Focusing of Synthetic Aperture Radar Images of Moving Targets using Minimum Entropy Adaptive Filters

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Abstract - Synthetic aperture radar (SAR) imaging systems are used for generating high-resolution images for target detection and identification. However, when imaging moving targets, the imaging process is degraded by target motion. These effects generally manifest as a form of smearing in the azimuthal direction. Since the motion parameters are generally not known, it requires a processing technique that can estimate the motion information from the SAR measurements and use these estimates to reconstruct the image. Adaptive filters are well suited to do this. In this study, an adaptive technique based on the minimum entropy filter is developed to minimize the effect of smearing in SAR images of moving targets. The minimum entropy filter utilizes the entropy function as the cost function to be optimized. The use of the minimum entropy filter with simulated SAR measurements of moving targets clearly shows significant improvement in the image quality when the entropy function is optimized. The filters were tested on images of targets with many different motion parameters. The minimum entropy filter consistently produced the best motion compensation. The filters were also tested with field images of ships obtained from a C-band, SAR flown over the coast of Denmark. The filter was able to adaptively reduce the effects of azimuthal smearing.

INTRODUCTION

Synthetic aperture radar (SAR) imaging systems are used for generating high resolution images in remote sensing and military surveillance. In surveillance applications, the critical objective is to be able to detect and identify targets [1]. However, when imaging moving targets, the imaging process is degraded by the additional Doppler components due to target motion [2-3]. These effects generally manifest as a form of smearing in the azimuthal direction. Figure 1 shows an image of a moving target obtained from the Danish EMISAR imaging system. The azimuthal smearing and azimuthal shifting are clearly shown in the image.

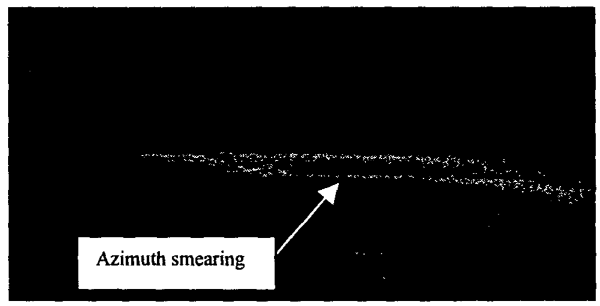


Figure 1 – SAR image of a moving ship from the Danish EMISAR imaging system. The azimuth smearing is clearly visible in this image.

In standard processing, smearing occurs with moving targets, because the SAR azimuth, matched filter is designed to compensate for the Doppler components due to the relative motion between the SAR platform and stationary targets. For moving targets, there will be additional Doppler components due to target motion. In the ideal case, if the motion parameters are known, a matched filter may be designed to properly focus the moving target. However, in practice, the motion parameters are not known. This requires a processing technique that can use all the available information to reconstruct the image as best as possible. Adaptive filters are well suited to do this. In this study, a processing technique based on the minimum entropy filter is developed to minimize the effect of smearing in SAR images of moving targets.

The minimum entropy filter is an adaptive filter that utilizes the entropy function as the cost function which is to be optimized [4]. In various image processing applications, the minimum entropy filter has been used for performing deblurring and blind deconvolution [5]. Various forms of entropy functions have been defined. In this study, both the logarithmic function and the image contrast function are used for focusing images of moving targets. Simulated images of ships with different motion parameters are used in this investigation. Motion effects due to target velocity, acceleration and higher order effects are investigated. Smearing due to limited coherence is also investigated. The minimum entropy filter is also used to focus SAR images of moving ships from the Danish EMISAR imaging system.

MINIMUM ENTROPY FILTERS

In adaptive filtering, a cost function is defined as a measure of the image or data property to be optimized. For the filter to be effective, the cost function has to reflect the property well. The minimum entropy filter utilizes the entropy function as the cost function. Several different forms of entropy have been defined [4]. However, generally the logarithmic function is used in most entropy filters. In this study, both the logarithmic function and the image contrast filter are used. The generic form of the entropy cost function is defined as

$$H = -\sum_{\text{all pixels}} q_i F(q_i),$$

where q_i is the image intensity and $F(q_i)$ is a function of the image intensity. The entropy as to be minimized while keeping the total power in the image constant, *i.e.*

$$\sum_{\text{all pixels}} q_i = \textbf{constant}.$$

The logarithmic entropy function is defined as $F(q_i) = \ln(q_i)$, and the image contrast function is defined as $F(q_i) = q_i^2$.

Studies have shown that by minimizing functions such as the image contrast function or the logarithmic function, certain images properties may be enhanced. In this study, the SAR images of moving targets are focused by minimizing the cost function. After using standard matched filter processing to obtain a first guess at focusing, the motion compensation filter is used to adjust for target motion.

In the motion compensation filter, pixels in the azimuth direction from a fixed range bin are Fourier transformed to generate the frequency domain representation. The motion compensation filter is a simple all-pass filter where only the phase of each frequency component is adjusted to focus the image [5]. By using an all-pass filter, the total image power is conserved.

Several different techniques have been developed for optimizing the cost function. The most widely used technique is the gradient descent technique. In the gradient descent technique, the cost function is optimized by adjusting the imaging parameter by an amount proportional to the derivative of the cost function with respect to the phase of the different frequency components. The rate at which the optimization occurs is determined by a learning rate and may be written as

$$\phi_{n+1}(f_i) = \phi_n(f_i) - \eta \frac{\partial H}{\partial \phi(f_i)}$$

Another optimization technique is the phase compensation method. In the phase compensation method, the optimization may be written as

$$\mathrm{Im}\left\{e^{j\phi(f_i)} W^*(f_i)\right\} = 0 \quad \textbf{and} \quad \phi_{n+1}(f_i) = \arg\{W_n(f_i)\}$$

The phase of each frequency component is adjusted according to equation. Both techniques are studied in this project.

RESULTS AND DISCUSSION

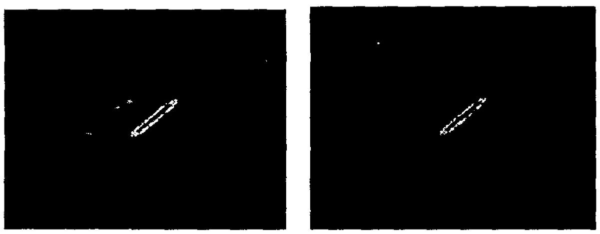
The minimum entropy filters are first tested with simulated SAR images. The use of simulated images enables one to test the accuracy of this focusing technique over a variety of imaging conditions. It also provides a comparison for the estimates of the motion parameters obtained from the minimum entropy filters. Figure 2 shows simulated SAR images generated using standard matched filter processing and using the minimum entropy motion compensation filter. The simulated image is generated for a target which is accelerating in the range direction. For standard processing, the target is both shifted and smeared in the azimuth direction. The minimum entropy filter utilizes the logarithmic entropy function and the phase compensation optimization method. Figure 2 shows that the minimum entropy filter is able to compensate for the additional motion of the target. The target appears to be well focused when the motion compensation is applied.

(a) (b)

Figure 2 – SAR image of moving ship using (a) standard processing and (b) the minimum entropy filter.

Figure 3 shows the images at the different entropy values. Clearly, as the entropy decreases the focusing improves. It appears that as the entropy decreases the images go through stages of partial focusing until these partially focused images finally coalesce to produce a single focused image. The relationship between the entropy and focusing is succinctly illustrated by these images.

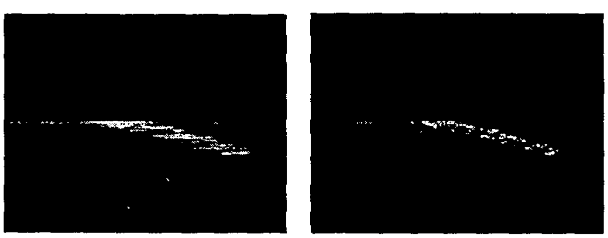
(a) H=-7.3 (b) H=-7.9



(c) H=-8.8 (d) H=-9.2

Figure 3 – Focusing of SAR images using minimum entropy filters – partially focused images shown as a function of the entropy.

Figure 4 shows two sets of field images obtained from the Danish EMISAR imaging system. Shown in Figure 4 are the images using standard processing and the minimum entropy filter. In both images, the minimum entropy filter is shown to focus the scattering centers on the ship. The scattering centers on the ship which are smeared in the azimuth direction in the images from the standard processing method are clearly focused when the motion compensation filter is used. The minimum entropy filter clearly removes most of the smearing in the azimuth direction. Some of the smearing observed in these images is attributed to scattering from the ocean surface which may be moving at a different velocity from the ships. Focusing the ship may not necessarily focus the scattering from the ocean surface. In spite of this, the utility of the additional focusing is clearly visible in both sets of images shown in Figure 4.



(a) Standard Processing (b) Minimum Entropy Filter

(a) Standard Processing (b) Minimum Entropy Filter

Figure 4 – SAR images from the Danish EMISAR imaging system, which are generated using (a) the standard processing method and (b) the minimum entropy filter.

Another important objective of this study is to extract the target's motion parameters from the optimized minimum entropy filter. This may be done by using the estimates of the phase correction term in the minimum entropy filter. Figure 5 shows the phase of the minimum entropy filter as a function of the frequency for the first EMISAR image shown in Figure 4. The minimum entropy filter appears to have a quadratic phase dependence on frequency. The quadratic phase dependence in the frequency domain translates to a quadratic phase dependence in the time domain. This suggests that the primary motion component of the target is either a range directed acceleration or an azimuth directed velocity. This supports the premise that the target's motion parameters may be extracted from the filter parameters. Methods for estimating the full set of motion parameters continue to be developed.

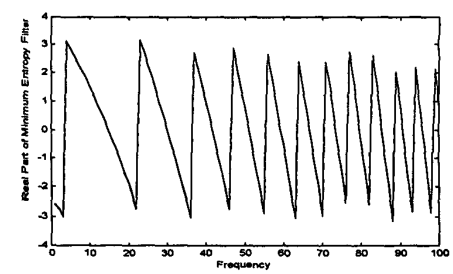


Figure 5 – Phase of the frequency response of the minimum entropy filter.

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