Optimal Polarizations for Radar Detection and Recognition of Targets in Clutter

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Abstract

Under DARPA sponsorship, MIT Lincoln Laboratory is investigating the detection and recognition of stationary ground targets in high resolution, fully polarimetric synthetic aperture radar (SAR) imagery. Using 0.3 m × 0.3 m ft SAR imagery of targets and clutter gathered by the Lincoln Laboratory 33 GHz sensor, this paper investigates several techniques for improving target detection performance through optimal processing of the fully polarimetric SAR data.

Introduction

Target detection performance depends upon two fundamental radar parameters: (1) the target-to-clutter ratio (T/C), and (2) the standard deviation (σ_C) of the background clutter. This is reflected in the equation that defines the classical two-parameter CFAR (constant false alarm rate) detector [1]:

$$\text{If } \frac{(T/C)}{\sigma_C} > K_{CFAR}, \text{ declare target present} \tag{1}$$

The detector uses clutter data around each cell under test to calculate the (T/C)-to-σ_C ratio and then compares the ratio with a CFAR constant, K_{CFAR} (see Figure 1). When a target is present, we would like the ratio to be as large as possible; when there is no target present, we would like the ratio to be small. To make the (T/C)-to-σ_C ratio as large as possible, we may either maximize T/C or minimize σ_C.

This paper compares two basic approaches for processing fully polarimetric, complex HH, HV, and VV data to increase the (T/C)-to-σ_C ratio. The first approach maximizes T/C by coherently combining the complex HH, HV, and VV data using an optimal set of (complex) weights; this is called polarimetric matched filter (PMF) processing. The PMF weights are selected only to maximize T/C; the standard deviation of the clutter, σ_C, is not reduced, but remains approximately the same as for a single-polarimetric-channel radar.

The second approach minimizes the clutter standard deviation, σ_C, by processing the fully polarimetric data using a polarimetric whitening filter (PWF). In PWF processing we first apply a whitening filter to the complex HH, HV, and VV data, resulting in a set of three uncorrelated, complex images having equal average power; these three images are then noncoherently summed to obtain the minimum-speckle SAR image (the noncoherent summing is equivalent to averaging three uncorrelated "looks"). Although the PWF approach produces a small loss in T/C (a "noncoherent-integration" loss), the standard deviation of the clutter background is significantly reduced. This reduction in σ_C has been found to result in significantly improved detection performance [2,3].

Using real, fully polarimetric SAR imagery of targets and clutter gathered by the Lincoln Laboratory sensor [4], this paper investigates (1) the increase in T/C achievable through polarimetric matched filter (PMF) processing and (2) the reduction in σ_C achievable through polarimetric whitening filter (PWF) processing. Also, the CFAR detection statistic (Equation 1) obtained using PWF imagery is compared with that obtained using single-polarimetric-channel imagery, and the best polarimetric processing approach for CFAR detection of stationary targets in ground clutter is determined.

Algorithm Descriptions

This section of the paper describes the polarimetric matched filter (PMF) and the polarimetric whitening filter (PWF). There are, of course, other approaches for processing fully polarimetric SAR data into SAR intensity images [3]. In this section, we also briefly describe the two-parameter CFAR detector used to detect targets in SAR intensity images.

Polarimetric Whitening Filter (PWF)

In [2] a simple quadratic processor was derived which combined complex HH, HV, and VV polarimetric images into a SAR intensity image having the desirable property that the speckle (or equivalently, the standard deviation of the background clutter) is minimized. This polarimetric processor, the polarimetric whitening filter (PWF), is given by the quadratic

$$y = \underline{X}^{\dagger} \Sigma_C^{-1} \underline{X} \tag{2}$$

where the radar measurement vector $\underline{x}$ consists of three complex elements, HH, HV, and VV,

$$\underline{X} = \begin{pmatrix} HH_I & + & jHH_Q \\ HV_I & + & jHV_Q \\ VV_I & + & jVV_Q \end{pmatrix} \tag{3}$$

and Σ_C is the polarization covariance matrix $\left(\Sigma_C = E\left\{\underline{X}\underline{X}^{\dagger}\right\}\right)$ of the radar return from typical terrain clutter. Note that this algorithm requires a priori knowledge of the clutter polarization covariance only. Results of a theoretical analysis of the detection performance using PWF imagery were reported in [2]; it was shown that the detection performance of the PWF is essentially identical to that of an optimal polarimetric detector [5].

Polarimetric Matched Filter (PMF)

In [5], a linear processor for combining the polarimetric measurements HH, HV, and VV, known as the polarimetric matched filter (PMF) was derived; this detector was designed to produce the maximum average T/C in a SAR intensity image. This optimal processor is given by the equation

$$y = \left| \underline{W}^{\dagger} \underline{X} \right|^2 \tag{4}$$

where $\underline{W}$ is a set of optimal weights used to combine the complex HH, HV, and VV data. The optimal weight vector, $\underline{W}$, is obtained as the solution to the eigenvalue-eigenvector problem

$$\Sigma_c^{-1} \Sigma_t \underline{W} = \lambda \underline{W} \tag{5}$$

where Σ_c is the polarization covariance of the clutter, Σ_t is the polarization covariance of the target, and $\underline{W}$ is the eigenvector corresponding to the eigenvalue, λ. The optimal weight vector, $\underline{W}_{max}$, is the eigenvector corresponding to λ_{max}, the maximum eigenvalue of the matrix $\Sigma_c^{-1}\Sigma_t$. Note that this processing approach requires a priori knowledge of both the target and clutter polarization covariances.

In [5], targets were characterized by polarization covariance matrices which were calculated by averaging fully polarimetric turntable measurements of targets over 360° of aspect angle. This paper calculates the target polarization covariance matrix at various aspect angles and then uses this information to determine the maximum T/C at each of the angles. The approach we used is described as follows:

(1) Fully polarimetric 2-D SAR target imagery (0.3 m × 0.3 m ft resolution) was used to calculate the polarization covariance of each target at various aspect angles around the target. We used 60° of aspect angle data per target, resulting in 60 polarization covariance matrices per target. At each aspect angle we calculated the target polarization covariance matrix from the complex polarimetric data (HH, HV, and VV) of the brightest 100 pixels on the target.

(2) The polarization covariance at the i^{th} aspect angle (denoted by Σ_{t_i}) was used to determine the polarization combination that maximized the T/C ratio at that aspect angle. To do this we evaluated the optimal PMF weights by maximizing the ratio

$$(T/C)_i = \frac{\underline{W}^{\dagger} \Sigma_{t_i} \underline{W}}{\underline{W}^{\dagger} \Sigma_c \underline{W}} \tag{6}$$

where $\underline{W}$ is the optimal weight vector (the PMF) for the i^{th} aspect angle, Σ_{t_i} is the polarization covariance matrix of the target at that aspect angle, and Σ_c is the polarization covariance matrix of the background clutter. In these calculations we used the covariance of typical meadow terrain to characterize the background clutter [6]:

$$\Sigma_c = 0.086 \begin{pmatrix} 1.0 & 0 & 0.53 \\ 0 & 0.19 & 0 \\ 0.53 & 0 & 1.0 \end{pmatrix} \tag{7}$$

(3) The target-to-clutter ratio defined in Equation 6 was maximized by solving the following eigenvalue-eigenvector problem at each aspect angle:

$$\Sigma_c^{-1} \Sigma_{t_i} \underline{W} = \lambda \underline{W} \tag{8}$$

The maximum eigenvalue (denoted λ_{max_i}) and its corresponding eigenvector (denoted $\underline{W}_{max_i}$) yield the desired solution. Also, λ_{max_i} is equal to the maximum achievable average T/C at the i^{th} aspect angle, which is obtained by processing the fully polarimetric data (at that specific target aspect angle) using the PMF:

$$y = | \underline{W}^{\dagger}_{max_i} \underline{X} |^2 \tag{9}$$

where the measurement vector $\underline{X}$ contains the three complex measurements HH, HV, and VV.

Other Polarimetric Processors

The simplest detectors would make use of single-polarimetric-channel SAR imagery. We compared target-to-clutter ratios obtained using PMF imagery (optimally calculated at each target aspect angle) with that obtained using HH, HV, HH-VV, and LL polarizations, as well as PWF images. The T/C achieved by using these other polarizations was calculated by substituting various weight vectors, $\underline{W}$, into Equation 6. For example, to evaluate the T/C achieved using LL polarization (left-circular transmit, left-circular receive) we substituted the following weight vector into Equation 6:

$$\underline{W} = \left[\frac{1}{2}, j, -\frac{1}{2} \right] \tag{10}$$

Similarly, the T/C obtained using the polarization combination HH-VV was obtained by substituting the following weight vector into Equation 6:

$$\underline{W} = [1, 0, -1] \tag{11}$$

The polarimetric combination (HH-VV) can be obtained by transmitting linear polarization at an angle of 45° (relative to horizontal) and receiving linear polarization at an angle of -45° (relative to horizontal). In fact, any polarimetric matched filter can be synthesized by using an appropriate transmit/receive polarization combination; similarly, any transmit/receive polarization combination can be synthesized by using an appropriate polarimetric matched filter [7].

Two-Parameter CFAR Detector

We define CFAR to mean the detection rule

$$\frac{X_t - \hat{\mu}_c}{\hat{\sigma}_c} \underset{\text{clutter}}{\overset{\text{target}}{\gtrless}} K_{CFAR} \qquad (12)$$

where X_t is the scalar pixel value of the cell under test, $\hat{\mu}_c$ is the estimated clutter mean (obtained from the clutter data in the CFAR stencil), $\hat{\sigma}_c$ is the estimated clutter standard deviation (also obtained from the clutter data in the CFAR stencil), and K_{CFAR} is a constant that defines the false alarm rate (see Figure 1). Since the SAR intensity images are converted to units of dB by taking 10 log y prior to running the CFAR detector over the image, Equation 12 takes the form given previously in Equation 1.

Results of Polarimetric Processing

We processed SAR imagery of three targets: a tank, an APC, and a howitzer. Targets with and without camouflage were processed. Sixty 0.3 m resolution SAR images of each target at 1 degree aspect-angle spacing were constructed, corresponding to a total aspect-angle coverage of 60 degrees per target. Table 1 summarizes average T/C losses (relative to PMF processing at each target aspect angle) for non-camouflaged targets; the best polarization combination of those evaluated was found to be to be HH-VV. Table 2 summarizes the corresponding average T/C losses for the camouflaged targets; again, the best polarization combination of those considered was found to be HH-VV.

Table 1

Average T/C Loss Relative to PMF Processing at Each Aspect Angle (Non-Camouflaged Targets)

	HH	HV	HH-VV	LL	PWF
TANK	1.7 dB	6.9 dB	1.7 dB	3.5 dB	3.0 dB
APC	3.6 dB	4.6 dB	0.4 dB	1.8 dB	2.9 dB
HOWITZER	1.9 dB	5.9 dB	3.6 dB	4.2 dB	3.3 dB
AVERAGE	2.4 dB	5.8 dB	1.9 dB	3.2 dB	3.1 dB

Table 2

Average T/C Loss Relative to PMF Processing at Each Aspect Angle (Camouflaged Targets).

	HH	HV	HH-VV	LL	PWF
TANK	1.6 dB	3.6 dB	2.0 dB	2.7 dB	2.2 dB
APC	4.1 dB	2.3 dB	1.8 dB	1.9 dB	2.3 dB
HOWITZER	2.7 dB	4.3 dB	3.6 dB	3.7 dB	3.1 dB
AVERAGE	2.7 dB	3.4 dB	2.5 dB	2.7 dB	2.5 dB

Figure 2 shows a typical plot of the loss in T/C (relative to that obtained using PMF processing at each target aspect angle) for one of the targets (an APC); losses for PWF processing and for HH, HV, HH-VV, and LL are plotted. The curves shown in Figure 2 indicate that the best polarization depends upon target aspect angle; for example, at some aspect angles HV was nearly optimal, while at other aspects HH-VV was nearly optimal. Note also that HV polarization exhibits a deep null at a 0° aspect angle, which corresponds to head-on.

Next, we calculated several important two-parameter CFAR detection statistics: (1) the peak T/C, (2) the clutter standard deviation (σ_c), and (3) the deflection ratio (T/C-to-σ_c). We ran the two-parameter CFAR detector (see Figure 1) over 86 target-in-clutter images and tabulated the above three statistics. Table 3 summarizes the results. The two most significant results are as follows:

(1) The best (coherent) polarization combination was found to be HH-VV; this polarization combination yielded in the best T/C (33.6 dB) and the best (T/C)-to-σ_c ratio (5.73).

(2) PWF processing was found to give the best (T/C)-to-σ_c ratio (8.07); this was due to the significant decrease in clutter standard deviation obtained from PWF processing. Although PWF processing produced a 3 dB lower T/C than HH-VV, the standard deviation of PWF clutter was 2 dB less than that of the HH-VV data; such a reduction in σ_c has been shown to result in significantly improved detection performance [8].

Table 3

Two-Parameter CFAR Detector Statistics (Average Values)

Polarization	(T/C) dB*	σ_c	$\frac{(T/C)}{\sigma_c}$
PWF	30.6	3.84	8.07
HH-VV	33.6	5.87	5.73
LL	32.2	5.83	5.54
HH	32.9	6.22	5.31
HV	29.0	5.86	4.97

*peak target amplitude to average clutter $(\hat{\mu}_c)$ measured by the CFAR (see Figure 1).

Summary

In [5], the polarimetric matched filter (PMF) was derived and its performance evaluated, using simple target and clutter polarization covariance matrix models. It was suggested in [5] that the target model used in these studies was too simple and that a more realistic target model should be developed, one that characterizes a target's polarimetric returns as a function of aspect angle around a target. This paper uses a more realistic target model, one for which the polarization covariance matrix of the target is calculated for each high resolution SAR target image under consideration. The target polarization covariance matrix is calculated from the brightest 100 pixels in the image; then the (optimal) PMF is determined for that image, and the maximum achievable T/C for that target image is determined.

First, we compared the T/C obtained using various polarization combinations (HH, HV, HH-VV, LL, and PWF) with that obtained using PMF processing at each target aspect angle. For the target data used in this study, we found that HH-VV polarization gave the best average T/C relative to PMF processing at each aspect angle.

Second, we evaluated several two-parameter CFAR detector statistics using a set of 86 target-in-clutter images. We verified that HH-VV polarization maximized the (T/C)-to-σ_C ratio for the four polarization combinations considered (HH, HV, HH-VV, and LL). However, we found that the (T/C)-to-σ_C ratio for PWF-processed data was considerably larger, implying that PWF-processed data would yield significantly improved detection performance.

References

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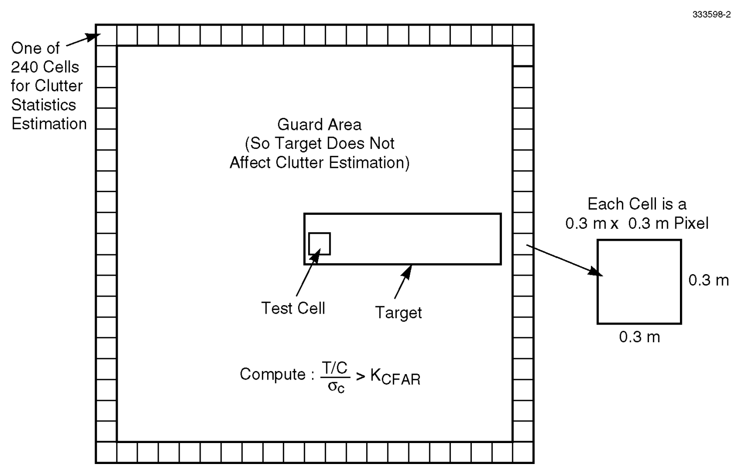

Figure 1: Two-parameter CFAR detector; X_t is the amplitude of the test cell; $\hat{\mu}_C$ and $\hat{\sigma}_C$ are the clutter mean and standard deviation estimated from the data in the CFAR stencil (see Equation 12).

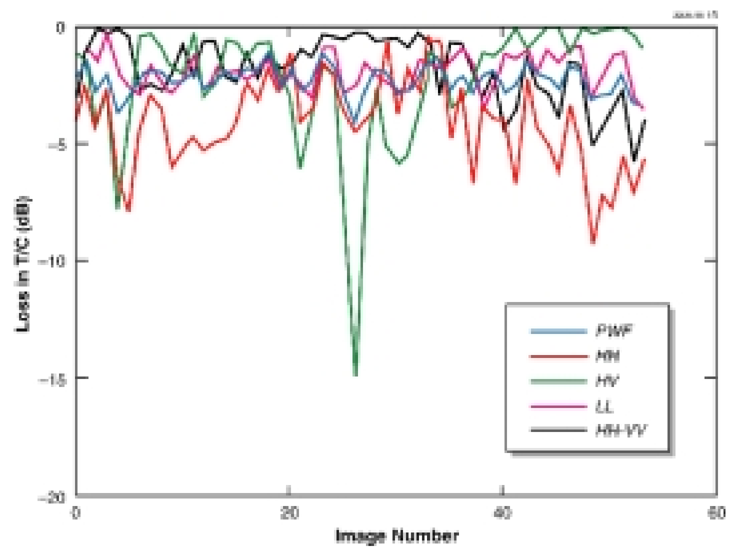

Figure 2: T/C loss (dB) relative to PMF processing at each aspect angle.