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In conventional radar signal and image processing, the background clutter and noise are assumed to follow the Gaussian model. Under this assumption, it has been shown that the conventional matched filter is optimal in target detection (reference 1). However, recent research has found that many nonhomogeneous types of clutter and noise, such as sea clutter, do not fit the Gaussian model well because of impulsive outliers or the so called "sea spike" (references 2 through 4). These types of clutter and noise lend themselves to a heavy tail in amplitude distribution; consequently, the conventional matched filter does not perform well. Most recent research has shown that the α-stable model is a better model. The α-stable model is a natural extension of the Gaussian model, and most radar clutter is modeled well by the α-stable statistics. A robust family of α-stable matched filters is a natural extension of the conventional matched filter (references 5 and 6). An optimal α-stable matched filter extracted from that family is being developed in a simple closed form (reference 7). This optimal α-stable matched filter significantly improves target detection in both real clutter data and simulated data. Moreover, the α-stable matched filter is computationally efficient. It can be applied in wide varieties of radar signal and image processing.

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RADAR SIGNAL/IMAGE PROCESSING ENHANCEMENTS USING ALPHA-STABLE TECHNIQUES

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ABSTRACT

In conventional radar signal and image processing, the background clutter and noise are assumed to follow the Gaussian model. Under this assumption, it has been shown that the conventional matched filter is optimal in target detection (Reference 1). However, recent research has found that many nonhomogeneous types of clutter and noise, such as sea clutter, do not fit the Gaussian model well because of impulsive outliers or the so called "sea spike" (References 2 through 4). These types of clutter and noise lend themselves to a heavy tail in amplitude distribution; consequently, the conventional matched filter does not perform well. Most recent research has shown that the α-stable model is a better model. The α-stable model is a natural extension of the Gaussian model, and most radar clutter is modeled well by the α-stable statistics. A robust family of α-stable matched filters is a natural extension of the conventional matched filter (References 5 and 6). An optimal α-stable matched filter extracted from that family is being developed in a simple closed form (Reference 7). This optimal α-stable matched filter significantly improves target detection in both real clutter data and simulated data. Moreover, the α-stable matched filter is computationally efficient. It can be applied in wide varieties of radar signal and image processing.

BACKGROUND

The symmetric α–stable model has three parameters (Reference 8): the location parameter δ to specify the point of symmetry, the dispersion parameter γ to specify the spread of data around δ, and the characteristic exponent parameter α ($0 < \alpha \leq 2$) to specify the heaviness of the tail. As a special case, when $\alpha = 2$ the α-stable model is Gaussian. Properties of the Gaussian model, such as bell shape, symmetry, and Central Limit Theorem, carry naturally to the symmetric α-stable model. Thus, the α-stable model is a natural extension of the Gaussian model and stands out from the Gaussian model by providing a unique parameter α that characterizes the heaviness of the tail of the clutter. Reference 5 shows that the real sea clutter called "HPC" (with radar look-down angle of 8 degrees and sea state of 3) obtained from the Naval Surface Warfare Center fits on the α-stable model better than on the Gaussian model, the K-distribution, and the Weibull distribution. The α-stable model is also shown in Reference 5 to fit four other types of real radar clutter data well.

Let u(t) be the radar transmit waveform and x(t) be the received signal. Then the conventional matched filter is expressed as

$$u^*(-t) \otimes x(t) \tag{1}$$

and the α-stable matched filter (Reference 6) is expressed as

$$u^*(-t) \otimes \frac{x(t)}{|x(t)|^{2-p}} \tag{2}$$

where

$\otimes$ = convolution operation
* = complex conjugate
$0 < p \le \alpha$

Note that the α-stable matched filter is actually a family of filters with parameter p, lending itself to the robustness in filter optimization. The α-stable matched filter distinguishes itself from the conventional one by multiplying a suppression factor $1/\,|x(t)|^{2-p}$ to the received signal for the purpose of suppressing the "spiky" clutter. For a Gaussian clutter ($\alpha = 2$), the optimal matched filter is the one with $p = 2$ in Equation 2. For a spikier clutter ($\alpha < 2$) the p corresponding to the optimal α-stable matched filter in Equation 2 should be reduced accordingly to achieve the goal of suppressing the spikier clutter. Thus, the α–stable matched filter is a natural extension of the conventional matched filter, with a parameter p as an extra dimension for detection optimization. The problem is to determine what value of p yields the optimal matched filter.

DISCUSSIONS

The following four tasks are accomplished under this research.

1. Exploration of the α-stable model. Under this task the characteristics of the α-stable model will be studied. Various methods of estimating the α-stable parameters will be evaluated and compared. Finally, real clutter data will be used to fit the α-stable model, and comparisons will be made to the data fit of Gaussian model, K-distribution, and Weibull distribution.

2. Development of an optimal α-stable matched filter. As demonstrated in Reference 6, with a proper selection of p, the α-stable matched filter as shown in Equation 2 does improve target detection capability. Subtle questions include: "What value of p would result in optimal α-stable matched filter?" and "Is the optimal p solely a function of the parameters (α, δ, and γ) of the α-stable model?"

Time and frequency ambiguity function (TFAF) is commonly used to detect targets in motion. If the clutter is non-Gaussian, one can expect that the conventional TFAF would not perform well. Formulating TFAF with the α-stable techniques and testing it with real data will be another important research topic under this task.

3. Enhancement of synthetic aperture radar (SAR) imagery and improvement of SAR capabilities of autofocussing, foliage penetration (FOPEN), ground penetration (GPEN), and ground moving target indication (GMTI) with α-stable techniques. SAR provides a 2-dimensional image, of which the axes are commonly referred to as the range and the azimuth. To form a SAR image, two basic processing steps are needed: range compression and azimuth compression. Each compression is processed using an appropriate matched filter. If the clutter of the image is spiky and fits a particular α-stable model well, then instead of using the conventional matched filter, one can expect that the use of an appropriate α-stable matched filter for either or both range and azimuth compression would result in clutter suppression and hence improve target detection.

The capabilities of autofocussing, FOPEN, GPEN, and GMTI are very important in the littoral surveillance mission. Again, one can expect that under a non-Gaussian clutter environment the conventional method will not perform well. Employing the α-stable techniques in the algorithms to enhance these capabilities is another research topic under this task.

4. Demonstration of the superiority of α-stable technology over the conventional method using real data. NP-3 SAR data were used in Reference 6 to show that the α-stable matched filter performs much better than the conventional one in a radar with a linear frequency module (LFM) waveform. Reference 6 also showed that the α-stable range compression filter outperforms the conventional one in clutter suppression and target detection.

Under this task, Navy platforms will be selected. The signal and image processing requirements of the selected Navy platforms will be investigated, and the processing algorithms will be studied. The corresponding algorithms using α-stable technique will be developed, and real data will be obtained. Finally, the α-stable techniques will be tested and demonstrated using the real data.

RESULTS

The family of α-stable matched filters is defined in Equation 2 with parameter p. Note that if a clutter is well modeled by the α-stable statistics, it will be characterized by the three parameters α , γ, and δ, and hence the optimal matched filter p is a function of these three parameters. As shown in Reference 7, if radar clutter fits the α-stable model, the optimal α-stable matched filter is solely a function of the parameter α, i.e., $Po = f(\alpha)$, where Po is the p in Equation 2 corresponding to the optimal matched filter. One simple form of such function is developed as

$$Po = f(\alpha) = 1.125 + 0.875 * (1 - (1 - 2 * (\alpha - 1.5))^{1/q}) \quad (3)$$

for q >1

Through vast simulation runs, it is found that with $q = 4$, Equation 3 provides an excellent close form for the estimation of optimal *Po*. As examples, corresponding to $\alpha = 1.5$, 1.6, 1.7, 1.8, 1.9, and 2, the estimated optimal *Po* from Equation 3 is *Po* = 1.13, 1.19, 1.26, 1.36, 1.49, and 2. The optimal *Po* derived from Equation 3 provides a simple and quick way to extract an optimal matched filter out of the entire family of α-stable matched filters. Using this estimated optimal matched filter for the target-detection processing via Equation 2, the α-stable matched filter outperforms the conventional matched filter significantly. Table 1 lists the gain in probability of detection of the optimal α-stable matched filter over the conventional matched filter for different α-clutter, with Pfa = 0.01. As expected, the spikier the clutter (smaller α value) the more gain the optimal matched filter produces.

alpha	1.5	1.6	1.7	1.8	1.9	1.92	1.94	1.96	1.98	2
Po (optimal)	1.13	1.19	1.26	1.36	1.49	1.45	1.49	1.53	1.69	2
SNR	-25	-23.5	-22	-20.5	-19	-19	-18.5	-18	-17.5	-17
Probability	0.757	0.705	0.637	0.58	0.543	0.469	0.533	0.559	0.596	0.64
Probability Gain	0.756	0.703	0.632	0.573	0.513	0.441	0.432	0.315	0.134	0

TABLE 1. Gain in Probability of Detection of the Optimal α-Stable Matched Filter Over the Conventional Matched Filter for Different α-Clutter.

α	1.5	1.6	1.7	1.8	1.9	1.92	1.94	1.96	1.98	2
Po (optimal)	1.125	1.173	1.230	1.304	1.415	1.447	1.485	1.535	1.609	2
SNR	-25	-23.5	-22	-20.5	-19	-19	-18.5	-18	-17.5	-17
Probability	0.757	0.705	0.637	0.58	0.543	0.469	0.533	0.559	0.596	0.64
Probability gain	0.756	0.703	0.632	0.573	0.513	0.441	0.432	0.315	0.134	0

NP-3 SAR data available in our laboratory were used to evaluate the performance of the optimal α-stable matched filter on real data. A subset of L-band SAR sea clutter data known as the "Puerto Rico l9p5lhh" of size 512 range bins by 2,048 pulses was observed. Fitting this sea clutter data by the α-stable model, pulse by pulse, with the exception of a few anomaly pulses the parameter estimation of α is fairly consistent, with an average value of 1.759 and standard deviation of 0.1. Using these 2,048 pulses for the Monte Carlo simulation in Equation 3 with $q = 4$, optimal *Po* = 1.314. This optimal filter outperforms the conventional matched filter by a gain of 0.60 in probability of detection, which is comparable to the result shown inTable 1.

CONCLUSIONS AND PROJECT STATUS

Radar clutter is usually modeled well by the α-stable statistics. A robust family of α-stable matched filters is a natural extension of the conventional matched filter. An optimal α-stable matched filter is being developed in a simple closed form in this ILIR project. This optimal α-stable matched filter significantly improves target detection in probability of detection in real clutter data as well as simulated data. Moreover, the α-stable matched filter is computationally efficient. It enhances target detection, recognition, and identification; and hence can be directly applied to automatic target detection (ATD) and automatic target recognition (ATR) algorithms in the Fleet. This technology can be used in a wide variety of radar signal and image processing. The process of implementing the α-stable technology in a platform is very simple:

1. Periodically model the received signal to update the α parameter.
2. Compute a new optimal α-stable matched filter using Equation 3
3. Employ the newly optimal α-stable matched filter (i.e., new optimal *Po*) in Equation 2 for target detection.

The α-stable approach appears to be an emerging and promising technology. The technology has significantly improved target detection in signal processing and enhanced the SAR image formation in image processing (Reference 6). It is firmly believed that this α-stable technology can be applied to enhance many other capabilities in image processing. Some examples to be performed in Task 3 include autofocusing, FOPEN, GPEN, and GMTI. At this time, one set of APS-137 SAR data from the P-3 Antisubmarine Warfare Improvement Program has been received (Reference 9). Developing optimal α-stable image processing techniques and evaluating their performance on APS-137 real data in Task 4 will be exciting.

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