Analysis of Anisotropic Scattering Behavior Using Sub-Aperture Polarimetric Sar Data

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***Abstract*—In this paper, a fully polarimetric analysis method is introduced to decompose synthesized SAR images into sub-aperture data sets, which correspond to the scene responses under different azimuthal look-angles. A statistical analysis of polarimetric parameters permits to clearly discriminate media showing a non-stationary behavior during the SAR integration. A method is proposed, which eliminates the influence of azimuthal backscattering variations in conventional polarimetric SAR data analysis.**

Keywords: Sub-aperture decomposition; SAR signal processing; SAR polarimetry

I. Introduction

During SAR integration, each scatterer of a scene is observed by the sensor under a set of azimuthal look-angles, defined by the antenna's aperture. Complex targets, characterized by anisotropic geometrical structures, may show a varying electromagnetic behavior, as they are illuminated from different positions. In this paper, a scene backscattering response is characterized using sub-aperture SAR data sets in the azimuth direction in order to analyze the responses of the whole observed scene under specific look-angles. A study of the evolution of polarimetric properties during the SAR azimuthal integration allows to identify and to eliminate the influence of non-stationary scattering behaviors from full resolution polarimetric signatures.

II. Azimuthal Variations over a Natural Scene

A. Sub-aperture decomposition principle

During SAR image formation, many low resolution echoes of a target, received under different squint angles, are integrated to form the full resolution SAR image. A single pixel in a SAR image corresponds to a certain range of angles limited by the azimuth antenna pattern. The azimuth look-angle, ϕ, is related to the wave number in azimuth k_x by :

$$k_x = \frac{2\omega}{c} \sin\phi \qquad (1)$$

with ω denoting the carrier frequency of the radar and c the speed of light. Sub-aperture decomposition in the azimuth direction consists in processing a set of images, each containing a different part of the SAR Doppler spectra, with a reduced resolution, but corresponding to different azimuth look-angles [1][2]. A trade-off has to be made concerning the number of sub-apertures, which determines the resolution in time and frequency domains. A large number enables a refined description of the data evolution during the azimuth look-angle variation, while a smaller number of sub-apertures gives a higher resolution in time-domain. The authors found that a number of eight sub-apertures offers a good compromise between the degree of spectral description and the spatial resolution.

B. Anisotropic polarimetric behavior

Polarimetric descriptors, such as H and $\underline{\alpha}$ [3], widely used in natural media physical parameter retrieval procedures[4-6], permit to determine in a quantitative way the importance of eventual non-stationary patterns from an applicative point of view. The sub-aperture decomposition technique, introduced in the former paragraph, is applied to polarimetric SAR data acquired by the DLR E-SAR sensor, at L band, over the Alling test site, Germany, mainly composed of agricultural fields and forest. The original image resolution is 2m in range and 1m in azimuth, corresponding to an azimuthal variation of the look-angle of approximately 7.5 degrees. Fig. 1 shows an example of the sub-aperture decomposition over a particular area, corresponding to plowed fields. Images of the span and H and $\underline{\alpha}$ parameters are represented for different azimuth look-angles and for the full resolution case. Large variations in the scattering mechanism nature and degree of randomness occur as the azimuth look-angle changes. It was also observed that some point targets and linear structures, such as diffracting edges or road berns, have back-scattering properties susceptible to vary in a very significant way. In particular, fences were found to present a scattering mechanism ranging from single bounce up to double bounce scattering depending on the SAR azimuthal look-angle. It is important to note, that forested areas have a constant behavior during the SAR integration and may be considered as isotropic media. For particular azimuth look-angles, some fields show a sudden change of behavior. The

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span reaches a maximum value, while the polarimetric indicators H and $\underline{\alpha}$ are characterized by low values. Stripes in the span image indicate that coherent constructive and destructive interferences occur within the pixels and are characteristic of Bragg resonant scattering over periodic surfaces.

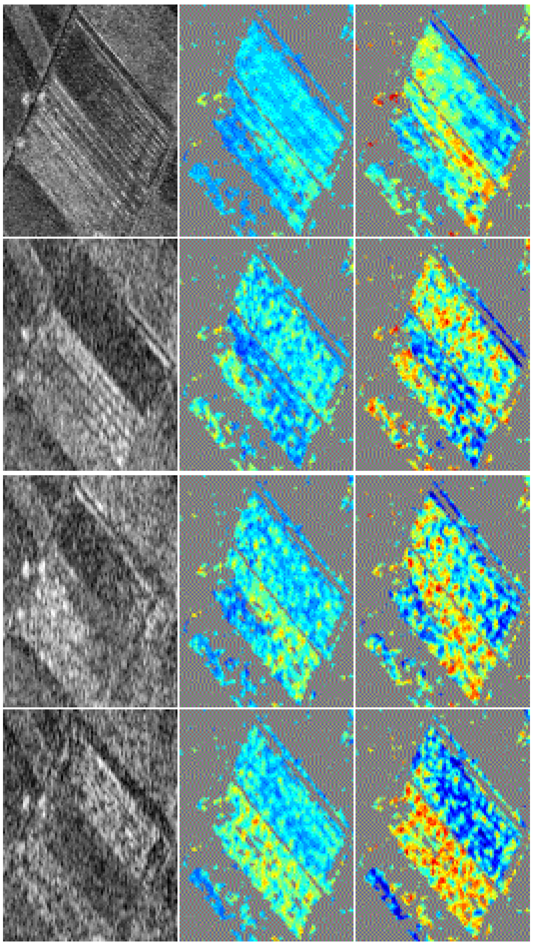

Figure 1. Polarimetric parameters over isolated fields at full resolution and after sub-aperture decomposition

Bragg resonance phenomenon is due to the coherent summation of simultaneously constructive contributions of a set of scatterers and is likely to happen during the observation of periodic surfaces or irregular surfaces with a strong periodic component. The resonance condition can be written as a function of the incident wavelength, λ, as follows :

$$2k_y = n\frac{2\pi}{P} \quad \Rightarrow \sin\theta\cos\phi_o = n\frac{\lambda}{2P} \tag{2}$$

where k_y correspond to the component of the incident wavenumber vector parallel to the ground, n is an unknown integer number and P is the surface period. The local incidence angle is denoted θ, while ϕ_o represents the azimuthal angular difference between the observation position and the normal to the rows of the periodic surface. According to (2), similar fields with different locations, i.e. corresponding to different incidence angles, or oriented along different directions, may resonate in different sub-apertures or not at all, if the conditions mentioned earlier cannot be satisfied for any look-angle within the antenna azimuth aperture. The joint dependence of the resonance condition on the incidence and azimuth angles can be observed over homogeneous fields having parts resonating in different sub-apertures. Polarimetric indicators, within the sub-apertures unaffected by the Bragg resonance, are similar to the ones observed over stationary fields.

III. Non-stationary target discrimination

A statistical analysis of the scene response over the different sub-apertures is used to detect targets showing non-a stationary behavior and locate its position in the azimuth spectrum by testing the statistics of a Maximum Likelihood (ML) ratio.

A. Maximum Likelihood detection

Each pixel of the SAR scene is associated to a set of sample coherency matrices, obtained from the different sub-apertures. It was shown that a sample n-look coherency matrix, $\mathbf{T}$, follows a complex Wishart probability function with n degrees of freedom, $W_C(n,\mathbf{\Sigma})$. A pixel has a stationary behavior if its R sub-aperture sample coherency matrices $\mathbf{T_i}$, with $i = 1,...,R$, follow the same distribution. In this case, the R coherency matrices fulfill the following hypothesis :

$$Hyp : \mathbf{\Sigma_1} = \mathbf{...} = \mathbf{\Sigma_R} \tag{3}$$

The validity of this hypothesis is tested by means of a maximum likelihood ratio Λ, built from the sub-aperture coherency matrices as follows :

$$\Lambda = \frac{\prod_{i=1}^{R} |\mathbf{T_i}|^{n_i}}{|\mathbf{T_t}|^{n_t}}, \text{ with } n_t = \sum_{i=1}^{R} n_i \text{ and } \mathbf{T_t} = \frac{\sum_{i=1}^{R} n_i \mathbf{T_i}}{n_t} \tag{4}$$

The variable n_i represents the number of scattering vectors used to compute the sample coherency matrix $\mathbf{T_i}$. The hypothesis is accepted and the target is considered to be isotropic, with an arbitrarily chosen probability of false alarm P_{fa}, if $\Lambda > c_\beta$ with $P_{fa}(c_\beta) = P(\Lambda \le c_\beta) = \beta$. The calculation of the ML ratio statistics was derived by Ferro-Famil et al. from the moment function of the ML ratio [7].

B. Location of non-stationarities in the azimuth spectrum

A similar approach can be applied to the location of non-stationary behaviors in the azimuth spectrum by comparing the contributions of each sub-aperture image in the global ratio [7]. For each pixel, the sub-aperture sub_j, with $j \in [1...N_{sub}]$, corresponding to the most anisotropic behavior among the whole set, satisfies to the following relation :

$$sub_j = \arg\max \Omega_{N_{sub}-1}(sub_j) \tag{5}$$

where $\Omega_{N_{sub}-1}(sub_j)$ is a maximum likelihood ratio calculated over $N_{sub}-1$ images, without incorporating the sub-aperture sub_j. For each pixel, it is then possible to iteratively discriminate, from an original set of R sub-apertures, the set corresponding to non-stationary behaviors. The application of this algorithm to the Alling data set reveals that a substantial number of pixels have a non-stationary behavior during the SAR integration and successfully determine its position in the Doppler spectrum. Most of the anisotropic scatterers belong to agricultural fields affected by Bragg resonance. Complex targets and diffracting edges, whose scattering characteristics highly depends on the observation position, are discriminated over built-up areas.

IV. SUB-APERTURE IMAGE RESTORATION

Once pixels with anisotropic behavior and the respective problematic sub-apertures are known, one can try to eliminate the anisotropic contributions, in order to improve the retrieval of physical properties from polarimetric data. An efficient way consists in equalizing, for each anisotropic pixel, the amplitude of non-stationary sub-apertures to the average amplitude of the unaffected ones. The scattering matrix $\mathbf{S}_{\mathbf{sub}_i}$ of a pixel in the ith sub-aperture sub$_j$ may be represented using the following expression :

$$\mathbf{S}_{\mathbf{sub_i}} = e^{j\xi_i} A_i \mathbf{S}_{\mathbf{rel_i}} \tag{6}$$

where ξ_i represents the absolute phase of $\mathbf{S}_{\mathbf{sub}_i}$, A_i is the square root of its span and $\mathbf{S}_{\mathbf{rel_i}}$ is a relative unitary scattering matrix. The amplitude equalization is performed by replacing the amplitude, A_k, of a pixel belonging to a non-stationary sub-aperture, sub$_k$, with the following estimate :

$$\widetilde{A}_k^2 = \frac{1}{N}\sum_N A_i^2 \tag{7}$$

where the sum is computed over the N remaining stationary sub-apertures. Restored polarimetric scattering coefficients may be estimated from a stationary coherency matrix, $\widetilde{\mathbf{T}}_{\mathbf{k}}$, computed using the contributions from all the stationary sub-apertures. An average relative scattering matrix, $\widetilde{\mathbf{S}}_{\mathbf{rel_k}}$ is estimated from an eigenvector analysis of $\widetilde{\mathbf{T}}_{\mathbf{k}}$, as proposed in [6], to reconstruct a stationary scattering matrix, $\widetilde{\mathbf{S}}_{\mathbf{sub_k}}$ as :

$$\widetilde{\mathbf{S}}_{\mathbf{sub_k}} = e^{j\xi_{ki}} \widetilde{A}_k \widetilde{\mathbf{S}}_{\mathbf{rel_k}} \tag{8}$$

In Fig. 2, polarimetric parameters of the full-resolution SAR image after restoration are shown. The image quality is comparable with the original one, shown in Fig. 1. Differences between polarimetric descriptors, entropy and $\underline{\alpha}$, evaluated in the original and restored images can be observed. Maximal variations of 70° and 0.8 are observed, over anisotropic point scatterers, for $|\Delta\underline{\alpha}|$ and $|\Delta H|$ respectively. Over non-stationary fields affected by Bragg-scattering, the average variations in $|\Delta\underline{\alpha}|$ and $|\Delta H|$ are respectively 7° and 0.2. Such values are significant with respect to the ranges of the polarimetric indicators, which in case surface scattering equal 40° for $\underline{\alpha}$ and 0.9 for the entropy.

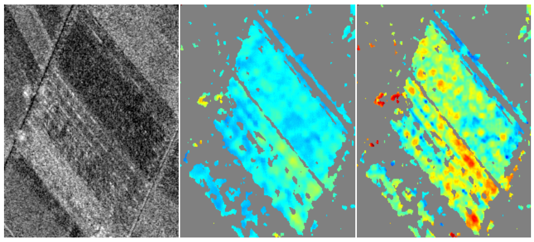

Figure 2. Polarimetric parameters over isolated fields at full resolution after restoration

V. CONCLUSION

Sub-aperture analysis of fully polarimetric SAR data is an interesting and important way to characterize the scattering behavior of many targets. As shown in this paper, the effect may not be neglected in a polarimetric analysis of anisotropic media without introducing severe errors. Particularly, the characterization of agricultural scenes with polarimetric descriptors can be heavily influenced by Bragg scattering on periodic surface. In this paper a method is proposed to detect problematic sub-apertures, i.e. azimuthal look-angles corresponding to non-stationary behavior, using multi-image ML test statistics. Results of this method are used to minimize the influence of azimuthal backscattering variations in conventional polarimetric SAR data analysis.

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