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Fast target detection in radar images using Rayleigh Mixtures and Summed Area Tables

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ABSTRACT

As the first step of automatic image interpretation systems, automatic detection of targets should be accurate and fast. For Synthetic Aperture Radar (SAR) images, Constant False Alarm Rate (CFAR) is the most popular framework used for target detection. In CFAR, modeling of the clutter is crucial since the decision threshold is calculated based on this model. In this study, we propose to model the background statistics using a Rayleigh Mixture (RM) model. Such an approach facilitates modeling of complex statistics, including but not limited to those involved in heavy tailed distributions, which are shown to be good fits especially for high resolution SAR images. We also propose an efficient method to evaluate CFAR thresholds according to the proposed model by use of Summed Area Tables (SAT). SAT provides a remarkable efficiency as the Rayleigh distribution is represented by only one parameter that can be estimated using simple moments. Tiling and parallel implementation is also utilized for fast computation of results. The outcome is a highly-accurate, extremely fast, and adaptive target detection approach that can be seamlessly used with a variety of complex SAR scenes. Our experiments compare the proposed approach with existing target detection methods and demonstrate its effectiveness as well as the benefits it provides.

1. Introduction

Synthetic Aperture Radar (SAR) is an active sensing system which is capable of capturing images day and night. It is also less vulnerable than optical systems to weather conditions depending on the operating frequency. Hence, demand for the images acquired by SAR systems is increasing concurrently with the increase in their quality. Meanwhile, the demand for automatic interpretation of SAR images is also on the rise as manual interpretation of such amount of data become intractable.

Identifying the existence of an object with different characteristics than the background clutter, i.e., automatic target detection (ATD) has been and continues to be one of the critical problems in automatic SAR image interpretation [1]. Since this is one of the very first steps of any automatic target recognition (ATR) process, accuracy and speed of target detection is crucial in order to satisfy the requirements of many intelligence and surveillance systems [2]. Given its importance, ATD is studied by many researchers and a variety of approaches have been proposed in the literature. Among these methods, Constant False Alarm Rate (CFAR) based approaches are commonly preferred since they have reasonable computational requirements, constant false alarm rate, adaptive threshold selection capability, and fast detection performance [3–7].

For SAR images, detection performance of a method is affected by the reflectivity difference between the object and the clutter and the reflectivity variability in the clutter region. CFAR based ATD methods mainly aim to detect objects while satisfying a desired false alarm rate under unknown clutter level. To this end, for each pixel in the image, a threshold value is calculated using the pixels in a pre-defined region around the corresponding pixel and a threshold is calculated in order to label that pixel as target. Most CFAR methods use a solid stencil approach meaning that the adaptive threshold is estimated using a fixed size window. The original CFAR approach [8] assumes the clutter follows a Gaussian distribution and the threshold is estimated accordingly. Since the estimated threshold is compared with the mean reflectivity of target cells per mean reflectivity of clutter cells, this method is called Cell Averaging CFAR (CA-CFAR).

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In the literature, a number of modifications to CA-CFAR have been proposed in order to improve its performance in various scenarios. Order statistics CFAR (OS-CFAR) has been proposed to enable detection of closely located objects that cause non-homogeneities in the background region [3]. Greatest of CFAR (GO-CFAR) and Smallest of CFAR (SO-CFAR) have been proposed for better detection performance in clutter edge regions and in the multi-target case, respectively [9]. Maximal reference cell based CFAR [10] has been proposed for better detection performance in multiple target situations. While all of these techniques produce good results in the scenarios for which they were designed, they usually perform worse than CA-CFAR in other cases. This has motivated researchers to develop more flexible and generic, so called *adaptive* CFAR algorithms [3] that could exhibit satisfactory performance over a variety of conditions.

Smith and Varshney [5] have proposed Variability Index CFAR (VI-CFAR), which estimates the statistics by evaluating a weighted average of the pixels in the background region. It is reported to be successful in both homogeneous and heterogeneous regions. Farrouki and Barkat [11] proposed Automatic Censored CFAR (AC-CFAR) by discarding the pixels of other possible targets in the background regions during the calculation of the clutter statistics. Another automatic censoring mechanism has been proposed in [12] where the transition in the clutter region is searched to discriminate homogeneous and non-homogeneous regions. This method dynamically switches between different CFAR detectors according to the background characteristics.

Although these methods have initially been considered for Gaussian distributed clutter, such an assumption fails in many of the applications. The modeling of the SAR image reflectivity distribution is one of the key steps of target detection and could be crucial depending on the characteristics of the observed scene [13]. There also exists a body of work focused particularly on one of these clutter distributions [14,15]. Traditional theory assumes the speckle noise on radar images to be Rayleigh distributed as both real and imaginary parts have Gaussian distribution due to the Central Limit Theorem. However, for high resolution SAR images, this assumption does not hold because of their impulsive behavior which leads to better fits to heavy tailed distributions [16]. There are also numerous studies which aim to describe the statistics of SAR images based on various statistical models [13]. Log-normal, K, G^0, and Weibull are the most commonly suggested distributions in the literature [17]. Nevertheless, none of these assumptions provide a good fit under complex and heterogeneous scenes composed of multiple clutter types.

In [17], an alternative heavy-tailed model for clutter distribution is adopted which is based on α-stable distributions. This α-stable distribution is a mixture of Rayleighs and a method for estimation of the model parameters is presented. However, this process is computationally expensive as it includes calculation of gamma functions and using some numerical optimization techniques like bisection. An earlier study proposed to model the clutter by a Rayleigh mixture distribution [18] involving a spherically invariant random process (SIRP) [19]. This approach can only model the temporal and spatial distribution of noise sources but not any effects due to the propagation of the radio signals [17].

Assuming a Weibull clutter distribution, Bisceglie has proposed a solid stencil CFAR algorithm [6] which also involves a number of operations including sorting and censoring, to adapt the background for both homogeneous and heterogeneous regions. Another study proposed to use the beta-prime distribution to handle the non-homogeneities of the background region together with the classical CA-CFAR approach [20]. However, this approach fails for the multi-target case since the threshold value increases significantly because of the target pixels in the background region. In [21], single look SAR image is assumed to be beta prime and the CA-CFAR procedure is followed for threshold estimation. Despite the performance improvement in clutter edges, for the multi-target situations, the detection probability decreases since the estimated thresholds increase. Gao [22] has proposed to use Parzen Window Density Estimation (PWDE) for evaluation of the CFAR threshold without prior information about the clutter distribution. This approach is used for detection of ships and the superiority of PWDE over the K-distribution assumption is demonstrated on real SAR images. On the other hand, the flexibility on modeling the clutter distribution causes substantial computational load. Recently, a CA-CFAR variant algorithm has been proposed which decides whether the clutter samples are independent and identically distributed (IID) or not by use of a goodness of fit test [23]. If the IID assumption holds for those samples, the target decision is made by applying CA-CFAR whereas a range-heterogeneous algorithm is applied otherwise.

Gao et al. [3] have also proposed an algorithm (AAF-CFAR) that decreases the computational cost of solid stencil CFAR approaches significantly. In AAF-CFAR, a global threshold is found first to censor the reflectivity values during the estimation of background statistics. Then, the CFAR threshold value is evaluated assuming the background follows the G^0 distribution as the window slides and the decisions are made as in conventional CFAR techniques. Furthermore, as the window slides, a method to update the old threshold value based on the reflectivities of the removed and added pixels is used.

In one of our previous studies, we proposed to use Rayleigh distribution for clutter modeling where target shape, guard region, and clutter region are adaptively determined for detecting targets in SAR images [24]. In that study, possible target regions are found on an edge preserving despeckled SAR image. However, the employed despeckling method is computationally expensive and requires high level of parallel implementation to enable the utilization of the algorithm in scenarios involving large scenes. Therefore, CPU and GPU parallelizations are realized to achieve target detection in reasonable time.

Note that, the discussed methods are to detect stationary targets. However, there may be moving targets which lead to false detections and/or missed targets. Recently, the studies about refocusing [25–29] are popular and they can be applied as a preprocessing step of ATD to increase the performance of the target detection approaches.

In this paper, we propose an accurate and fast target detection approach which performs well on images with an extensive variety of clutter types. For this purpose, we propose to use mixture of Rayleighs to model the background and estimate the CFAR threshold. The mixture of Rayleighs enables us to model complex distributions in a similar way to Parzen density estimation, viewed as a mixture of, e.g., Gaussians. As the clutter parameters are evaluated in local patches, the approach is adaptive to the clutter variation over the image. Furthermore, the Rayleigh distribution has only one parameter to estimate which makes the model fitting step computationally efficient. Summed Area Tables (SAT) are utilized for further reduction of the computational load and with parallel implementation of the algorithm using OpenMP [30], a satellite image sampled in 0.5 m that covers 25 km^2 that is around 100 megapixels is processed in 4 seconds with a standard PC. The performed experiments show that the proposed method is able to fit proper densities, including heavy-tailed models, to the background clutter and has good detection performance for an extensive set of images with various characteristics. The results are compared with the commonly used approaches in the literature and the success of the approach is presented in terms of both detection capability and computational efficiency.

The rest of the manuscript is organized as follows. In Section 2 some background on CFAR target detection, target detection using

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