ROLL INVARIANT TARGET DETECTION BASED ON POLSAR CLUTTER MODELS

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ABSTRACT

Based on the Kennaugh-Huynen decomposition, the Target Scattering Vector Model (TSVM) allows to extract four roll-invariant parameters. Those parameters are necessary for an unambiguous description of the target scattering mechanism. The proposed method consists in applying the TSVM prior to the GLRT-LQ detector for the detection of any oriented target.

Index Terms— Polarimetric Synthetic Aperture Radar, Roll-invariant decomposition, Target detection.

1. INTRODUCTION

In this paper, a method is proposed for detecting Polarimetric Synthetic Aperture Radar (PolSAR) targets. The proposed method is a combination of the Target Scattering Vector Model (TSVM) and the Generalized Likelihood Ratio Test - Linear Quadratic (GLRT-LQ) detector. The TSVM provides an unique and roll-invariant decomposition of the observed target vector by means of four independent parameters. The combination of those two methods will allow the detection of any oriented targets (trihedral, dihedral, dipole, helix, ...).

This paper is organized as follows. The context of the study is first described. Then, the TSVM algorithm is exposed. Next, the proposed algorithm for a roll-invariant target detection is presented. Then, some detection results are shown on a real PolSAR data-set acquired by the RAMSES sensor at X-band.

2. ROLL-INVARIANT TARGET DECOMPOSITION

2.1. Context

Let $\mathbf{k}_{dip}$ and $\mathbf{k}_{dih}$ be respectively the steering vectors in the Pauli basis of two oriented dipole and dihedral. They are respectively defined by:

$$\mathbf{k}_{dip} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ \cos(2\psi) \\ \sin(2\psi) \end{bmatrix} \text{ and } \mathbf{k}_{dih} = \begin{bmatrix} 0 \\ \cos(2\psi) \\ \sin(2\psi) \end{bmatrix} \quad (1)$$

where ψ is the orientation of the maximum polarization with respect to the horizontal polarization [1].

Consequently, for a roll-invariant target dipole or dihedral detection, the tilt angle ψ should be removed. In 1993, Krogager has proposed an algorithm to derive ψ which uses the phase difference between right-right (S_{RR}) and left-left (S_{LL}) circular polarizations of the scattering matrix $\mathbf{S}$ [2]:

$$\psi_{Krogager} = \left[\text{Arg}\left(S_{RR}S_{LL}^{*} + \pi\right)\right]/4. \quad (2)$$

where S_{RR} and S_{LL} are respectively defined by :

$$\begin{cases} S_{RR} &= \left(S_{HH} - S_{VV} + 2jS_{HV}\right)/2 \\ S_{LL} &= \left(S_{VV} - S_{HH} + 2jS_{HV}\right)/2 \end{cases}$$

This estimated orientation angle $\psi_{Krogager}$ is valid under certain condition on the target. To overcome this problem, authors propose to apply the TSVM method which provides an unique and roll-invariant decomposition of any targets [1].

2.2. The Kennaugh-Huynen con-diagonalization

In PolSAR imagery, coherent targets are fully described by their scattering matrix $\mathbf{S}$. To retrieve parameters with a physical meaning, Kennaugh and Huynen have proposed to apply the characteristic decomposition on the scattering matrix [3] [4] [5]. Under the reciprocity assumption, the cross-polarization terms S_{HV} ans S_{VH} are equal. It yields:

$$\mathbf{S} = \mathbf{R}(\psi)\mathbf{T}(\tau_m)\mathbf{S_d}\mathbf{T}(\tau_m)\mathbf{R}(-\psi), \quad (3)$$

where $\mathbf{R}(\psi)$ and $\mathbf{T}(\tau_m)$ are defined by :

$$\mathbf{R}(\psi) = \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix}, \quad (4)$$

and:

$$\mathbf{T}(\tau_m) = \begin{bmatrix} \cos\tau_m & -j\sin\tau_m \\ -j\sin\tau_m & \cos\tau_m \end{bmatrix}. \quad (5)$$

$\mathbf{S_d}$ is a diagonal matrix which contains the two complex coneigenvalues μ_1 and μ_2 of $\mathbf{S}$ as:

$$\mathbf{S_d} = \begin{bmatrix} me^{2j(\nu+\rho)} & 0 \\ 0 & m\tan^2\gamma\, e^{-2j(\nu-\rho)} \end{bmatrix} = \begin{bmatrix} \mu_1 & 0 \\ 0 & \mu_2 \end{bmatrix}. \quad (6)$$

The Kennaugh-Huynen con-diagonalization allows to characterize a coherent target by means of six independent parameters : ψ, τ_m, m, γ, ν and ρ. ψ is the rotation angle (see (1)). This parameter is used for the subtraction of the target orientation from the target vector, which leads to a roll-invariant decomposition. This step is named desying. τ_m is the target helicity, it characterizes the symmetry of the target. m is the maximum amplitude return. γ and ν are respectively the characteristic and skip angles. ρ is the absolute phase of the target. This term is not observable except for interferometric applications.

2.3. The Target Scattering Vector Model

In 2007, Touzi has proposed a new model: the Target Scattering Vector Model (TSVM). It consists in the projection in the Pauli basis of the scattering matrix con-diagonalized by the Takagi method [1]. It leads:

$$\begin{aligned}\overrightarrow{e_T}^{\mathbf{SV}} &= m e^{j\Phi_s} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(2\psi) & -\sin(2\psi) \\ 0 & \sin(2\psi) & \cos(2\psi) \end{bmatrix} \\ &\times \begin{bmatrix} \cos\alpha_s \cos(2\tau_m) \\ \sin\alpha_s e^{j\Phi_{\alpha_s}} \\ -j\cos\alpha_s \sin(2\tau_m) \end{bmatrix}. \end{aligned} \quad (7)$$

α_s and Φ_{α_s} are the symmetric scattering type magnitude and phase. They are derived from the con-eigenvalues μ_1 and μ_2 of the scattering matrix $\mathbf{S}$ by:

$$\tan(\alpha_s)\, e^{j\Phi_{\alpha_s}} = \frac{\mu_1 - \mu_2}{\mu_1 + \mu_2}. \quad (8)$$

The symmetric scattering type magnitude α_s reduces to the so-called α parameter issued from the Cloude-Pottier decomposition for a symmetric scatterer (*i.e.* $\tau_m = 0$).

Due to the con-eigenvalue phase ambiguity, the Kennaugh-Huynen decomposition is not unique. Huynen's orientation angle ψ should be re-evaluated. To remove this ambiguity, the following relation is applied to restrict the domain definition of ψ to the interval $[-\pi/4, \pi/4]$:

$$\begin{aligned}&\overrightarrow{e_T}^{\mathbf{SV}}(\Phi_s, \psi, \tau_m, m, \alpha_s, \Phi_{\alpha_s}) \\ &\quad = \overrightarrow{e_T}^{\mathbf{SV}}(\Phi_s, \psi \pm \frac{\pi}{2}, -\tau_m, m, -\alpha_s, \Phi_{\alpha_s}). \end{aligned} \quad (9)$$

As the last term of (7) is independent of the target orientation angle, it yields that the four parameters m, α_s, Φ_{α_s} and τ_m are roll-invariant. In the following, the TSVM method is first applied on the original PolSAR data-set to provide a roll-invariant target vector. To compute the target orientation angle with the TSVM decomposition, the following relation is implemented [5] [6] [7]:

$$\psi_{TSVM} = \frac{1}{2}\text{Arctan}\left(\frac{2\Re\text{e}\Big\{(S^*_{HH} + S^*_{VV})S_{HV}\Big\}}{\Re\text{e}\Big\{(S^*_{HH} + S^*_{VV})(S_{HH} - S_{VV})\Big\}}\right). \quad (10)$$

2.4. Comparison between ψ_{TSVM} and $\psi_{Krogager}$

According to the TSVM, the following relation between the orientation angle ψ_{TSVM} estimated by the TSVM method and $\psi_{Krogager}$ estimated with the phase difference between right-right and left-left circular polarizations can be proved [8]:

$$\begin{aligned}\psi_{TSVM} &= \psi_{Krogager} - \frac{1}{4}\text{Arctan}\left(\frac{\tan(\alpha_s)\sin(\Phi_{\alpha_s})}{\tan(\alpha_s)\cos(\Phi_{\alpha_s}) + \sin(2\tau_m)}\right) \\ &+ \frac{1}{4}\text{Arctan}\left(\frac{\tan(\alpha_s)\sin(\Phi_{\alpha_s})}{\tan(\alpha_s)\cos(\Phi_{\alpha_s}) - \sin(2\tau_m)}\right). \end{aligned} \quad (11)$$

Fig. 1 shows a comparison between the orientation angle ψ_{TSVM} estimated via the TSVM and $\psi_{Krogager}$ as a function of three roll-invariant TSVM parameters: τ_m, Φ_{α_s} and α_s. Fig. 1(a) shows the evolution of ψ_{TSVM} and $\psi_{Krogager}$ with the helicity τ_m for $\alpha_s = \pi/3$ and $\Phi_{\alpha_s} = \pi/3$. Fig. 1(b) and Fig. 1(c) show respectively this relation as a function of the target scattering phase Φ_{α_s} for $\alpha_s = \pi/3$ and $\tau_m = \pi/8$, and as a function of α_s for $\Phi_{\alpha_s} = \pi/3$ and $\tau_m = \pi/8$. For $\tau_m = 0$, the target is symmetric. It leads that ψ_{TSVM} is equal to $\psi_{Krogager}$, as observed in black in Fig. 1(a). Moreover, for a null target scattering phase Φ_{α_s}, $\psi_{Krogager}$ and ψ_{TSVM} are equal. Similar observations can be done for $\alpha_s = 0$ and $\alpha_s = \pi/2$ as shown in Fig. 1(c).

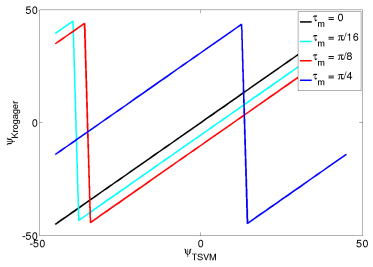
For $\tau_m = 0$, $\Phi_{\alpha_s} = 0$, $\alpha_s = 0$ or $\alpha_s = \pi/2$, the orientation angle estimated by the phase difference between right-right and left-left circular polarizations is equal to this estimated by the TSVM. It leads that both tilt angles are equal for a wide class of targets including trihedral, dihedral, helix, dipole, quarter wave, ... For all other cases, the orientation angle $\psi_{Krogager}$ is biased, and ψ_{TSVM} should be used instead for a roll-invariant target characterization.

3. ROLL-INVARIANT TARGET DETECTION

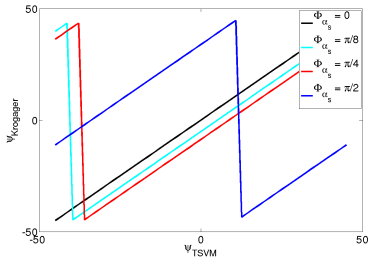
The general principle of the proposed roll-invariant target detection algorithm can be divided into five steps. First, the orientation angle ψ is computed and the "roll-invariant" target vector is extracted. This step is named desying. Then, the covariance matrix $[M]$ of the clutter is estimated. Next, the similarity measure between the steering vector and the "roll-invariant" target vector is computed. The false alarm probability is fixed, and finally we conclude or not on the detection.

3.1. Binary hypothesis test

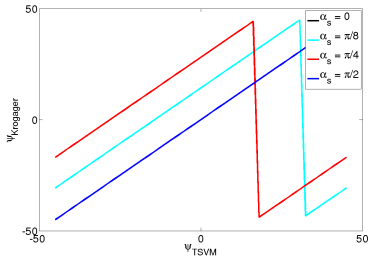
The target detection problem can be formulated as a binary hypothesis test shown in (12). Under the null hypothesis H_0, the observed target vector $\mathbf{k}$ is only the clutter $\mathbf{c}$. Under the alternative hypothesis H_1, the backscattered signal can be decomposed as the sum of the reference signal $\mathbf{p}$ times an unknown scalar complex parameter α with the clutter $\mathbf{c}$. Here, the clutter is modeled as a Spherically Invariant Random Vector (SIRV), *i.e.* $\mathbf{c} = \sqrt{\tau}\mathbf{z}$. $\mathbf{c}$ is defined as the product of a



(a)



(b)



(c)

Fig. 1. Comparison between ψ_{TSVM} and $\psi_{Krogager}$: (a) as a function of τ_m for $\alpha_s = \pi/3$ and $\Phi_{\alpha_s} = \pi/3$, (b) as a function of Φ_{α_s} for $\alpha_s = \pi/3$ and $\tau_m = \pi/8$ and (c) as a function of α_s for $\Phi_{\alpha_s} = \pi/3$ and $\tau_m = \pi/8$

square root of a positive random variable τ (representing the texture) with an independent circular complex Gaussian vector $\mathbf{z}$ with zero-mean and covariance matrix $[M] = E\{\mathbf{z}\mathbf{z}^H\}$ (representing the speckle).

$$\begin{cases} H_0 : \mathbf{k} = \mathbf{c} \\ H_1 : \mathbf{k} = \alpha\mathbf{p} + \mathbf{c} \end{cases} \tag{12}$$

The optimal detector under the SIRV hypothesis is given by the following relation:

$$\Lambda\left([M]\right) = \frac{p_{\mathbf{k}}(\mathbf{k}/H_1)}{p_{\mathbf{k}}(\mathbf{k}/H_0)} = \frac{h_p\left((\mathbf{k}-\mathbf{p})^H[M]^{-1}(\mathbf{k}-\mathbf{p})\right)}{h_p\left(\mathbf{k}^H[M]^{-1}\mathbf{k}\right)} \underset{H_0}{\overset{H_1}{\gtrless}} \lambda.$$

where $h_p\left(\cdot\right)$ is the density generator function. Its expression is given by:

$$h_p\left(x\right) = \int_0^{+\infty} \frac{1}{\tau^p} \exp\left(-\frac{x}{\tau}\right) p_\tau(\tau)\, d\tau.$$

This optimal detector depends on the texture probability density function p_τ.

3.2. GLRT-LQ detector

The Generalized Likelihood Ratio Test - Linear Quadratic (GLRT-LQ) detector can be used to detect a particular target. Let $\mathbf{p}$ be a steering vector and $\mathbf{k}$ the observed signal. The GLRT-LQ between $\mathbf{p}$ and $\mathbf{k}$ is given by [9]:

$$\Lambda\left([M]\right) = \frac{|\mathbf{p}^H[M]^{-1}\mathbf{k}|^2}{\left(\mathbf{p}^H[M]^{-1}\mathbf{p}\right)\left(\mathbf{k}^H[M]^{-1}\mathbf{k}\right)} \underset{H_0}{\overset{H_1}{\gtrless}} \lambda, \tag{13}$$

where $[M]$ is the covariance matrix of the population under the null hypothesis H_0, *i.e.* the observed signal is only the clutter.

In general, the covariance matrix is unknown. One solution consists in estimating the covariance matrix $[M]$ by $[\hat{M}]_{FP}$, the fixed point covariance matrix estimator. It is the maximum likelihood estimator of the normalized covariance matrix under the deterministic texture in a Spherically Invariant Random Process. Its expression is given by the solution of the following recursive equation [10]:

$$[\hat{M}]_{FP} = f([\hat{M}]_{FP}) = \frac{p}{N}\sum_{i=1}^{N} \frac{\mathbf{k}_i\mathbf{k}_i^H}{\mathbf{k}_i^H[\hat{M}]_{FP}^{-1}\mathbf{k}_i}. \tag{14}$$

Replacing $[M]$ by $[\hat{M}]_{FP}$ in (13) leads to an adaptive version of the GLRT-LQ detector.

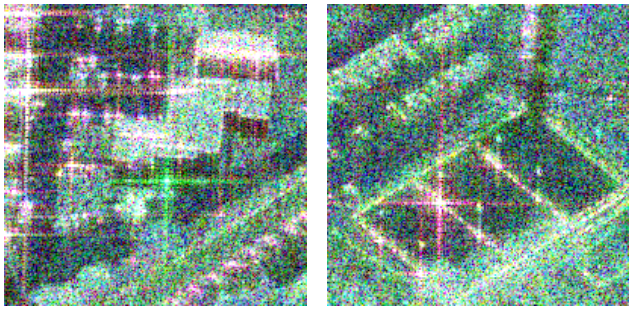
If the covariance matrix is estimated by the fixed point estimator (14), it has been proved, for large N, the relation between the false alarm probability p_{fa} and the detection threshold λ:

$$p_{fa} = (1-\lambda)^{(a-1)}\ {}_2F_1(a, a-1; b-1; \lambda), \tag{15}$$

with $a = \frac{p}{p+1}N - p + 2$ and $b = \frac{p}{p+1}N + 2$. N is the number of pixels used to estimate the covariance matrix $[M]$. p is the dimension of the target vector ($p = 3$ for the monostatic case). ${}_2F_1(\cdot,\cdot;\cdot;\cdot)$ is the Gauss hypergeometric function.

4. DETECTION RESULTS ON A RAMSES X-BAND DATA-SET

In this section, a real data-set acquired by the RAMSES sensor at X-band is analyzed. Fig. 2 shows a colored composition in the Pauli basis of the target vector. This data-set is



(a) (b)

Fig. 2. Toulouse, RAMSES PolSAR data, X-band (150×150 pixels). Colored composition in the Pauli basis of the target vector $[k]_1$-$[k]_3$-$[k]_2$. Images containing a dihedral (a) and a narrow diplane (b).

composed by two particular targets: a dihedral (in green on Fig. 2(a)) and a narrow diplane (in red on Fig. 2(b)). Both GLRT-LQ Krogager and GLRT-LQ TSVM detectors (tilt angle estimated respectively by $\psi_{Krogager}$ and ψ_{TSVM}) are applied on this data-set. Table. 1 shows the criterion characteristics for the dihedral and the narrow diplane. As those two targets have theoretically a null target helicity τ_m, both detectors should have similar performance. For a fixed false alarm probability of 5×10^{-3}, the detection threshold is $\lambda = 0.931$. For the dihedral, The GLRT-LQ TSVM is able to detect the target ($0.956 > \lambda$) whereas the GLRT-LQ Krogager detector fails ($0.912 < \lambda$).

Similar conclusions can be done for the narrow diplane as observed on Table. 1.

	dihedral				
	GLRT-LQ	ψ	α_s	Φ_{α_s}	τ_m
Krogager	0.912	0.761			
TSVM	0.956	0.770	-1.453	0.450	-0.178
Pure target			1.571	∞	0

	narrow diplane				
	GLRT-LQ	ψ	α_s	Φ_{α_s}	τ_m
Krogager	0.828	-0.023			
TSVM	0.849	-0.026	1.210	-0.172	0.052
Pure target			1.249	0	0

Table 1. Detector characteristics for the dihedral and the the narrow diplane.

5. CONCLUSION

In this paper, authors have proposed to the use Target Scattering Vector Model to extract the roll-invariant target vector. Some comparisons have been done between the orientation angle estimated with the phase difference between right-right and left-left circular polarizations and this issued from the TSVM. Next, authors have proposed to use the TSVM for a roll-invariant target detection. The GLRT-LQ similarity measure has been implemented and validated on high resolution PolSAR data for the detection of particular targets such as an oriented dihedral.

Further works will deal with the use of optimal detectors based on the statistics of the PolSAR clutter. Special interest will also be dedicated to bistatic PolSAR imagery where the cross-polarization terms of the scattering matrix $\mathbf{S}$ are not equal in general [11]. In this case, two orientation angles, one at the emission and one at the reception, should be taken into account.

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