVI for dual-pol ISAR data is given as [4]:

$$\text{RVI} = \left(\frac{\langle |S_{VH}| \rangle}{\langle |S_{VV} + S_{VH}| \rangle} \right)^{1/2} \left(\frac{4 \times \langle |S_{VH}| \rangle}{\langle |S_{VV} + S_{VH}| \rangle} \right) \tag{8}$$

RVI is a scattering randomness measure that ranges from 0 to 1, but it is less sensitive to radar measurement geometry. For smooth surfaces, the RVI is close to zero, it increases as the vegetation grows. It is heavily reliant on biomass and vegetation cover. The RVI is less sensitive to radar measurement geometry and terrain, and is unaffected by absolute calibration errors in the radar data. The RVI results are compared with [1] that relies on two parameters and enhances estimates.

$$\text{DpRVI} = (1 - m_{\text{Dp}} \cdot \beta) \tag{9}$$

where β is eigen value spectrum of $\mathrm{T}_\mathbf{2}$ (5) and m_{Dp} is degree of polarization as reported in [8].

3. EXPERIMENTAL RESULTS

In SAR applications, target scattering estimations are performed in the absence of in-situ data. Differently from ex-

Fig. 1. ISAR COBRA radar (f_c = 9.6 GHz) system is deployed to scan rotating trees with different arrangements of tree types.

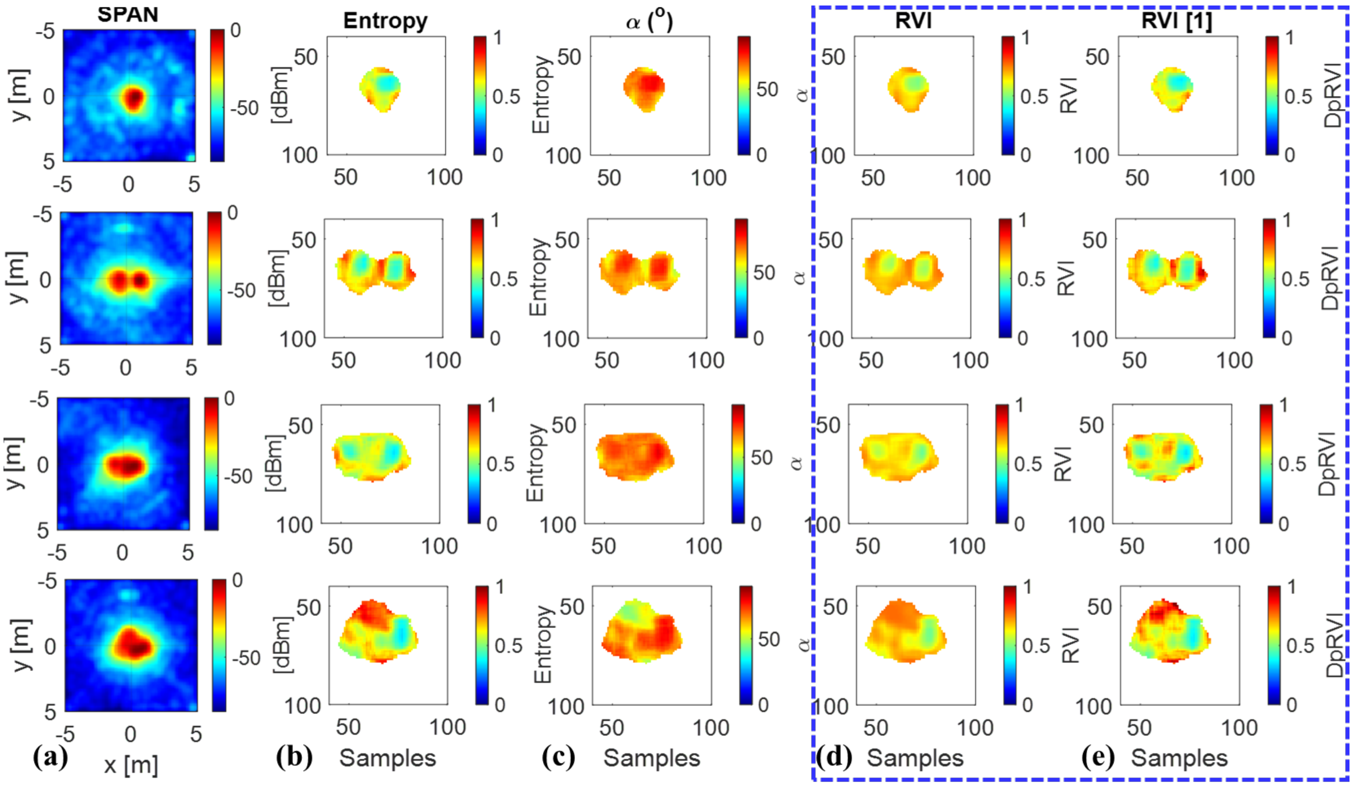

Fig. 2. Each rows shows tree arrangements tree-1, tree 1 and 2, tree 1 – 3, and tree 1 – 4. (a) ISAR imagery of trees and total Span using both VV and VH polarization, Span defines total canopy of target's shape (b) Entropy images of trees (c) Alpha (α) is the mean scattering angle (d) Spatial signatures of RVI based on eq-(8), (e) Spatial signatures of RVI based on eq-(9).

isting works [1], and [7], in order to have in-situ data we exploit ISAR setup and trees as target to investigate the scattering mechanism and quantify RVI of natural targets. We carried out experiments by leveraging ISAR signals emitted from radar to evaluate the feasibility and performance of the method proposed in section 2. Fig. 1 demonstrates the measurement setup and the turntable where we placed our tree targets. Four types of trees are used in ISAR experimental campaign including three broad-leaf trees and one fir-leaf tree. The measurements were recorded using 'Fraunhofer' X-Band radar with bandwidth of 500 MHz. An antenna with an aperture angle of 5° illuminates the complete scene. The transmitted polarization is linear in the vertical plane and the received channels are kept vertical (VV) and horizontal (VH) in such settings. The signals received at both receivers are calibrated by removing the offset delay between them.

The range-compressed ISAR data obtained after a matched filtering process by using Fourier transform. 2D hamming window is applied on the range and cross-range dimensions to decrease side-lobes. Finally, SWFC is utilized to focus the data and generate the final complex ISAR image in its local coordinates on an equispaced grid. Fig. 2 (a) shows the span λ or mean magnitude of 2D ISAR images of trees which is helpful to identify the canopy information of trees. The top part of the trunk is distinguishable in the near range of the image. The natural targets are typically low scatters, but one can clearly identify the targets with one or two trees, and with increasing volume for three or four trees, the canopy is valid enough for distinguishing and identifying the targets. The dual-pol H-α decomposition allows the study of the scattering mechanism of the target, which depends on the coherency matrix, by exploiting the VV and VH polarization data. H-α decomposition has fair characteristics, such as covering the upper half of the scattering mechanism plane, relevance to scattering types, and covering the probability density distribution for these scatterings. In Fig. 2 (b), the higher values of entropy indicate very low amplitude backscatter where tree canopy areas show sparse vegetation. The presence of 'α' (mean angle) values in dense leaf areas, where most values are greater than 45°, represents multiple surface scattering, as shown in Fig. 2 (c). Its first time the RVI signature has been obtained using dual-pol ISAR images, and its value of randomness ranges between 0 and 1, as given in Fig. 2 (d) and 2 (e). RVI is estimated using a 5 $\times$ 5 boxcar filter via two approaches (references [4] and [1]), one relies only on polarizations and the other relies on degree of polarization and eigen spectrum respectively. The spatial signatures are qualitatively the same, indicating that ISAR images can be utilized for RVI estimation. The VV-VH combination is likely to produce better results due to the greater interaction of the wave

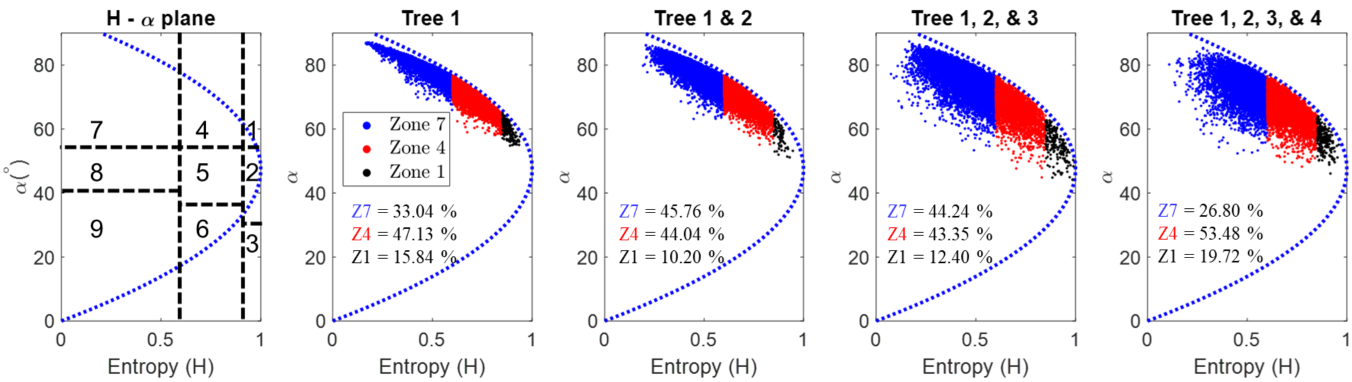

Fig. 3. H-α decomposition shows that scattering mechanism falls in zone 1, 4, and 7 based on Lee and Pottier method.

with the trees as they are more vertically oriented. The vegetation index increases for a given canopy of four trees when the fir tree is included because the fir tree is dense and more vegetated, as compared to three cases.

The results of H-α decomposition based on the Lee and Pottier method are given in Fig. 3. In order to create a correspondence with [3], the scattering classes are limited due to the type of target which constrains the scattering types. The H-α space of the dual polarization decomposition is classified into 3 zones. This allows to classify the scattering types and mechanisms of each targets. Apparently, the number of pixels in each plot varies since the canopy in each case increases as tree types and arrangements are different. Nevertheless, based on the H-α plane the scatterings for each case appears in zones 1, 4, and 7, which corresponds to high, medium, and low entropy vegetation multiple scatterings zones, respectively. For given set of scatterings α varies from $45°$ to $90°$. The response is the result of a multiple surface scatter, however, entropy gradually increases from lower to medium and then reaches at higher level. Additionally, the ratio of scattering samples differed in each zone for all cases, as annotated in Fig. 3.

4. CONCLUSION

In this paper, we consider a novel case study involving natural targets (trees), and then identify scattering mechanisms using ISAR images with dual-pol decomposition. The conventional SFWC ISAR imaging method is implemented to obtain focused complex ISAR images at first. For our datasets, a box-car filter of size 5×5 provides feasible results without reducing spatial information. The RVI agrees well with biophysical parameters since it increases with vegetation growth and H-α images follow theoretical limitations, while the attained results are validated by Lee and Pottier's H-α decomposition. The given method shows a good agreement for the scattering characterization by exploiting ISAR images with dual-pol decomposition. In future lines of work, we plan to incorporate both Sentinel-1 SAR and Sentinel-2 Optical images to analyze scattering types and estimate the RVI for the purpose of crop or forest vegetation characterization. Additionally, physical models will be utilized to assess both sparse and non-sparse vegetation, as outlined in [1], [4], and [7].

5. ACKNOWLEDGMENT

The research has received funding from Marie Skłodowska-Curie Actions Innovative Training Networks (MSCA-ITN) under the MENELAOS-NT, GA 860370. The authors acknowledge FHR for providing access to their experimental campaign facility for conducting ISAR measurements and collecting data.

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