Compact and Full Polarimetric SAR Imaging for Target Characterization

Hafidha Bouzerar(1),Siham Mebrek(1), Boularbah Souissi(2),Abdelhamid Daamouche(1)

(1)UMBB University, Boumerdes, Algeria.
(2)USTHB University, Algiers, Algeria.

***Abstract*— Recent interest in dual polarization Synthetic Aperture Radar (SAR) systems, in which a single polarization is transmitted (e.g. linear horizontal or right circular), followed by reception of two orthogonal polarization , has lead to a novel approach to dual-pol SAR, the so-called compact polarimetric imaging (CPSAR) mode. This paper provides techniques that allow construction of pseudo quad-pol information from dual-polarization SAR systems based on a few simple assumptions. Compact polarimetry showed promise of being able to reduce the complexity, cost, mass, and data rate of a SAR system while attempting to maintain many capabilities of a fully polarimetric system.**

Keywords— Hybrid polarity (HP), reconstruction methods, Synthetic Aperture Radar (SAR).

I. INTRODUCTION

In the latest years, the development of more efficient and precise techniques to watch over the vast natural surfaces (e.g. seas, oceans, forests, lands) by satellite or radar images allows analysts to have constant observations of the state of the Earth. This is very important to monitor climatic changes and useful for the mapping of natural resources [1].

SAR instruments employ various acquisition modes when collecting the images. The various acquisition modes have different resolution, and spatial coverage. Additionally, to gain large amount of polarimetric information about the backscattering properties of the targets within the SAR scenes, quad-polarimetric (pol) SAR mode can be used. Such a SAR instrument transmits in two polarizations, and receives in two polarizations. One drawback of the quad-pol mode is the small spatial coverage, as the swath width (SW is only 50 km.

Therefore, the dual-pol mode, with only one polarization at the transmitter and two polarizations at the receiver, will produce a SW that is twice of that obtained from a quad-pol system, and at the same time have a high resolution. As a result of the dual-pol mode, the amount of polarimetric information about the interaction mechanisms between the incoming wave and the target will be reduced. To be able to have both high spatial coverage and at the same time, a large amount of polarimetric information, the compact polarimetry SAR mode was introduced [2].

The compact polarimetry mode is a SAR acquisition mode where only one polarization is transmitted, and two orthogonal polarizations are received. This configuration of polarization channels is also used in dual-polarimetric systems, but for compact polarimetric systems the choice of polarization for the transmitted and received channels is important [1]. For dual-pol SAR systems the common polarizations are horizontal and vertical, while for compact-pol systems the polarizations are either circular or diagonal polarizations.

This paper provides a comparison of the information content of full quad-pol data and the pseudo quad-pol data, derived from compact polarimetric SAR modes. A pseudo-covariance matrix can be reconstructed following well-known methods: Souyris' and Nod's reconstruction methods , and two novel algorithms Eigenvalue and degree of polarization (DoP)-based reconstruction methods are propoed. It is shown to be similar to the full polarimetric (FP) covariance matrix.

An ESAR L-band data set of Oberpfaffenhofen, Germany, is studied to assess the pseudo-quad-pol data derived from compact polarimetric.

II. DATA USED

The DLR ESAR L-band full polarized image of Oberpfaffenhofen Test Site Area (DE) of Germany (**Figure 1**), obtained on September 30th, 2000, and was used to validate the comparison of the reconstruction methods. Its spatial resolution is 3m×3m and an incidence angle ranging between 27° and 55°. The test area, composed of 2816×1540 pixels, mainly includes forested area, urban area, bare soils, and aircraft runway.

III. FULL AND COMPACT POLARIMETRIC THEORY.

Scattering matrix elements are the fundamental quantities measured by a polarimetric SAR system, which represents the relation between the polarizations of the incoming and outgoing waves [3].

$$S = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \quad (1)$$

Where, H and V denote horizontal and vertical polarizations.

Figure 1: Pauli basis image of the E-SAR Oberpfaffenhofen.

The equivalent scattering vector in the Lexicographic and Pauli basis is given by [4]:

$$\underline{kl} = \frac{1}{\sqrt{2}} \left[S_{HH} \quad 2\sqrt{S_{HV}} \quad S_{VV} \right]^T \quad (2)$$

$$\underline{kp} = \frac{1}{\sqrt{2}} \left[S_{HH} + S_{VV} \quad S_{HH} - S_{VV} \quad 2S_{HV} \right]^T \quad (3)$$

The superscript T indicates the transpose operator.

By assuming reflection symmetry the covariance matrix becomes less complex, and this will ease the reconstruction of a pseudo quad-pol covariance matrix from the compact-pol data.

Reflection symmetry manifests itself in the polarimetric scattering by nulling the correlation between like- and cross-polarized scattering amplitudes.

$$\langle S_{HH} S_{HV}^* \rangle = \langle S_{HV} S_{VV}^* \rangle = 0 \quad (4)$$

Applying therefore the symmetry assumption, the resulting covariance matrix takes the form [5]:

$$C = < \overrightarrow{k_l} . \overrightarrow{k_l^{*T}} > = \frac{1}{2} \begin{bmatrix} \langle |S_{HH}|^2 \rangle & 0 & S_{HH} S_{VV}^* \\ 0 & 2\langle |S_{HV}|^2 \rangle & 0 \\ S_{VV} S_{HH}^* & 0 & \langle |S_{VV}|^2 \rangle \end{bmatrix} \quad (5)$$

Where the subscript *T denotes the conjugate transpose operator. The symbol < > indicates ensemble averaging.

Compact polarimetry is a technique that allows construction of pseudo quad-pol information from dual-polarization SAR data. Any polarization state of the receiving antenna can be synthesized. There exist three modes in compact polarimetry. The scattering vectors k_{cp} for $\frac{\pi}{4}$, dual circular polarimetric (DCP), and right circular transmit, linear (horizontal and vertical) receive or hybrid (CTLR). The scattering vectors are given by [6]:

$$\vec{k}_{\frac{\pi}{4}} = \frac{1}{\sqrt{2}} \left[S_{HH} + S_{HV} \quad S_{VV} + S_{HV} \right]^T \quad (6)$$

$$\vec{k}_{CTLR} = \frac{1}{\sqrt{2}} \left[S_{HH} - jS_{HV} \quad S_{HV} - jS_{VV} \right]^T \quad (7)$$

$$\vec{k}_{DCP} = \frac{1}{2} \left[S_{HH} - S_{VV} + j2S_{HV} \quad j(S_{HH} + S_{VV}) \right]^T \quad (8)$$

Several different approaches have been suggested to study compact-pol data. This study concerns on the reconstruction of a pseudo quad-pol covariance matrix from the compact-pol. This reconstruction allows applying well-known full-polarimetric methods to the reconstructed matrix.

IV. RECONSTRUCTION METHODS

In state-of-the-art for reconstruction methods some assumptions about the target must be made. The performance of the reconstruction will depend on the accuracy of these assumptions, namely the ones that will have the least negative impact on the restored data. There are currently four main reconstruction methods; Souyris, Nord, DoP, and Eigenvalue. The upcoming sections present these methods in more details and investigate the validity of these methods for our data.

1) SOUYRIS' RECONSTRUCTION METHODS

This reconstruction process is done by assuming reflection symmetry, and that the compact-pol data represents natural surfaces. Applying reflection symmetry to the covariance matrix; the correlation between the cross- and co-pol elements is cancelled, which leaves us with fewer unknown elements.

Thus, it is necessary to introduce another assumption to bring the number of unknowns down to four. Souyris [7] built a relation based on the scattering behavior of fully polarized and fully depolarized backscattered waves. The following non-linear equation was suggested for this purpose.

$$\frac{X}{H+V} = \frac{1-|\rho_{HHVV}|}{4} \quad (9)$$

Where H=$|S_{HH}|^2$, V=$|S_{VV}|^2$, X=$|S_{HV}|^2$, P=$S_{HH}S_{VV}^*$, and the coherence parameter is defined as [7]:

$$\rho_{HHVV} = \frac{P}{\sqrt{HV}} \quad (10)$$

The parameters are found by an iterative approach, where ρ_{HHVV} and X are updated every iteration step as shown for the hybrid mode [6].

$$C_{QP}^{(i)} = \begin{bmatrix} H & 0 & P \\ 0 & 2X & 0 \\ P^* & 0 & V \end{bmatrix} = C = \frac{1}{2} \begin{bmatrix} 2C_{11} - X^{(i)} & 0 & +2jC_{12} + X^{(i)} \\ 0 & 2X^{(i)} & 0 \\ -2jC_{12}^* + X^{(i)} & 0 & 2C_{22} - X^{(i)} \end{bmatrix} \quad (11)$$

Where

$$C = \begin{bmatrix} C_{11} & C_{12} \\ C_{12}^* & C_{22} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} H + X & -jP - jX \\ -jP^* + jX & V + X \end{bmatrix} \quad (12)$$

The main limitation of the iterative process in Souyris' method is the initial step when $X_{(0)}$=0. The initial assumption that the cross-pol intensity is zero may cause significant errors in the reconstruction process.

2) NORD'S RECONSTRUCTION METHOD

The relationship between scatter powers in different polarimetric channels was established based on the scattering behavior of fully polarized and fully depolarized backscattered waves [8].

$$\frac{\langle |S_{HV}|^2 \rangle}{\langle |S_{HH}|^2 \rangle + \langle |S_{VV}|^2 \rangle} = \frac{1-|\rho_{HHVV}|}{N} \quad (13)$$

The parameter N is relative to the ratio between cross and co-polarization channels and the coherent coefficient between HH and VV channels. The choice of reconstruction parameter N is crucial to performing CP SAR reconstruction algorithms.

Souyris used a constant value of 4 for N based on the assumption that volume scattering was the dominant scattering mechanism. Nord defined a model for N [9] as the ratio of the double-bounce backscatter to the cross-pol backscatter.

$$N = \frac{|S_{HH} - S_{VV}|^2}{|S_{HV}|^2} \quad (14)$$

The modified pseudo quad-pol algorithm is applied once with the seed value of N =4, resulting in the original reconstructions. The value of N is then estimated from the resulting pseudo quad-pol covariance matrix.

3) *DoP RECONSTRUCTION METHOD*

It is possible to perform the DoP-based reconstruction method on all compact polarimetric modes. The goal is to find the depolarized power and further assign this power value to the power term in the cross-pol intensity.

It may be reasonable to relate the DoP to the cross-pol intensity. However, this will only hold if we assume that the dominant contribution to the cross-pol intensity is from depolarization effects. This is reasonable for a natural surface such as grass. The DoP is defined as [10]:

$$DoP = \frac{\sqrt{q_1^2+q_2^2+q_3^2}}{q_0} \quad 15)$$

Where (q_0, q_1, q_2, q_3) are stokes parameters.

The power of the depolarized scattering component can be calculated from the first parameter in the Stokes vector and the DoP [11]:

$$P_{DoP} = (1 - DoP)q_0 \quad (16)$$

q_0 is the total power. The cross-pol intensity X is assigned to P_{DoP} in the following way:

$$2\widehat{X} = (1 - DoP)q_0 \quad (17)$$

The factor 2 originates from the reciprocity assumption. If the DoP is low, more power is assigned to X, and vice versa. The QP elements can be found by subtracting the estimated cross-pol intensities from the elements in the sample HP covariance matrix.

4 *EIGENVALUE RECONSTRUCTION METHOD*

The main limitation of DoP-based reconstruction method is that it assigns all the depolarized power to the cross-pol intensity. The Eigenvalue-based technique minimizes this limitation.

To find the eigenvalues of C_2 matrix, the characteristic equation can be written as:

$$\det(C_2 - \lambda I_2) = 0 \quad (18)$$

C_2 is completely characterized by its two real nonnegative eigenvalues, which can be expressed in terms of scattering amplitudes through the Stokes vector.

$$q = (q_0, q_1, q_2, q_3)^T \quad (19)$$

The Stokes vectors associated to the HP mode can be expressed in terms of scattering mplitudes.

$$\begin{cases} \lambda_{1=\frac{1}{2}}\left(q_0 + \sqrt{q_1^2+q_2^2+q_3^2}\right) \\ \lambda_{2=\frac{1}{2}}\left(q_0 - \sqrt{q_1^2+q_2^2+q_3^2}\right) \end{cases} \quad (20)$$

The estimated cross-pol intensity obtained from the Eigenvalue-based reconstruction can be expressed using the degree of polarization (DoP) [11].

$$\langle |S_{HV}|^2 \rangle = \frac{\lambda_2 q_0}{2\lambda_1} = \left(\frac{1-DoP}{1+DoP}\right)\frac{q_0}{2} \quad (21)$$

V. RESULTS AND DISCUSSION

Performance of reconstruction algorithms based on the polarization state extrapolation for X channel at L-band is shown by the scatter plots. The overall trend that appears is that the pseudo quad-pol results best match the co-pol magnitudes the original quad-pol data, which is due to their stronger returned signal and higher SNR. As can be observed, X remains the most delicate term to reconstruct due to its low radiometry, which is typically 7–10 dB below H and V and the fact that the iterative process is based on an approximation.

By a visual comparison between the CTLR and π/4 modes (**Figure 2**) the scatter plots are very close to each other showing that the reconstructed pseudo quad-pol data have the same distribution. Those results are compatible with the quantitative ones shown in **Table 1**. Comparing the results with those derived from the π/4 and CTLR mode, no single mode is obviously better than the others for reconstructing the original covariance matrix. Both modes tend to overestimate$|S_{HV}|^2$. For the co-pol, the reconstruction performance of the CTLR mode is better than that of the π/4 mode.

The Souyris reconstruction method is suitable to forest or dense vegetation areas. However, for the surface types dominated by the surface scattering or even scattering, the performance of Souyris method is deteriorated. Therefore, Nord's method, using the updated parameter N shows a better performance for reconstructing cross-pol and co-pol intensities.

The main limitation on Souyris and Nord's reconstruction methods is the number of iterations, this limitation has been eliminated by DOP method, i.e. do not require any user input. The scatter in **Figure 3** shows an improvement; most of the pixels under 45° line are corrected and eliminated. Also, the errors and bias are reduced with respect to the previous methods.

The difference between the Eigenvalue and DoP method is that we normalize with 1+DoP, hence; from **Table 2**, the reconstructed cross-pol intensity shows less overestimation (standard deviation is reduced). The bias is removed (median error is very small 0.0235dB.

The pseudo quad provides a reliable estimate of the surface and double bounce. While the value of the bias is reached the maximum compared to the cross-pol in the other methods when considering forested areas (**Table 2**). This is due to more multiple scattering, and spatial variation in scattering characteristics for forested areas.

Table 1: Medians and standard deviations of the PQP reconstruction errors for HV relative to the FQP values.

		Souyris	Nord
hybrid	Std.dev	0.1988	0.0614
	Median	0.1103	0.1002
π/4	Std.dev	0.2015	0.1018
	Median	0.1012	0.0585

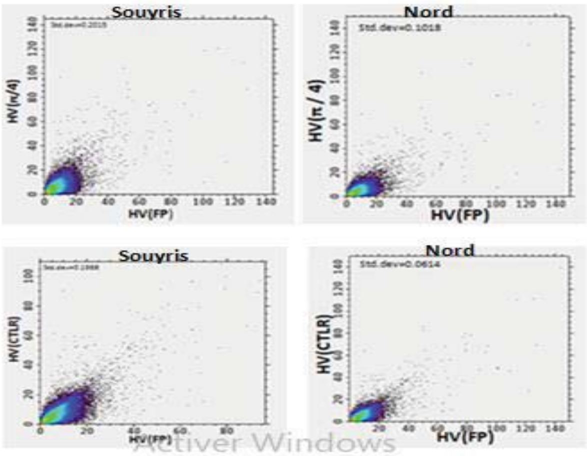

Figure 2: Souyris and Nord's reconstructed results for π/4 and CTLR mode. These scatter plots show all pixels for the Oberpfaffenhofen image.

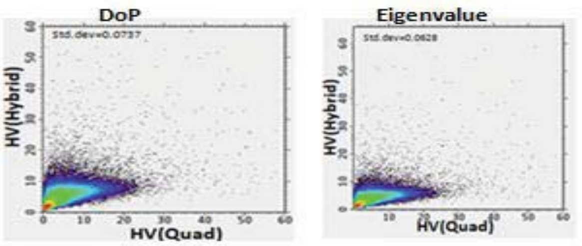

Figure 3: DoP and Eigenvalue-based reconstructed results CTLR mode. These scatter plots show all pixels for the Oberpfaffenhofen image.

VI. CONCLUSION

The majority of the results from all methods have overestimated the cross-pol intensities. Souyris' reconstruction method is valid for areas that are dominated by volume scattering by assuming some approximations. Those approximations are feasible but the errors associated with retrieval of the PQP from CP are high for quantitative estimation. Nord has proposed a modified algorithm which compensates for the double bounce scattering. Consequently , Nord's method performs better than Souyris and has shown a smaller errors, both std and bias are reduced. Generally the circular transmit linear receive mode shows a better behavior than the π/4 mode, since it is less affected by the atmosphere.

Table 2: Medians and standard deviations of the PQP reconstruction errors for HV relative to the FQP values.

	DoP			Eigenvalue		
Hybrid	Grass	Urban	Forest	Grass	Urban	Forest
Std.dev	0.0143	0.0680	0.0882	0.0138	0.0677	0.0888
Median	0.0278	0.0695	0.0138	0.0273	0.0677	0.0138

The benefit with both the DoP and Eigenvalue-based methods is that they do not require any user input. Hence, DoP and Eigenvalue reconstruction methods managed to improve the results in reconstructing cross-pol components.

Several issues still have to be investigated in order to complete the study of this topic. The most important concern is the extended of the work to all bands, and doing the interpretation to the other CP configurations to determine which polarimetric configurations allow best reconstruction results.

REFERENCES

[1] E. Pottier J.S Lee, "Polarimetric Radar Imaging from Basics to Applications," *Optical Science and Engineering*, CRC Press, New York, 2009.

[2] A. Marino, I. Cameron H. Woodhouse, "A Standard Index of Spatial Resolution for Distributed Targets in Synthetic Aperture Radar Imagery," International Journal of Remote Sensing, 2009..

[3] M. Boerner W. Taylor, "Basic Concepts in Radar Polarimetry," in UIC-ECE Communication, Sensing and Navigation Laboratory, 2007.

[4] J. S Lee, Laurent Feroo-Famil E. Pottier, "Advanced Concepts".

[5] Maurizio Migliaccio, Carl E. Brown Ferdinando Nunziata, "Reflection Symmetry for Polarimetric Observation of Man-Made Metallic Targets at Sea," IEEE Journal of Oceanic Engineering, vol. 37, no. 3, July 2012.

[6] Mounira Ouarzeddine, Aichouche Belhadj-Aissa Boularbah Souissi, "Investigation of the capability of the Compact Polarimetry mode to Reconstruct Full Polarimetry mode using RADARSAT2 data," Advanced Electromagnetics, vol. 1, no. 1, May 2012.

[7] Nick Stacy, Tom Ainsworth, Jong-Sen Lee, Pascale Dubios-Fernandez Jean-Claude Souyris, "SAR Compact Polarimetry (CP) for Earth Observations and Planetology: Concept and Challenges".

[8] Michael J. Colllins Michael Denbina, "Iceberg Detection Using Compact Polarimetric Synthetic Aperture Radar," Atmosphere-!ocean, vol. 50, no. 4, pp. 437-446, July 2012.

[9] Thomas L. Ainsworth, Jong-Sen Lee, Nick J. S. Stacy Michael E. Nord, "Comparaison of Compact Polarimetric Synthetic Aperture Radar Modes," IEEE Traansactions on Geoscience and Remote Sensing, vol. 47, no. 1, January 2009.

[10] R. Keith Raney, "Hybrid-Polarity SAR Architecture," IEEE Transactions on Geoscience and Remote Sensing, vol. 45, no. 11, pp. 3397-3404, November 2007.

[11] Stian N. Anfinsen Martine M. Espeseth Camilla Brekke, "Hybrid-Polarimetry and Reconstruction Methods for Sea Ice with L- and C-Band SAR," IEEE Geoscience and Remote Sensing Letters, vol. 13, no. 3, pp. 467-471, March 2016.