Abstract

Recent developments in target decomposition theorems indicates that the polarimetric signature of a target describes scattering mechanisms, such as depolarization, even bounce, or odd bounce, that may assist in the differentiation of a man-made targets from natural clutter, a critical first step in Automatic Target Recognition (ATR). Cloude’s alpha-entropy decomposition of the coherency matrix, similar to Mueller matrix, was developed to classify natural terrain, but contains features which should make it useful for ATR. The alpha-entropy decomposition finds the entropy, a parameter describing the uniformity or purity of the scattering mechanisms, and alpha, a parameter which measures the average strength of the odd-bounce mechanism over the others. This decomposition into its scattering mechanisms does not use the absolute magnitude of the scattering from the target. Therefore, it is expected to provide information about the target which is completely independent from all ATR algorithms which are based on a single polarization RCS alone.

The alpha-entropy decomposition is applied to measurements of hard targets in clutter, and to the clutter alone. These measurements are made
with the University of Michigan’s Coherent-on-Receive MMW polarimeters. Operating at 35 and 94 GHz, over a 1 GHz bandwidth each, these polarimeters are capable of measuring the scattering matrix by synthesizing any transmitted polarization state and by coherently measuring both $v$ and $h$ received polarizations simultaneously.

1 Introduction

Various techniques for Automatic Target Recognition (ATR) with radar exist which employ power thresholds and pattern recognition (for high resolution systems). Radar polarimetry holds great promise for ATR because the subresolution physical structure of a scene, be it a target or clutter, gives rise to a particular polarimetric signature, but to date polarimetry has been used primarily to reduce fading via pre-whitening of radar images.

Recently, Cloude and Pottier [1] introduced a new polarimetric analysis technique which they used for classification of land uses. This technique may also be applied to the problem of distinguishing man-made objects from natural terrain because it is based on identifying the most disparate scattering mechanisms, and their relative strengths, of the object under observation. These scattering mechanisms are highly dependent on the wavelength-scale geometry of the scatterers.

In this paper, this polarimetric analysis is applied to millimeterwave measurements of clutter alone and with some targets within clutter at 35 and 95 GHz for the purpose of evaluating this technique for its usefulness in ATR.

2 Entropy-Based Polarimetric Analysis

Polarimetric radars operate by sequentially transmitting two orthogonal polarization states, such as vertical and horizontal, and measuring the received backscatter at two orthogonal polarization states, usually the same as those used for transmit, either sequentially or simultaneously. In addition to measuring the backscattering amplitude at these four combinations of transmit and receive polarization states, a polarimetric radar measures the three relative phase differences between these polarization states. Mathematically, the scattering process can be described by a complex $2 \times 2$ scattering matrix:

$$
\begin{bmatrix}
E_v^s \\
E_h^s
\end{bmatrix} = \frac{e^{-jkr}}{r} \begin{bmatrix}
S_{vv} & S_{vh} \\
S_{hv} & S_{hh}
\end{bmatrix} \begin{bmatrix}
E_v^i \\
E_h^i
\end{bmatrix}
$$

(1)
where $E_{v(h)}^i$ is the vertical (horizontal) component of the transmitted electric field and $E_{v(h)}^s$ is the vertical (horizontal) component of the electric field scattered by the target at a distance $r$ from the target or clutter. The wavenumber is given by $k = 2\pi/\lambda$. For backscattering, $r$ is usually taken as the range from the radar to the scatterer, and thus $E^s$ is the received field. Also, the reciprocity theorem [2] adds an additional constraint on the magnitude and phase of the two cross polarized components for backscatter: $S_{vh} = S_{hv}$, so that the scattering matrix contains three independent complex elements. The Radar Cross Section (RCS) can be described in terms of the scattering matrix elements as

$$\sigma_{pq} = 4\pi|S_{pq}|^2$$

where $p, q = v$ or $h$.

While this presentation is given in terms of horizontal and vertical polarizations, it is general in the sense that other polarization states, such as left and right circular, can be synthesized from it [3].

The average properties of the scattering matrix are of more interest in polarimetric analysis than the elements of the scattering matrix themselves. To this end, a $3 \times 3$ coherency matrix $T$ is constructed from the ensemble average of products of the scattering matrix:

$$T = \left\langle \begin{array}{ccc}
(S_{hh} + S_{vv}) & (S_{hh} + S_{vv})^* & (S_{hh} - S_{vv})^* \\
(S_{hh} - S_{vv}) & (S_{hh} + S_{vv}) & (S_{hh} - S_{vv})^* \\
2S_{vh}^* & 2S_{vh} & 2S_{vh}^*
\end{array} \right\rangle$$

The brackets indicate the matrix is composed of the ensemble average of its elements, and $x^*$ indicates the complex conjugate of $x$. The coherency matrix is very similar to the Mueller matrix except that it is $3 \times 3$ to reflect the fact that there are only 3 independent elements of the scattering matrix. For bistatic scattering, a $4 \times 4$ coherency matrix has been employed [4].

The coherency matrix can be decomposed into its eigenvalues and eigenvectors:

$$T = U \begin{bmatrix}
\lambda_1 & 0 & 0 \\
0 & \lambda_2 & 0 \\
0 & 0 & \lambda_3
\end{bmatrix} U^T$$

where the superscript $T$ indicates matrix transpose, $\lambda_i$ are the eigenvalues of $T$ and $U$ is the matrix composed of three eigenvectors of $T$ normalized to the following...
Because the coherency matrix is Hermitian, the eigenvalues are real; moreover, they are nonnegative. One interpretation of this decomposition is that the target under observation is randomly composed of one of three scattering matrices, each of the form

$$U = \begin{bmatrix}
\cos \alpha_1 & \cos \alpha_2 & \cos \alpha_3 \\
\sin \alpha_1 \cos \beta_1 e^{j \delta_1} & \sin \alpha_2 \cos \beta_2 e^{j \delta_2} & \sin \alpha_3 \cos \beta_3 e^{j \delta_3} \\
\sin \alpha_1 \sin \beta_1 e^{j \gamma_1} & \sin \alpha_2 \sin \beta_2 e^{j \gamma_2} & \sin \alpha_3 \sin \beta_3 e^{j \gamma_3}
\end{bmatrix}$$ \hspace{1cm} (5)

The matrix absolute phase $\phi$ is arbitrary; the coherency matrix does not preserve the absolute phase of the scattering matrix. The level of disorder in the target can then be measured by calculating the entropy:

$$H = \sum_{i=1}^{3} -P_i \log_3 P_i$$ \hspace{1cm} (7)

The entropy has a range of zero, for no disorder, to one, for polarimetric scattering that behaves like a noise source.

The decomposition of the coherency matrix has a specific interpretation. The value of $\cos \alpha_i$ represents the relative strength of odd-bounce scatterers (scattering from such objects as spheres or trihedrals) over even-bounce scatterers (such as a dihedral). Moreover, the value of $\beta_i$ can have a physical interpretation as the half-angle of the orientation of the dihedral-like scattering mechanisms.

The overall strength of odd-bounce mechanisms are quantified by a term $\alpha$ using the probability of each mechanism:

$$\alpha = P_1 \alpha_1 + P_2 \alpha_2 + P_3 \alpha_3$$ \hspace{1cm} (8)

Similar expressions give mean values for $\beta$, $\gamma$ and $\delta$.

In Fig. 1, the curves outline the valid region of alpha–entropy space. Surface scattering tends to have a low alpha value and generally falls in the lower left hand corner of the plot; scattering from a cloud of dipoles occurs near $\alpha = 45^\circ$; dihedral and multiple scattering lies near the top of the plot.

This analysis does not use the overall magnitude of the scattering; thus it is expected to yield insights into the scattering mechanisms useful to ATR which are independent of the strength the scatterer.
Figure 1: Entropy-Alpha space. The valid range of $\alpha$ depends on the value of the entropy $H$; non-physical regions of the $H - \alpha$ plane are marked. Low values of $\alpha$ indicate single scattering, like surface scatter. Dipole scattering occurs near $\alpha = 45^\circ$ and dihedral scattering occurs near $\alpha = 90^\circ$. The regions within the valid $H - \alpha$ plane are those used by Cloude and Pottier for land use classification.
Figure 2: Setup for the indoor polarimetric measurements. The target in this instance is a sphere suspended above a manufactured rough surface which can rotate to provide independent samples. The radar is in the background.

3 Measurement Description

An indoor and outdoor set of MMW measurements were conducted at the University of Michigan using their 35 GHz and 95 GHz scatterometers. The object of both sets was to explore the polarimetric characteristics of man-made targets in the presence of distributed clutter. The outdoor set used a motorcycle as the man-made target and the edge of a wood as the clutter; the indoor set used a manufactured rough surface as the clutter and spheres and trihedrals were used as the man-made target. The manufactured rough surface had a Gaussian height distribution with rms height of 1.03 mm and a Gaussian correlation function with correlation length of 5.16 mm. In both sets, clutter was also measured in the absence of any man-made target.

For the indoor set, the man-made target was suspended a few centimeters above the spot where the radar boresight intercepted the surface. The angle of incidence of the radar was set to $70^\circ$. To obtain independent samples, the surface was mounted on a turntable and was rotated $1^\circ$ per sample. The target did not rotate with the surface. The configuration is shown in Fig. 2.
Figure 3: Entropy-alpha values for a set of man-made targets over a rough surface. The circles indicate spheres, the triangles trihedrals, and the boxes are for the surface alone without a suspended man-made target.
Figure 3 displays the entropy and alpha values for a number of man-made targets suspended over the rough surface. The surface at this frequency is moderately rough, and as a result it has rather high entropy. But as a surface, it also has a rather low $\alpha$ value. The large sphere has a very large double bounce mechanism involving the surface of the sphere and the rough surface, and as such its $\alpha$ value is considerably higher. The small sphere, however, does not interact as much with the surface, and therefore its constant scattering matrix over the ensemble average serves to reduce the entropy and $\alpha$ of the scene over that from the rough surface alone. The large trihedral was placed with its boresight facing downward toward the surface. Its edges, which appear as dipoles, and interactions with the surface serve to increase the $\alpha$ value over that of the surface alone. The smaller trihedral was oriented so that its boresight pointed back to the radar. The fact that its $\alpha$ value is near the lower limit of valid values indicates that single scattering is indeed dominating this scene. The large entropy, however, is not easily explained in terms of the designed experiment. Its mount, as for all the man-made targets, was not entirely rigid, and the high entropy may be a result of small motions of the target between samples. Each of these datapoints were created by averaging over 360 samples, each at a different turntable position.

As a first attempt at discovering if this analysis indeed distinguishes between targets, a repeat measurement was made of the surface alone and of the small sphere over the surface. This is why there are two marks for these two targets in Fig. 3. While it appears that the measurements are repeatable, these results are not conclusive. A 35 GHz experiment with the 3 inch diameter sphere over the rough surface was made in an attempt to quantify the expected variance in $\alpha$ and $H$. In this experiment, the turntable was rotated only $\frac{1}{4}$ per sample, and different numbers of non-adjacent samples were averaged together to observe the convergence of $\alpha$ and $H$. From the results of this experiment, some of which is shown in Fig. 4, one can conclude that at 64 samples, the standard deviation of the entropy is 0.03 and the standard deviation of $\alpha$ is 1°. In Fig. 4, some basic properties of the convergence of $H$ are evident. For only one sample, the entropy is always zero; for only two samples, the entropy never exceeds $\log_3 2 = 0.631$. This is because for one sample, two eigenvalues of the coherency matrix must be zero, while for only two samples at least one of the eigenvalues must still be zero. For greater number of samples, the values are roughly centered on the correct value of $\alpha$ and $H$, and have decreasing variance as the number of samples increases.

This averaging is very similar to the process by which fading is reduced, except that for fading reduction averaging in frequency is equivalent to averaging
Figure 4: Convergence of Entropy-alpha values for different number of samples in the average. The target is a 3 inch diameter sphere over a manufactured rough surface. The frequency of the measurement is 35 GHz.
spatially [5]. It appears that this is not so with respect to this polarimetric analysis, as frequency averaging within a single look has not resulted in a convergence to single set of alpha-entropy values. For a single look, even if two frequencies are decorrelated from each other with respect to fading, the scattering mechanisms are still the same. Thus, averaging over frequency to determine $\alpha$ or $H$ will not work, since the next look will have sufficiently different scattering mechanisms as to appear as a different target class.

A set of outdoor measurements were conducted at 95 GHz to determine if this polarimetric analysis could discern a complicated man-made target (a Yamaha DT175 motorcycle) from strongly backscattering clutter (the edge of a wood), as shown in the photograph in Fig. 5. An example of a time domain radar trace is shown in Fig. 6. The radar cross section of the motorcycle and the trees were comparable for all polarizations. Yet an alpha-entropy analysis yields a clear separation between the presence and absence of the bike in the clutter, mostly in the $\alpha$-direction, as shown in Fig. 7.

Figure 5: A motorcycle against strongly backscattering clutter.
Figure 6: Typical time-domain trace of the motorcycle at the edge of the wood. Note that the bike is not clearly distinguishable from the trees in either amplitude or range.
Figure 7: Alpha–entropy values for an edge of a wood and for a motorcycle at the edge of the wood. The number of spatial samples for each average are shown. The different dots represent different frequency points in the radar bandwidth of 1 GHz. The separation is complete.
4 Conclusions

Several man-made objects have been measured in the presence of clutter at millimeter wavelengths for the purpose of evaluating alpha–entropy polarimetric analysis as a possible basis for an ATR algorithm. The convergence properties of the alpha–entropy analysis were explored, by averaging in both space and frequency. While frequency averaging can be valuable to reduce fading, it is not useful in this polarimetric analysis because the scattering mechanisms that give rise to the polarimetric signature do not change within one look over small frequency changes. For spatial averaging, it was experimentally determined that a sample size of 64 yields a standard deviation of $1^\circ$ in $\alpha$ and 0.03 in entropy. A motorcycle situated at an edge of a wood was measured to determine if its presence could be distinguished from the edge of the wood alone. While it was difficult to determine the presence or absence of the motorcycle by looking at the radar cross sections, the motorcycle’s presence was distinct from the trees alone when plotted in the alpha–entropy plane.

References


