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The Use of Multiple-Polarization Data in Foliage Penetrating (FOPEN) Synthetic Aperture Radar (SAR) Applications

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The Use of Multiple-Polarization Data in Foliage Penetrating (FOPEN) Synthetic Aperture Radar (SAR) Applications

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Abstract

Foliage penetrating (FOPEN) synthetic aperture radar (SAR) systems are capable of producing images of targets concealed under a foliage canopy. The quality and interpretability of these images, however, is generally limited by dense foliage clutter and by fundamental foliage-induced image degradation. Use of a polarimetric SAR to provide multiple polarization channels can mitigate these effects by offering target and scene information beyond that provided by a single-polarization SAR. This paper presents the results of a literature survey to investigate the use of multiple-polarization data in conjunction with FOPEN SAR applications. The effects of foliage propagation on SAR image quality are briefly summarized. Various approaches to multiple-polarization-based FOPEN target detection are described. Although literature concerning FOPEN target recognition is scarce, the use of multiple-polarization data for in-the-clear target recognition is described. The applicability of various target detection and recognition applications for use with concealed target SAR (CTSAR) imagery is considered.

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Contents

1 Introduction

Synthetic aperture radar (SAR) is widely used in military and civilian applications to produce high-resolution images of remote scenes. In recent years there has been a trend toward development and deployment of higher- and higher-frequency radar systems operating in the X, Ku, and Ka bands, due to the fundamental correspondence between frequency and achievable resolution. At the same time, however, phenomenological limitations of high-frequency radars have led to renewed interest in lower-frequency radars operating in the VHF, UHF, L, and S bands. A primary motivation for operating in these lower bands is the inability of higher-frequency radiation to penetrate foliage. Foliage penetrating (FOPEN) radars operate in these lower-frequency bands to enable detection and imaging of targets concealed under a foliage canopy.

Although FOPEN provides the potential for remote sensing of concealed targets, the practical difficulties inherent in detecting and imaging such targets are significant. In addition to the coarser resolution available in lower frequency bands, the propagation of radiation through a foliage canopy leads to a number of effects not generally encountered when imaging in-the-clear targets. In order to mitigate some of these effects and to provide a greater amount of information about scenes and targets being imaged, a number of FOPEN radar systems utilize multiple transmission and/or reception antenna polarizations. Multiple-polarization radar systems offer the potential for more powerful target-detection algorithms, an important consideration in the dense clutter environment of FOPEN imagery.

This paper provides a summary of the use of multiple-polarization data in FOPEN SAR applications as reported in the literature. Section 2 provides a brief review of basic FOPEN phenomenology and the effects of propagation through foliage, highlighting issues pertinent to the analysis of FOPEN imagery. Most FOPEN SAR applications concern the detection of targets concealed under a foliage canopy; the use of multiple-polarization data for FOPEN target detection is described in Section 3. The use of multiple-polarization data for target recognition is considered in Section 4. Because there is almost no published work specifically concerning FOPEN target recognition, this section provides an overview of the use of multiple-polarization data for in-the-clear SAR target recognition. Section 5 considers the applicability of the approaches described in Sections 3 and 4 for use with imagery collected by the concealed target SAR (CTSAR) system [22]. Section 6 summarizes the paper.

2 Basic FOPEN Phenomenology

FOPEN imaging involves a fundamental trade-off between resolution and foliage-penetration capability: high-resolution imaging demands a high center frequency, but penetration of foliage demands a wavelength long enough to propagate through tree cover. FOPEN radars have typically operated at VHF or UHF. At higher frequencies, propagation through foliage introduces more severe imaging effects.

The effects of propagation through foliage can be broadly separated into four categories: attenuation, backscatter, phase variation and depolarization. These effects can be briefly summarized as follows.

- Attenuation is intrinsic to the propagation of radiation through any medium. Propagation through foliage leads to attenuation of the radar signal in part by absorption and in part by the scattering of transmitted energy away from the target and sensor.
- Backscatter is the reflection of transmitted energy back to the sensor by interactions with single or multiple foliage elements or by interaction between these elements and the ground. Foliage backscatter tends to have a distributed component arising from reflections and interactions between individual leaves and branches; it also has localized, relatively strong components arising from tophat-like ground-bounce returns from individual tree trunks.
- Phase variation is the random variation in signal phase arising from propagation through a distributed, nonuniform medium (i.e., a foliage canopy). Because SAR requires coherent measurements of phase across the viewing aperture, phase variation leads to spatially variant blurring and defocusing of the formed image.
- Depolarization is the random redistribution of return-signal energy across polarization channels. It is attributable to the same factors as phase variation.

These effects vary strongly with frequency, geometry, and polarization. Because FOPEN SAR applications are driven in large part by these effects, the impact of frequency, geometry, and polarization on FOPEN image quality and interpretability is briefly summarized below.

2.1 Frequency

Foliage attenuation increases significantly with frequency [13][36][41]. Two-way HH-polarization signal attenuation reported in [13] for a 30° depression angle increases from 5.5 dB at UHF to 17.0 dB at L band and to 33.6 dB at C band. Foliage backscatter coefficients, on the other hand, vary by no more than 2 dB across these same frequency bands [13]. This demonstrates the primary motivation for the use of lower-frequency transmissions in FOPEN imaging: as frequency increases, target return signals diminish until they are overwhelmed by foliage clutter, and target detection becomes impossible. An additional motivation for lower-frequency operation is the impact of phase variation, which is more marked at higher frequencies [36][42].

2.2 Geometry

Variations in depression angle can have significant effects on FOPEN image quality. In particular, foliage attenuation and phase variation both tend to be more severe at smaller depression angles [13][42]. This is due primarily to the increase in foliage path length as depression angle decreases. Foliage backscattering exhibits the opposite dependence: it is more pronounced at high depression angles [13].

2.3 Polarization

Foliage attenuation exhibits a slight dependence on attenuation. In particular, attenuation tends to be slightly larger for VV polarization than for HH polarization [13][36]. This is especially noticeable at lower frequencies [13], at which attenuation is primarily driven not by leaves and branches, but instead by tree trunks, most of which are vertically oriented.

Foliage backscatter exhibits a more marked dependence on polarization than does attenuation. Reported values for foliage backscatter are generally largest for HH polarization. In a typical scenario [13], HH backscatter exceeds VV backscatter by roughly 2 dB and cross-polarization (HV or VH) backscatter by roughly 7 dB. One reason backscatter is generally more pronounced at HH polarization than at VV polarization is the presence at VV polarization of a Brewster angle—i.e., a depression angle at which V-polarized transmitted energy would theoretically be completely absorbed by a smooth, uniform ground plane [39]. For typical soil compositions this Brewster angle appears to correspond to a depression angle of about 20° [23][31]. Utilization of VV polarization near this depression angle thus offers some benefit in terms of reducing foliage backscatter. This does not necessarily imply an improvement in signal-to-clutter ratio (SCR), however: if ground-bounce returns comprise a significant fraction of the energy reflected by a target, then target signatures will also be reduced in magnitude for VV polarization at this depression angle. Similarly, the weaker backscatter in cross-polarization channels noted above does not necessarily result in a higher SCR at HV and VH polarizations, since cross-polarization returns from manmade targets are also generally weaker than their co-polarization responses.

A polarization-dependent phase variation is reported in [36]. Although exact values are not reported, [36] indicates that phase variation was smallest for VV polarization, slightly more marked for HH polarization, and significantly more pronounced in cross-polarization channels.

3 Approaches to FOPEN Target Detection

Target detection is the processing of imagery to identify objects believed to correspond to some class of interest. In the context of FOPEN SAR, the object class of interest is typically the class of manmade vehicles. The goal of a FOPEN SAR target detector, then, is to process SAR imagery in order to reject clutter and identify regions believed to correspond to manmade objects.

The dense clutter environment of FOPEN images makes target detection challenging. Target detection algorithms designed for in-the-clear, narrow-band, narrow-aperture SAR imagery tend to perform poorly on FOPEN imagery [2][6][30]. This is attributable in large part to the wide aperture over which FOPEN SAR images are generally formed. In wide-aperture SAR images, the magnitude of a tree-trunk return can be similar to that from a manmade target. Simple peak detectors thus tend to have an extremely high false alarm rate when applied to FOPEN images [2][6]. This has led numerous researchers to investigate the use of more sophisticated techniques for single-polarization FOPEN target detection. These approaches include application of aperture-based matched filters or algorithms designed to detect broadside flashes [1][2][3][6][30][33], utilization of wideband spectral information to discriminate targets from clutter [8][23][34], and modifications to standard constant-false-alarm-rate (CFAR) detectors, which typically assume the presence of homogeneous clutter with moderate SCR, to operate in FOPEN clutter environments [4][5][18].

The references cited above all perform FOPEN target detection using single-polarization SAR data. Several authors have investigated the use of multiple-polarization data for FOPEN target detection. One approach is to combine multiple polarization channels to produce a single-channel magnitude image that can then be screened using a single-channel target detection algorithm, such as a peak detector or one of the more sophisticated techniques cited above. The most basic method of combining multiple polarization channels into a single-channel magnitude image is to form a so-called "span" image [15][25][46]. Each span image pixel is taken to be the squared magnitude of the complex polarimetric measurement vector at that pixel. In particular, if the polarimetric measurement vector at pixel *ij* is denoted by $\mathbf{x}_{ij}$, where

$$\mathbf{x}_{ij} = \begin{bmatrix} HH_{ij} & HV_{ij} & VH_{ij} & VV_{ij} \end{bmatrix}', \tag{1}$$

then the span image value at pixel *ij* is simply

$$S_{ij} = \mathbf{x}'_{ij}\mathbf{x}_{ij}. \tag{2}$$

(If only a subset of the four linear polarization channels in (1) is available, a span image can still be formed exactly as in (2).) If target returns are distributed across polarization channels, formation of a span image can boost the SCR above that available from any single polarization channel and can thus facilitate target detection [25][46]. On the other hand, if target returns are largely restricted to a single polarization channel, span-image formation will tend to reduce SCR and will thus have a counterproductive effect.

A more sophisticated approach to combining polarization channels to form a single-channel magnitude image is to exploit the statistical properties of clutter across polarization channels. One method for doing this is the polarimetric whitening filter (PWF) [25][26]. The PWF is designed to minimize an intuitive measure of clutter speckle [25], and tends to suppress bright clutter returns that are often mistaken for targets. Application of the PWF requires that the covariance structure of polarimetric clutter measurements be known in advance or be estimated on the fly. Letting $\mathbf{x}_{ij}$ again denote the polarimetric measurement vector at pixel *ij*, and letting **Q** be the known or estimated polarization-channel covariance matrix for clutter pixels, the PWF forms a single-channel magnitude image by taking

$$PWF_{ij} = \mathbf{x}'_{ij}\mathbf{Q}^{1/2}\mathbf{x}_{ij} \tag{3}$$

at each pixel. (Note that if polarization channels are uncorrelated, **Q** is the identity matrix and the PWF of (3) reduces to the span image of (2).) Use of PWF imagery in place of single-polarization or span imagery generally imparts some performance gain to simple peak-detection or CFAR target-detection algorithms [26]. Because the PWF does not take the polarimetric signatures of targets into consideration, however, it often exhibits undesirable side effects. For instance, use of the PWF can lead to suppression of some types of bright target returns, or to a reduction in SCR [14].

The PWF relies on assumed or calculated statistical clutter properties. In diverse, complex, or poorly understood clutter environments, use of the PWF may be difficult or inappropriate. An alternative approach is to utilize phenomenological or statistical knowledge of the polarimetric properties of targets. Target signatures are often dominated by dihedral-like ground-bounce returns. Dihedrals have characteristic polarimetric signatures: a broadside return from a perfectly conducting dihedral oriented to simulate a ground-bounce vehicle return has a polarimetric signature of the form

$$\mathbf{d}_{ij} \sim \alpha \begin{bmatrix} 1 & 0 & 0 & -1 \end{bmatrix}', \tag{4}$$

where α is a complex scalar. A natural approach to processing imagery to enhance the detectability of dihedral-like target returns in clutter, then, is to form a matched-filter image by projecting $\mathbf{d}_{ij}$ onto the polarization-channel measurement vector of each pixel:

$$MF_{ij} = \mathbf{d}'_{ij} \mathbf{x}_{ij} \, . \tag{5}$$

This approach is the basis for a number of detection algorithms. It is used in [9] and [15] in conjunction with subaperture-based approaches. These efforts demonstrate at least some utility for target detection, although it is not clear that they provide more detection benefit than other investigated approaches [15].

The authors of [19] incorporate features of the PWF and dihedral-matched-filter approaches by augmenting the assumption of a dihedral-like polarimetric target signature as in (4) with a consideration of the statistical polarimetric properties of clutter. They develop a likelihood-ratio test based on clutter and target models. This test enables a target/clutter decision to be made at each pixel. The authors demonstrate the performance of their detector on in-the-clear SAR imagery of camouflaged and uncamouflaged targets. Their detector is shown to outperform a PWF-based detector. A similar approach is used, and similar results are obtained, in [10]. Although the approaches of [10] and [19] were developed and demonstrated in the context of in-the-clear SAR, the basic concept and means of implementation are also applicable to FOPEN SAR.

The polarimetric detection approaches described above all utilize derived statistical or phenomenological clutter or target models for target detection. In many cases such models may be unavailable or unreliable. An alternative to using derived statistical or phenomenological models for target detection is to use empirical polarization-based features for detection. Appropriately chosen empirical features potentially offer greater robustness to variations in clutter and target structure than those based on explicit statistical or phenomenological models. Two empirical-feature-based approaches to FOPEN target detection using empirical features are outlined in [21] and [17]. The authors of [21] suggest a target detector based on the ratios of the returns in different polarization channels. Unfortunately, only anecdotal evidence is presented for the utility of these features. The authors of [17] suggest using correlations of co- and cross-polarization returns across adjacent subapertures as detection features. The authors demonstrate that these features are relatively separable between target and clutter classes.

4 Approaches to FOPEN Target Recognition

Literature addressing target recognition (i.e., classification of targets subsequent to their detection) in the specific context of FOPEN is almost nonexistent. This is due to several factors. First of all, classification of targets into distinct classes generally requires fine-resolution imagery. FOPEN SAR resolution is coarse compared to that provided by typical in-the-clear SAR systems, which have been the subject of most SAR target recognition research. Second, significant signature variability imparted by propagation through foliage presents fundamental difficulties not generally encountered in conjunction with in-the-clear target recognition. Finally, the inherent difficulties of FOPEN target detection tend to steer emphasis away from FOPEN target recognition, since a reliable target detection algorithm is a prerequisite for useful target recognition. These factors present significant impediments to FOPEN target recognition. The fundamental physical and phenomenological limitations of FOPEN image resolution and quality, coupled with a relative lack of investigation, make it unclear whether FOPEN target recognition is even a tractable problem.

A literature search turned up only one reference [32] devoted entirely to FOPEN target recognition. The authors of [32] use principal component analysis to develop templates for classification of detected targets. They consider various methods of incorporating polarimetric information to aid target classification. Unfortunately, none of the considered approaches leads to a clear benefit in the ability to distinguish between target classes. This most likely represents a shortcoming in the fundamental classification approach of [32] rather than an absence of classification benefit in polarimetric data.

The use of multiple-polarization data to aid target recognition has been investigated more extensively in the context of in-the-clear SAR imaging applications. The authors of [27] and [28] describe an automatic target recognition (ATR) algorithm that utilizes polarization-based features for classification. The algorithm described in [27] and [28] has three stages: targets are first detected in a PWF image; numerous empirical and phenomenological features, including several polarization-based features, are used for preliminary classification; final classification is then performed using a template-based minimum-mean-squared-error approach. It is demonstrated in [28] that this ATR has performance superior to that of a similar single-channel HH-polarization ATR. While the approach of [27] and [28] is designed for in-the-clear SAR imagery, it is also applicable, at least in theory, to FOPEN SAR imagery, although the fundamental limitations of FOPEN image quality and signature stability described above would certainly have a detrimental effect on its suitability and performance.

The authors of [11][29][35][40] also consider the use of polarization-based features for SAR ATR. They propose using phenomenology-based polarimetric features that represent classifications of bright target pixels or scattering centers into one of a number of canonical reflector types. For instance, the authors of [11] and [29] use full-linear polarization data to classify target pixels as dihedrals, trihedrals, cylinders, dipoles, and other canonical reflector types. Their ability to extract these features robustly suggests that such features would be useful in a fielded target recognition system. As with the previously considered approach, however, the fundamental characteristics of FOPEN SAR imagery would have a negative impact on the suitability and performance of this approach.

A topic related to target recognition is terrain classification, or the segmentation of SAR imagery into distinct regions representing specific classes of terrain and vegetation type. The use of polarimetric information for SAR terrain classification is widespread [7][12][43][44][45]. Typical approaches to terrain classification utilize classification features related to the statistical properties of the polarimetric measurement vectors associated with different terrain or vegetation types. For instance, the authors of [7] employ features related to the coherency and entropy of the polarization measurements over localized scene regions. They demonstrate the utility of their approach on several different data sets, including one collected at L band. The approach of [7] is used in [38] to classify scattering centers on a manmade target. A related technique is used in [20] for the same purpose.

5 Implications for CTSAR

The preliminary CTSAR system [22], as flown in October 2001, had two fundamental operational peculiarities that distinguished it from other multiple-polarization FOPEN systems. First of all, the preliminary CTSAR system, like the current CTSAR system, was an L/S band system. As previously noted, most FOPEN radars have been designed to operate at lower frequencies, typically at VHF or UHF. Second, the preliminary CTSAR system provided only dual-polarization data—that is, for a given imaging scenario, it was able to provide either HH and HV data channels or VV and VH data channels, but not a full set of linear polarization channels.

Since its flight in 2001, CTSAR has been transitioned to a full-polarization system, still operating at L/S band. The operation of CTSAR at L/S band and the transition from dual-polarization to full-polarization measurement capability both have important implications for the applicability of the target detection and recognition approaches described in previous sections. These implications are discussed in the following sections.

5.1 Implications of L/S Band Operation

L/S band operation of CTSAR is motivated by the desire for a finer resolution than that provided by existing FOPEN systems. This higher resolution comes at the price of a reduced ability to penetrate foliage. As described in Section 2.1, foliage attenuation increases at higher frequencies, while foliage backscatter remains relatively stable.

CTSAR thus essentially trades SCR for resolution. FOPEN target detection algorithms designed for use with VHF/UHF SAR data might prove inapplicable or ineffective for CTSAR, since low-frequency target detection algorithms are generally designed to detect targets that appear as a small number of bright pixels. On the other hand, increased resolution could aid in the discrimination between targets and clutter elements such as tree trunks, which are smaller than targets of interest. Such discrimination has generally been a problem in lower-frequency FOPEN systems.

A benefit of increased resolution is the increased potential for development of a successful ATR. Target recognition is fundamentally intractable for coarse-resolution imagery. As previously described, however, the development of a useful FOPEN ATR system would require robustness to the significant signature variability that is the hallmark of FOPEN imaging. Most existing ATRs have generally not demonstrated good robustness characteristics. Development of robust ATR algorithms even for in-the-clear SAR operation is a difficult and ongoing research topic [37].

5.2 Implications of Transition from Dual-Polarization Operation

As previously noted, the preliminary CTSAR system provided only a dual-polarization measurement capability. Although a dual-polarization measurement capability provides value beyond that offered by a single-polarization system, it also imposes restrictive limitations on the application of the multiple-polarization techniques described in Sections 3 and 4. Fortunately, CTSAR has been transitioned to a full-polarization system that will be tested in the summer of 2002. The following analysis makes it clear that this is a significant improvement.

Without full-polarization imagery, most of the target detection approaches described in Section 3 would be non-beneficial. For instance, formation of the single-channel span and PWF images as described in Section 3 is still possible with dual-polarization data, but there are indications that the utility of these techniques would be greatly diminished without the availability of a full complement of polarimetric measurements [14][25]. In other words, dual-polarization span- or PWF-image-based target detection would likely show little, if any, benefit compared to single-channel detection. Similarly, although the dihedral-matched-filter approaches discussed in Section 3 could be modified to operate on dual-polarization HH/HV or VV/VH imagery, they would be much less effective due to the concentration of the canonical dihedral signal energy in the HH and VV channels (see (4)). With the transitioning of CTSAR to a full-polarization system, however, all of the detection approaches of Section 3 are applicable as designed.

Full-polarization measurements also provide a greater potential benefit to target recognition applications than would be provided by a dual-polarization system. Most of the target recognition techniques described in Section 4 would be inapplicable given only dual-polarization data. Use of the polarization-based features employed in [27] and [28], for example, requires the availability of full-polarization measurements. Similarly, the phenomenological scattering-center classification approaches of [11][29][35][40] require full-linear polarimetric data, since the absence of the HH or VV channel makes classification between canonical scattering-center types largely infeasible [16].

In short, transitioning CTSAR from a dual-polarization system to a full-polarization system adds a great deal of value to the overall system—much more than is added in the transition from a single-polarization system to a dual-polarization system. Effective exploitation of polarimetric information simply requires the availability of a full set of polarization channels. The transitioned full-polarization CTSAR system provides this capability.

6 Summary

FOPEN SAR imaging is characterized by much more severe clutter environments and image degradation than typically encountered for in-the-clear SAR imaging. These fundamental FOPEN imaging limitations greatly complicate the development of FOPEN target detection and recognition algorithms. Multiple-polarization SAR offers the potential to mitigate these effects, at least in part, by providing more information about the scenes and targets being imaged.

Several authors have investigated the use of multiple-polarization data to enhance target detection. Several approaches combine the available polarization channels in order to reduce the effects of clutter, aiming to increase SCR or to decrease clutter speckle. Other approaches rely explicitly on an assumed target polarimetric signature structure to enhance target returns in a clutter environment. The success of these approaches demonstrates that the availability of multiple-polarization data can benefit FOPEN target detection.

Unlike FOPEN target detection, FOPEN target recognition has received very little attention, due to the extreme signature variability imparted by penetration of a foliage canopy and the generally coarse resolution of FOPEN imagery. In the context of in-the-clear SAR imaging, however, the use of multiple-polarization data has been investigated, and appears to offer some benefit over single-polarization data. It remains to be seen whether this benefit makes it easier to surmount the fundamental impediments facing FOPEN target recognition.

The operating conditions of the CTSAR system impact the applicability of published approaches to utilizing multiple-polarization data. The relatively high-frequency operation of CTSAR, compared to other FOPEN systems, provides improved imaging resolution at the expense of poorer foliage-penetration capability and greater foliage-induced signature variability. The preliminary CTSAR system flown in October 2001 provided dual-polarization measurements. This provided value beyond that offered by a single-polarization system, but was a significant limitation compared to the capabilities of a full-polarization system. Fortunately, the transition of CTSAR to a full-polarization system enables effective use of polarization information.

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