

New experiments in the use of infrared polarization in the detection of small targets^{*}

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ABSTRACT

In this paper, we will discuss a novel technology, which we have recently developed for automatic target detection and recognition by polarimetric imaging systems. This technology consists of an approach to non-cooperative small target detection that uses statistical techniques to exploit a target's Stokes vector infrared signature. This is applicable to sensors whose signature measurements are sensitive to the polarization of the targets and their backgrounds. Fusion is achieved by constructing the joint statistical measures for the target's polarization states. Target polarization states are in terms of the intensity, percent of linear polarization, and the angle of polarization plane. Applications of the proposed approach, for military targets under variations in target geometry are made in terms of receiver operating characteristic condition curves. The new results, which have been obtained on data from the Air Force's IRMA polarimetric infrared simulation tool, indicate the usefulness of polarimetric infrared signatures for the automatic detection of small targets.

1. INTRODUCTION

We address the problem of detecting small military targets on the ground by means of an autonomous polarimetric sensor on board a high altitude air or space borne platform. In such scenarios, the scene imagery is composed of targets that are small, having relatively few pixels, embedded in the background clutter. The role of this system is to act as a target screener, by indicating the potential areas of interest. These detected target regions will be passed to other higher resolution multi-spectral sensors for classification. An autonomous sensor system would incorporate a micropolarizer array and digital signal processors. The digital signal processors would host algorithms for detecting small targets in the polarimetric

^{*} Supported by Air Force Research Laboratory/VSSS, Contract Number F29601-99-C-0117, Project Officer Capt Mario A. Serna.

Report Documentation Page			Form Approved OMB No. 0704-0188		
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1. REPORT DATE 2001		2. REPORT TYPE		3. DATES COVERED -	
4. TITLE AND SUBTITLE New experiments in the use of infrared polarization in the detection of small targets				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Firooz Sadjadi; Cornell Chun				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Lockheed Martin Corp,3333 Pilot Knob Road,Eagen,MN,55121				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 13	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

images. These algorithms are described in Section 2 where their performances on synthetic polarimetric infrared imagery are evaluated.

The authors have recently reported on their works in the detection and classification of relatively large size targets by means of polarimetric infrared sensor signatures.¹ The present work is significant by its being the first report of the development and evaluation of automatic detection in polarimetric imagery containing targets subtending only a small number of pixels.

A beam of incoherent radiation emitted or reflected from a target's surface can be completely described at a given wavelength by the four Stokes parameters, (I, Q, U, V). The first Stokes parameter I is a measure of the total intensity of radiation. The second parameter Q measures the amount of linear polarization in the horizontal direction. The third parameter U measures the amount of linear polarization at 45 degrees from the horizontal. The fourth parameter V is associated with the circular polarization.

We do not include images of V in this study of automatic target detection for two reasons. First the significance of circularly polarized light in target detection is currently being debated by researchers. The second reason is that sensors that can image V in the infrared in real time are only beginning to be developed. Sensing V requires a quarter-wave waveplate. Microscale waveplates for imaging V are currently in an early stage of development.²

The Stokes parameters can be transformed into percent of polarization P and angle of polarization ϕ using the relations,³

$$\begin{aligned} P &= \frac{\sqrt{Q^2 + U^2}}{I} * 100 \\ \phi &= \frac{1}{2} * \arctan\left(\frac{U}{Q}\right) \end{aligned} \quad (1)$$

Conventional methods of determining polarization from images rely on the use of a single polarizer covering the entire imaging sensor. In one method, a sequence of four images is taken with a linear polarizer oriented at 0°, 45°, 90°, and 135°. This method can determine the first three of the Stokes parameters at each image pixel:

$$\begin{aligned} I &= \frac{1}{2} * (i_0 + i_{45} + i_{90} + i_{135}) \\ Q &= i_0 - i_{90} \\ U &= i_{45} - i_{135} \end{aligned} \quad (2)$$

where, i_x is the intensity measured with the polarizer oriented at x degrees.

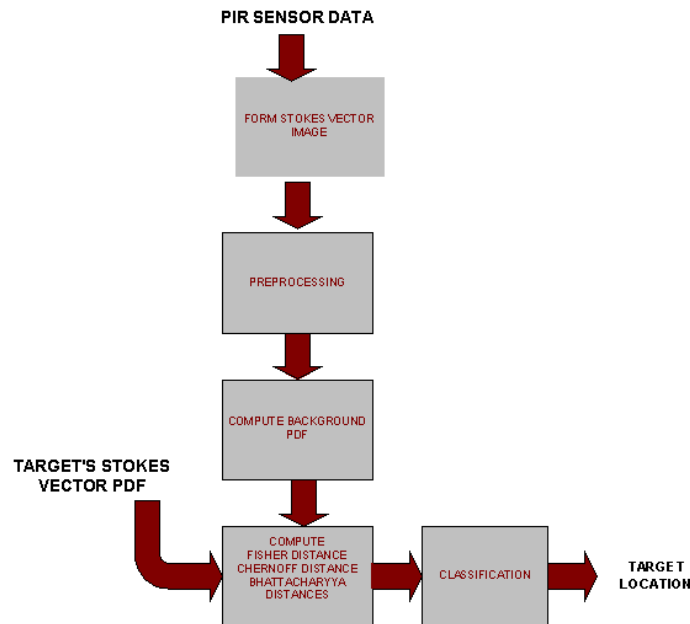


Figure 1. Processing architecture for polarimetric IR automatic the target detection.

2. TARGET DETECTION ALGORITHMS.

Figure 1 shows our overall approach for the automatic target detection. The output of the polarimetric infrared (PIR) sensor is used to generate arrays of Stokes vectors. Preprocessing algorithms operate on the polarimetric images to improve the image quality and perform non-uniformity compensation and image enhancement. Then an estimate of the probability density function (PDF) of a region in the Stokes images is made and compared with the PDFs of the targets of interests. The Bayesian probabilities of error or bounds on the errors such as Chernoff, Bhattacharyya and Fisher are used to detect the targets in clutter and determine the location of the targets in the imagery.

2.1. A STATISTICAL APPROACH FOR DETECTING SMALL TARGETS IN POLARIMETRIC INFRARED IMAGERY.

The goal of Target Detection is to estimate the presence or absence of a target, e.g. a T-72 tank or a M-35 truck, given a set of measurements. Many types of sensors have been proposed for small target detection applications including passive infrared imaging sensors and active Radars. Passive sensing systems, for many types of targets, especially airborne ones, use target motion as a cue for the target detection. However, for stationary small targets the separation of small targets from background clutter is a challenging problem. The goal of the task summarized in this section is to exploit the polarization states of small stationary targets and their backgrounds to improve the performance of target detection systems.

2.1.1 Target Detection.

Our objective is to classify a target from a set of measurements y_k . The target is a member of some target class T_c ($c=0$ for clutter; $c=1$ for target). Some of the measurements y_k are sufficiently class-dependent in some way to enable classification.

The observations are denoted.

$$\mathbf{Y}_\tau = \{y_l: l \in \tau\} \quad (3)$$

where τ denotes the set of polarization states.

Using this notation, the Bayes-optimal classifier can be constructed from the joint conditional probability density $p(T_c | Y_t)$. Then the minimum error classifier is

$$\hat{T}_c = \arg \max_{T_c} p(T_c | Y_t) \quad (4)$$

One can assume that each polarization state output represents a conditional density function $p(f(x, y) | \pi)$. Where π represents a particular polarization output state. Then the effect of using all of the sensory outputs is equivalent to the use of the total probability function. The total probability density function can be obtained by:

$$p(Y) = \sum_{\pi} p(f(x, y) | \pi) p(\pi) \quad (5)$$

In order to improve processing efficiency in terms of storage and speed, bounds on the Bayesian probability of errors, such as Chernov and Bhattacharyya bounds and Fisher Criterion are considered. The Fisher Criterion is defined in terms of the second order statistics of the targets and their backgrounds:

$$F = \frac{(\mu_1 - \mu_0)^2}{\sigma_1^2 + \sigma_2^2} \quad (6)$$

Where μ and σ are the mean and standard deviations and subscripts 0 and 1 refer to clutter and target classes respectively.

The fused Fisher Criterion for the observed three polarization signatures are defined as the following:

$$F_{fused} = m_I \frac{(\mu_{t_I} - \mu_{b_I})^2}{\sigma_{t_I}^2 + \sigma_{b_I}^2} + m_P \frac{(\mu_{t_P} - \mu_{b_P})^2}{\sigma_{t_P}^2 + \sigma_{b_P}^2} + m_\phi \frac{(\mu_{t_\phi} - \mu_{b_\phi})^2}{\sigma_{t_\phi}^2 + \sigma_{b_\phi}^2} \quad (7)$$

where the m coefficients are the functions of the a priori probabilities of the three signatures.

2.2. SIMULATION OF POLARIMETRIC IMAGES.

2.2.1 Simulation software.

To evaluate our target detection algorithms we used computer-simulated polarimetric images. The polarimetric images were generated using the software package IRMA (Infrared Modeling and Analysis). IRMA is the Air Force's premier research tool for high resolution rendering and polarimetric signature prediction modeling and is used to generate synthetic imagery to develop and test smart tactical weapons. IRMA is capable of generating multispectral-polarimetric infrared imagery of targets and backgrounds in a tactical battlefield scene for a variety of operating conditions, backgrounds, locations, weather, and time-of-day. Along with infrared images, IRMA generates ground truth data for evaluating target detection and recognition algorithms.

We used IRMA version 4.1, which was developed for polarization-sensitive sensors in the millimeter wave band. In order to use IRMA for this study, we had to alter the input data files for IRMA to include data in the infrared band.

2.2.2 Modified Stokes Parameters.

To be consistent with theories using the Bidirectional Reflectance Function (BRDF), the authors of IRMA, use the modified Stokes parameters ($S_{m,0}$, $S_{m,1}$, $S_{m,2}$, $S_{m,3}$) which are related to the conventional Stokes parameters (I, Q, U, V) as

$$\begin{aligned} S_{m,0} &= \frac{1}{\eta} \cdot \langle |E_v|^2 \rangle = \left(\frac{1}{2} \right) \cdot (I + Q) \\ S_{m,1} &= \frac{1}{\eta} \cdot \langle |E_h|^2 \rangle = \left(\frac{1}{2} \right) \cdot (I - Q) \\ S_{m,2} &= \text{Re} \left[\frac{1}{\eta} \cdot \langle E_v E_h^* \rangle \right] = \left(\frac{1}{2} \right) \cdot U \\ S_{m,3} &= \text{Im} \left[\frac{1}{\eta} \cdot \langle E_v E_h^* \rangle \right] = \left(\frac{1}{2} \right) \cdot V \end{aligned} \tag{8}$$

where E_v and E_h are components of the electric field in the vertical and horizontal directions respectively and η is the impedance of free space.^{4,5} An image of $S_{m,0}$ is simply the image captured using a camera with a linear polarizer oriented vertically in front of the lens. Similarly $S_{m,1}$ is the image captured with the polarizer oriented horizontally. The image of $S_{m,2}$ corresponds to the image with the linear polarizer at 45° minus the image with the polarizer at -45° , with the difference image divided by 2.

The image of $S_{m,3}$ corresponds to the image with a right-circular polarizer minus the image with a left-circular polarizer with the difference image divided by 2. As mentioned earlier no circular polarization images were used in this study.

2.2.3 Images from IRMA.

Using IRMA we generated polarimetric images of a tactical scene. In this scene, four aircraft hangars are connected by runways and the target is parked on the grass. In some images [Left side of Figure 2, Figure 3 and Figure 4] the target was a T-72 tank. In other images [Right side of Figure 2, Figure 3 and Figure 4] a M-35 truck was substituted for the tank. For the polarimetric sensors, we assumed we are using off-the-shelf components. We included the characteristics of the Santa Barbara Focalplane SBF-119 640x512 InSb focal plane array. We also included the characteristics of a 400 mm lens available from Applied Physics Specialties.

Figure 2 and Figure 3 are images with the same format 640x512 as the SBF-119. The images in Figure 4 have the format 256x256, which would be the central region of the 640x512 images from the SBF-119.

Among the simplifying assumptions made in this scenario are

i) All surfaces have the same temperature 24 C. ii) Only two surface materials exist: Grass which emits unpolarized light and glossy paint, which emits polarized light with characteristics described by Fresnel equations. We use a complex index of refraction of $1.5 + i 0.15$, which is representative of paint in the wavelength range, 3–5 microns.⁶ And iii) No sun is present. The range from sensor to target varies from 1 km to 12 km. At 1 km the target and a hangar are well resolved [Figure 2]. At 5 km the target subtends 10 pixels [Figure 3] and at 12 km only 4 pixels [Figure 4]. These represent stressing scenarios for the target detection and recognition processor.

2.2.4 Simulation of noise and analog-to-digital conversion.

In order to simulate the noise introduced by the focal plane array and the A-to-D converter, we took the output image files from IRMA and used them as input files for a program, which we wrote in Mathcad. The output from the Mathcad program represents the realistic output from a 14-bit A-to-D converter. This output then goes to the signal processors for nonuniformity correction, and then into the target detection processor.

The raw output data from the A-to-D converters are images i_0 , i_{45} , and i_{90} . i_0 is the frame captured when a linear polarizer which passes horizontally polarized light is placed in front of the imaging sensor. Similarly i_{45} and i_{90} are frames for a polarizer passing light linearly polarized in a plane 45° from horizontal and in a vertical plane respectively. The Stokes parameters can be calculated from

$$\begin{aligned} I &= i_0 + i_{90} \\ Q &= i_0 - i_{90} \\ U &= (2 \cdot i_{45}) - I \end{aligned} \tag{9}$$

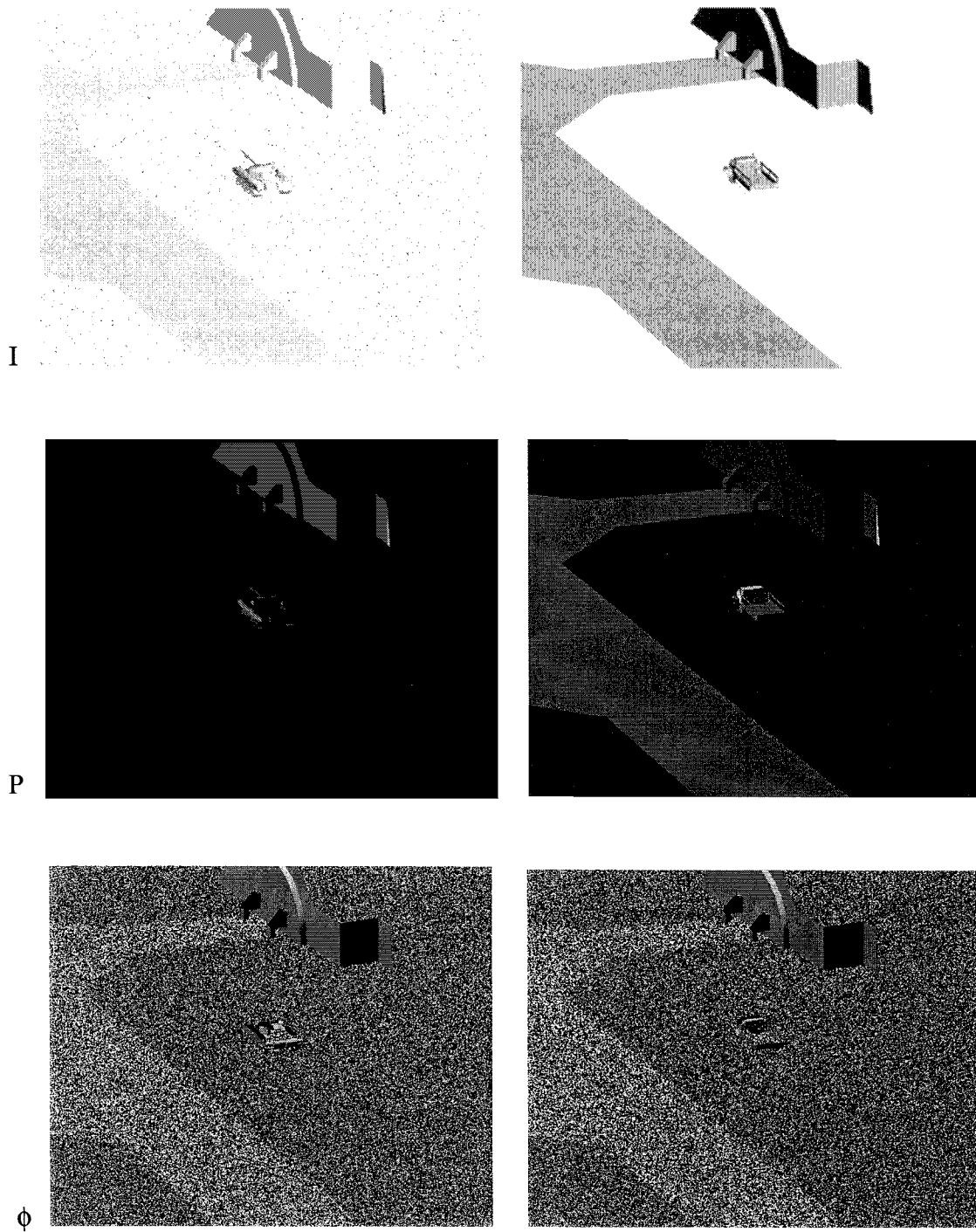


Figure 2. Polarimetric images at range of 1 km. Left, T-72 tank. Right, M-35 truck.

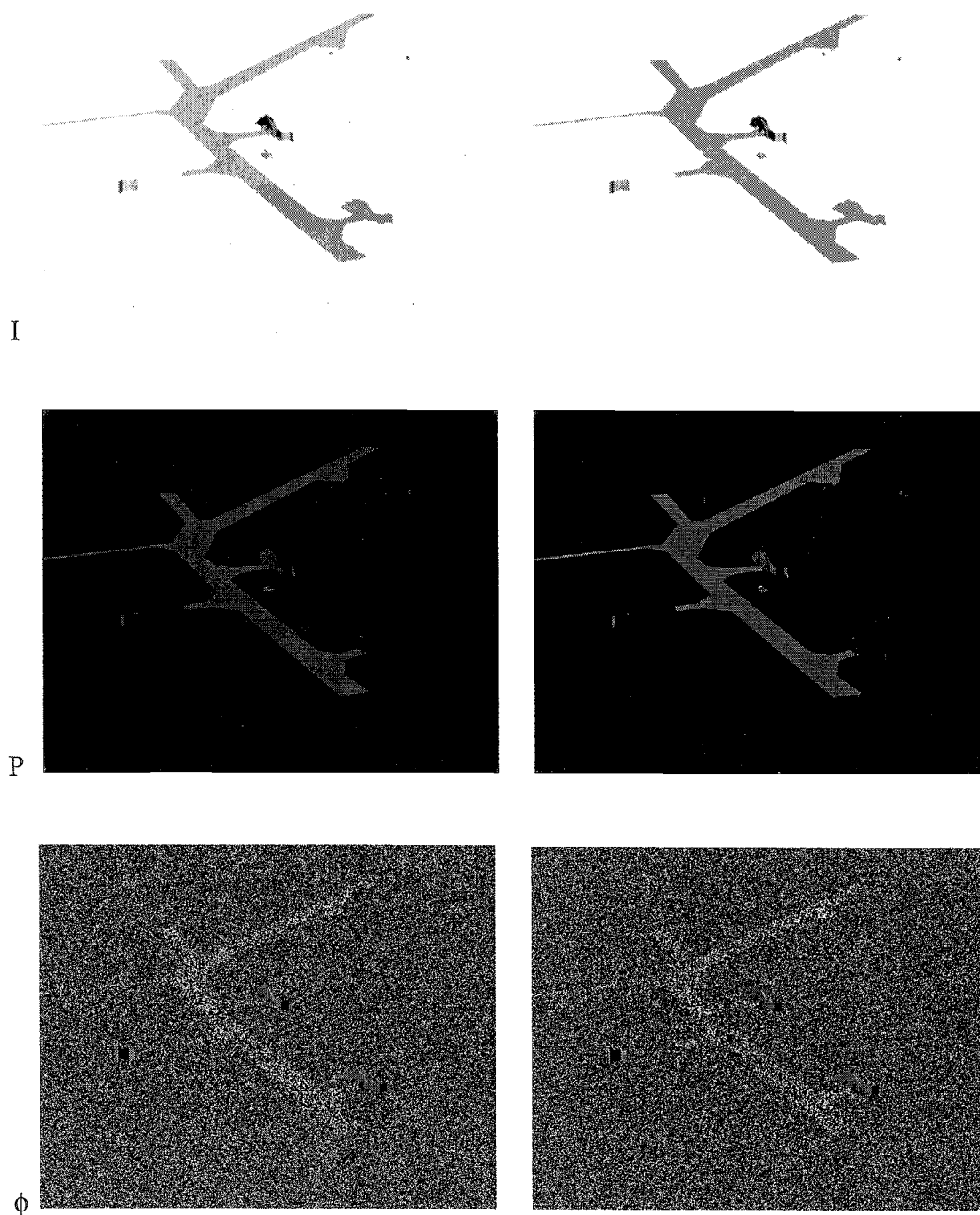


Figure 3. Polarimetric images at range of 5 km. Left, T-72 tank. Right, M-35 truck.

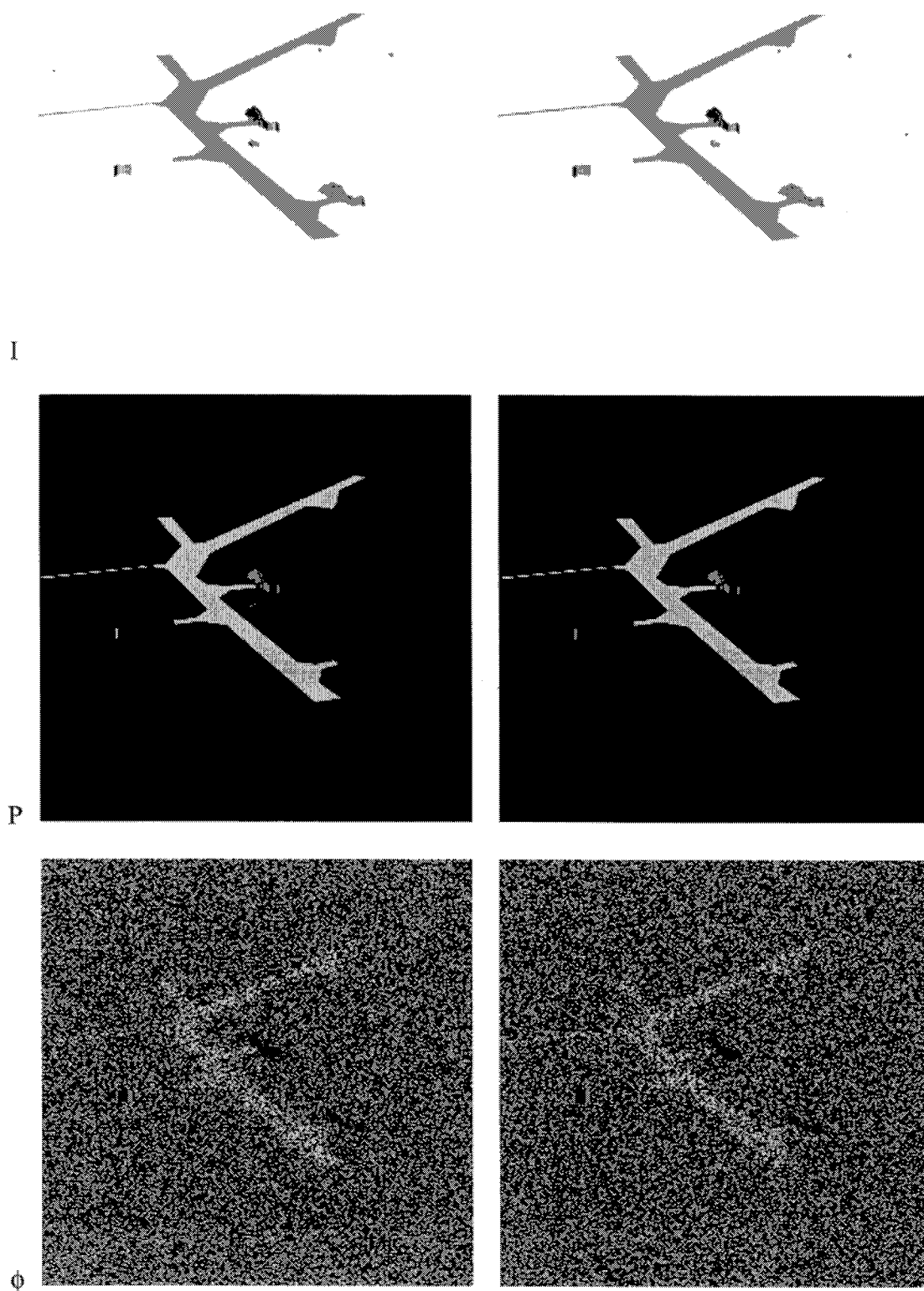


Figure 4. Polarimetric images at range of 12 km. Left, T-72 tank. Right, M-35 truck.

The first three Stokes parameters can be transformed into percent of linear polarization P and angle of polarization ϕ using the Equation (1).

2.2.5 Experiments and Performance Evaluation.

Using the infrared polarimetric imagery generated by IRMA [Figures 2, 3, and 4], a number of experiments were performed and the performance of the target detection approach was evaluated. Statistical measures were obtained on a moving window. The size of the window was varied from 3x3 to 5x5 and 7x7 and was finally set at 3x3 due to the better performance at the 3x3 window size. The inputs were I , P and ϕ images and the input parameters were the statistics of the potential targets. The outputs were in the form of images of the minimum total probabilities of error distances and bounds on these errors. The results of one such bound, namely the Fisher distance is reported in this paper. The pixels associated with the smallest values were declared as those of the target. By systematically changing the threshold values, a Receiver Operating Characteristic (ROC) curve was obtained. The ROC curve displays the performance of the polarimetric-diverse target detection algorithms.

The receiver operating characteristic (ROC) curve displays the probability of correct detection versus probability of false alarm. We use ROC curves to compare the performances of the target detection approach for different targets at different ranges. In this study the other scene parameters were kept unchanged. Figure 5, Figure 6 and Figure 7 show the ROC curves for a T-72 tank and a M-35 truck at the ranges of 1, 5, and 12 km, respectively.

2.2.6 Discussion.

Comparing the ROC plots in Figures 6 and 7 shows that, for otherwise similar conditions, the Target Detector performs very similarly for a T-72 tank and a M-35 truck. For both tank and truck, the ROC curves indicate good performances. Furthermore the curves show that performances improve as range to the targets increases from 1 to 12 km. However, when M-35 is much closer to the observer, at 1 km range, right-hand-side in Figure 5, the ROC behaves differently. There seems to be a semblance of a discrete behavior that needs further investigation. At relatively short distances of 1 km or less, techniques that exploit the detailed orientation, shape and texture information become suitable for target detection/classification.[†]

3. SUMMARY AND CONCLUSIONS

In this paper we reported on the results of a study of the problem of detecting military targets on the ground by means of an autonomous polarimetric sensor onboard a high altitude air or space platform. In such scenarios, the scene imagery is composed of targets that are small, having relatively few pixels and embedded in the background clutter. The role of this system is to act as a target screener, by indicating the potential areas of interest. These detected target regions will be passed for sensing to other higher resolution, multi-spectral sensors for

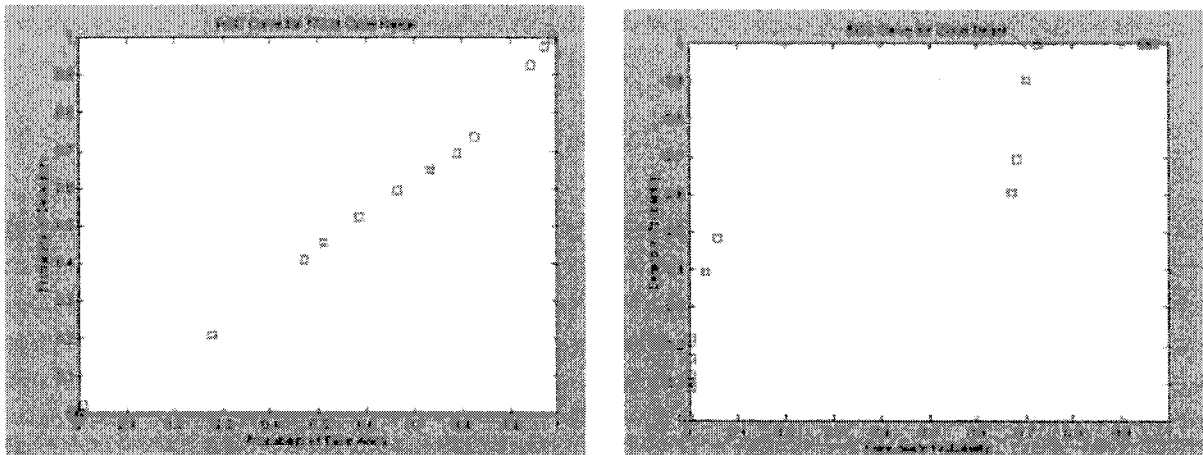


Figure 5. Receiver Operating Characteristic curves for the (left) T-72 tank and (right) M-35 truck at range 1 km.

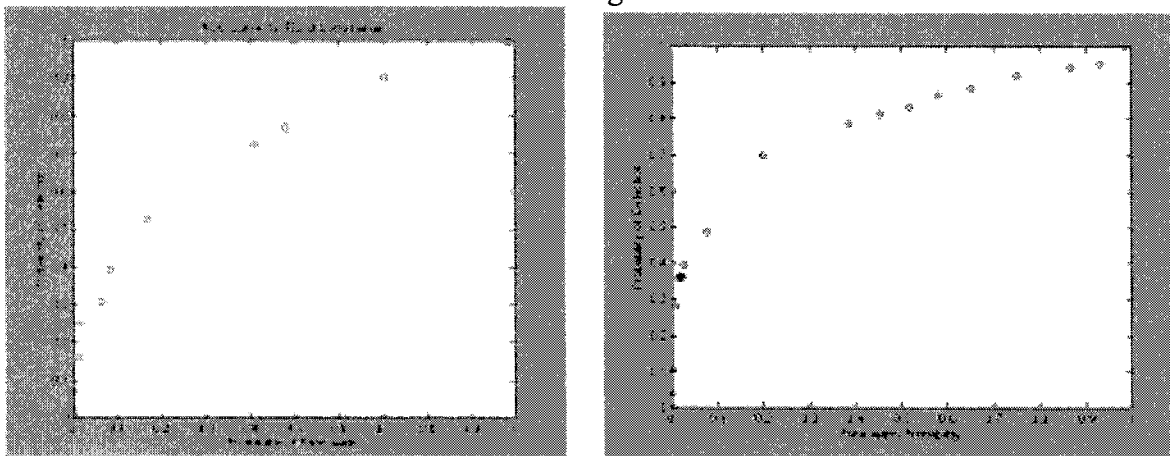


Figure 6. Receiver Operating Characteristic curves for the (left) T-72 tank and (right) M-35 truck at range 5 km

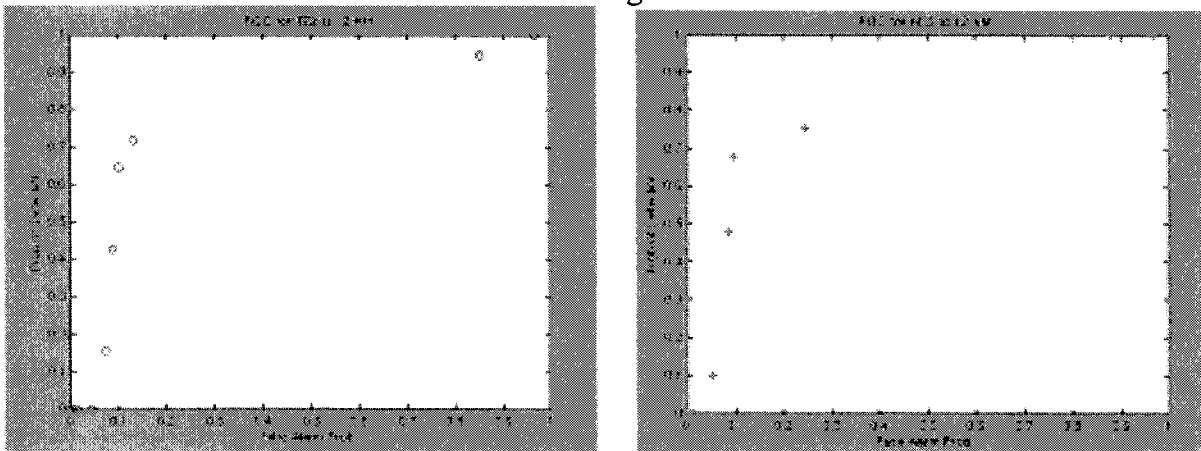


Figure 7. Receiver Operating Characteristic curves for the (left) T-72 tank and (right) M-35 truck at range 12 km.

classification. In this paper, we described:

- A statistical approach, using bounds on the Bayesian total probabilities of errors, for using an array of Stokes vectors to detect the small targets from the background clutter.
- An experimental design for the performance evaluation of the target detection algorithm at ranges of 1 to 12 km, using a set of physics-based synthetically created polarimetric IR imagery of scenes, containing two tactical military targets. The algorithm performances, shown in terms of the ROC curves, indicate that relatively good detection and low false alarm probabilities are achieved even when the number of pixels on targets are as low as 4. Furthermore the results indicate that the algorithm performance actually improves as the distance from sensor to target increases from 1 to 12 km.

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