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A Novel Method for Ship Detection in SAR Images Based on Information Geometric Optimization

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Abstract—The aim of this letter is to provide a novel method connecting statistical optimization and information geometry for ship detection in synthetic aperture radar (SAR) imagery. The method consists of two steps: initial detection and iterative optimization. For the first stage, the Weibull clutter model is used for initial detection. For the second step, the metric tensor of the Weibull distribution manifold is constructed for iterative optimization. Experiments show that the proposed method is effective in reducing false alarms and obtains a satisfactory detection performance.

1. INTRODUCTION

The detection of ships in SAR image is an important process for automatic ship recognition based on SAR image. The needs of military, commercial, and civilian users worldwide make ship detection become a hot topic in SAR image processing and research. There are two types of methods for ship target detection in SAR images: data-drive methods and model-drive methods. Among data-drive methods, deep learning approaches have started showing an ability to extract robust and invariant depth features for ship detection in SAR image [1]. The discrimination performance of deep learning relies on large-size training data sets. However, the size of labeled ship target training samples is so limited that deep learning tools cannot achieve promising discrimination results. Among model-drive methods, constant alarm false rate (CFAR) processing is an important method in modern SAR image processing [2]. CFAR detectors are designed to search for pixel values which are unusually bright compared to those in the surrounding area, which depend on the design of sliding window, statistical modeling of clutter distribution, and estimation of model parameters. Algorithms designed for one type of imagery may not be appropriate or may need to adjust for different types of imagery. Every detection method has its own advantages and disadvantages; generally, we use certain detection method according to the actual condition. Besides, many detection errors are caused by mixed pixels and sea clutter of the SAR image. In order to improve the detection effect and on the basis of analyzing the characteristic of SAR image, a method of information geometric optimization is proposed to extract features in this letter. This theory can be used to explore new detection methods.

Information geometry studies the geometrical structure of a family of probability distributions, which is useful for various application in statistics, optimization, signal processing, and machine learning [3]. It erects a bridge across the gap between the pure theory of differential geometry67 and engineering practice. For the application of the theory of information geometry, one of geometrical structures has been extensively studied for a manifold of probability distributions. It is based on the Fisher information metric, which is invariant under reversible transformations of random variables [4]. Differential geometric properties of various families of probability density functions can be used to obtain representations of practical situations involving statistical models. Considering a family of probability density functions $\{p(x;\theta)\,|\theta \in \Theta\}$, each element of $\{p(x;\theta)\,|\theta \in \Theta\}$ satisfies $\int_{-\infty}^{+\infty} p(x;\theta)\,dx = 1$ for all

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$\theta \in \Theta$, where Θ denotes the parameter space of a parameter statistical model. Let $L = \log p(x;\theta)$. It yields $\int_{-\infty}^{+\infty} \frac{\partial^2 p(x;\theta)}{\partial\theta^i \partial\theta^j} dx = 0$ for all $\theta \in \Theta$. The $(i,j)^{th}$ element $g_{i,j}$ of the Fisher information matrix is

$$g_{i,j} = \int_{-\infty}^{+\infty} \frac{\partial L}{\partial\theta^i} \frac{\partial L}{\partial\theta^j} p(x;\theta) dx = -\int_{-\infty}^{+\infty} \frac{\partial^2 L}{\partial\theta^i \partial\theta^j} p(x;\theta) dx \tag{1}$$

for coordinates (θ^i) about $\theta \in \Theta$ [4]. Obviously, the Fisher information matrix induces a metric g on the parameter space Θ. We denote $g = \sum_{i,j} g_{i,j} d\theta^i \otimes d\theta^j$. This allows geometrical tools to measure distances between lengths along trajectories through perturbations of models of relevance. Let $T_\theta = T_\theta(\Theta)$ be the tangent space at each point $\theta \in \Theta$, and let $\left(\frac{\partial}{\partial\theta^i}\right)_{(1\le i\le n)}$ be the coordinate vector fields in a local chart. Thus, the tangent vectors $u, v \in T_\theta$ can be written as $u = \sum_{i=1}^{n} u^i \frac{\partial}{\partial\theta^i}$ and $v = \sum_{i=1}^{n} v^i \frac{\partial}{\partial\theta^i}$. Then [5]

$$g(u,v) = \sum_{i,j} g_{i,j} u^i v^j \tag{2}$$

2. PROPOSED METHODS

The Weibull distribution model is one of the most commonly used models of synthetic aperture radar (SAR) image data. In this letter, it is adopted to characterize the statistics of SAR images. Without loss of generality, we restrict ourselves to the two parameter Weibull distribution. A random variable x is said to be a Weibull distribution with scale parameter λ and shape parameter κ, if its probability density function has the form [2]

$$p(x;\lambda,\kappa) = \frac{\kappa}{\lambda}\left(\frac{x}{\lambda}\right)^{\kappa-1} \exp\left(-\left(\frac{x}{\lambda}\right)^{\kappa}\right) \qquad x \ge 0 \tag{3}$$

By using the maximum likelihood estimation of the Weibull parameters based on m observed record values $x_i > 0$, we have [6]

$$\lambda = \frac{m}{(1/\kappa)\sum_{i=1}^{m} x_i^{\lambda} \ln x_i - \sum_{i=1}^{m} \ln x_i} \tag{4}$$

$$\kappa = \left[\left(\frac{1}{m}\right)\sum_{i=1}^{m} \ln x_i^{\lambda}\right]^{1/\lambda} \tag{5}$$

Mean μ and standard deviation σ of the Weibull distribution are

$$\mu = \lambda\Gamma\left[(\kappa+1)/\kappa\right] \tag{6}$$

$$\sigma = \sqrt{\lambda^2\Gamma\left[(\kappa+2)/\kappa\right] - \mu^2} \tag{7}$$

where Γ denotes the gamma function.

According to the theory of information geometry, a symmetric second order covariant tensor field g can be constructed.

$$g_{1,1} = \sigma, \quad g_{1,2} = g_{2,1} = 2\mu\sigma, \quad g_{2,2} = 4\mu^3\sigma + 2\mu\sigma^2 \tag{8}$$

and

$$g\left(\frac{x-\mu}{\sigma}, \frac{x-\mu}{\sigma}\right) = \sigma^{-1}(x-\mu)^2\left[1 + 2(2+\sigma)\mu + 4\mu^3\right] \tag{9}$$

The first step is to detect the ship in SAR image by using CFAR detector based on Weibull model. A CFAR detector is designed to search for pixel values which are unusually bright compared to those in the surrounding area.

Let $X = (x_1, \cdots, x_N)$ denote the image data, where N denotes the number of image pixels, and each x_i denotes the logarithm of gray-level intensity of the ith pixel. The CFAR detector based on the Weibull model is

$$x_i > \mu_0 + \sigma_0 T \quad \Leftrightarrow \quad target \quad pixel \tag{10}$$

$$T = \frac{\sqrt{6}}{3.1416}\left[\ln\left(\ln\left(\frac{1}{P_{fa}}\right)\right) + 0.5764\right] \tag{11}$$

where P_{fa} denotes the given probability of false alarm, x_i the pixel value under test, μ_0 d the background mean, σ_0 the background standard deviation, and T the adaptive threshold parameter.

For the second step, the potential function of the Weibull manifold is constructed to optimize detection result of the first step. According to the principle of maximum potential function, we have

$$C^* = \arg\max_{C} \{U(X\,|C, \mu, \sigma)\} \tag{12}$$

where $C = (c_1, \cdots, c_N)$ denotes the class labels, $c_i \in C$, $C = \{0, 1\}$, and the potential function is defined as

$$U(x_i\,|c_i, \mu_{c_i}, \sigma_{c_i}) = \sigma_{c_i}^{\tau-2}(x_i - \mu_{c_i})^2\left[1 + 2\left(2 + \sigma_{c_i}^{\tau}\right)\mu_{c_i} + 4\mu_{c_i}^3\right] \tag{13}$$

where τ denotes the modification parameter, and $\tau > 2$.

We return now to a more detailed algorithm implementation in the above-mentioned theory and methods.

The main steps of the ship detection algorithm are as follows:

Step 1) Weibull-based CFAR detector is used for detecting ship in SAR image I. The detected result is denoted by I_1 (a binary image).

Step 2) According to the initial detection result I_1, the pixels of the image I are divided into two groups (suspected target pixels and background pixels). Let $\{c_i, \mu_{c_i}, \sigma_{c_i}\}_{c_i \in C^{(0)}}$ denote an initial parameter estimate based on two sets of pixel values.

Step 3) Provided that $\{c_i, \mu_{c_i}, \sigma_{c_i}\}_{c_i \in C^{(k)}}$, for all $1 \le i \le N$, the potential function problem for $C^{(k+1)}$ is maximized.

$$C^{(k+1)} = \arg\max_{C} \{U(X\,|C, \mu, \sigma)\} \tag{14}$$

Step 4) Repeat Step 3 until a maximum number of iterations K is achieved.

3. EXPERIMENTAL RESULTS AND ANALYSIS

The input ERS-1,2 SAR image, with a size of 150×150, is shown in Fig. 1(a). The data are C-VV, with an incidence angle $\sim 23^\circ$. The pixel resolution is 30 meters in azimuth direction and 26.3 meters in range direction. The signal-to-noise ratio (SNR) of the image is 12 dB.

$$\text{SNR} = 10\log\frac{\frac{1}{N_t}\sum_{i=1}^{N_t} x_i}{\frac{1}{N_b}\sum_{i=1}^{N_b} x_i} \tag{15}$$

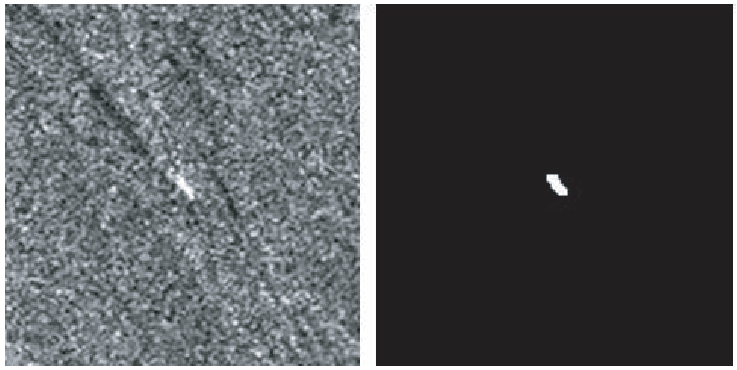
where log denotes the natural logarithm, N_t the number of target pixels, N_b the number of clutter pixels, and x_i the pixel values.

During the experiments, the first step is to detect the ship in SAR image by using CFAR detector against Weibull clutter. The target-window size is 25×25, and the probability of false alarm $P_{fa} = 10^{-6}$. For the second step, the maximum number of iterations $K = 5$, and the modification parameter $\tau = 4$.

The underlying idea of information geometric optimization is the use of the information geometry method to measure the difference between the ship and ocean-clutter statistical distributions of the SAR images. As shown in Fig. 1(b), the proposed method has a good performance of SAR image ship detection.

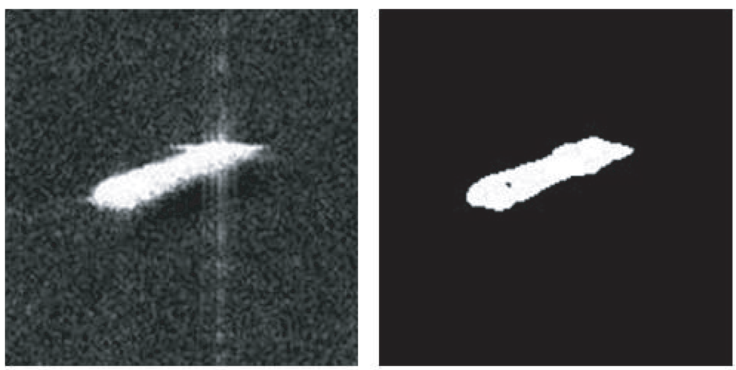
To further illustrate the performance of the presented method, a high-resolution SAR image is used in the experiments. The SAR image with a size of 150×150 is shown in Fig. 2(a). The SNR of this image is 29 dB. The detected result is shown in Fig. 2(b).

Comparing the detection results using the SAR images, Fig. 3 shows the detected results by using Weibull-based CFAR detector. It tends to have many false alarms by using design parameters, the target-window size 25 × 25 and the probability of false alarm $P_{fa} = 10^{-6}$. In fact, even if the detector is not CFAR for the true distribution of sea clutter, it will still only pick out bright pixel values. Fig. 4 shows the detected-results by using the notch filter mode [7] which seems to provide a slightly lower clutter level than those in the Weibull-based CFAR mode.



(a) (b)

Figure 1. SAR image and detected result by using the proposed method. (a) Original image. (b) Detected result.



(a) (b)

Figure 2. SAR image and detected result by using the proposed method. (a) Original image. (b) Detected result.

(a) (b)

Figure 3. Detected results by using the Weibull-based CFAR detector. (a) Detected result of Fig. 1(a). (b) Detected result of Fig. 2(a).

(a) (b)

Figure 4. Detected results by using the notch filter mode [7]. (a) Detected result of Fig. 1(a). (b) Detected result of Fig. 2(a).

(a) (b)

Figure 5. Detected results by using the method proposed in [8]. (a) Detected result of Fig. 1(a). (b) Detected result of Fig. 2(a).

Figure 5 shows the detection results obtained by using the lognormal ρ-metric method proposed in [8]. During the experiments, the square shaped sliding window is set as 11×11 pixels, and the parameter value $\rho = 4$. According to the principle of the algorithm [8], the detector picks out target pixels in SAR image according to local statistical change information. In this letter, the underlying idea of the proposed algorithm is to measure the whole difference of target and sea clutter statistic distributions of SAR image. The results from these comparison indicate that the proposed detector performs much better for ship detection in SAR images.

4. CONCLUSIONS

Information geometry is developed to study the structure underlying probability distributions by using differential geometry. The Weibull distribution is a good statistical model of sea clutter. This letter proposes a novel detection method based on information geometric optimization algorithm for ship detection in SAR images. Compared to other similar detectors, the proposed detector fully takes advantage of the geometric structure of the Weibull manifold between ship targets and their surrounding clutter. It can achieve a good performance for ship detection, which has a great application value.

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REFERENCES

1. Lin, Z., K. Ji, X. Leng, and G. Kuang, "Squeeze and excitation rank faster R-CNN for ship detection in SAR images," *IEEE Geosci. Remote Sens. Lett.*, Vol. 16, No. 5, 751–755, 2019.
2. Gao, G., *Characterization of SAR Clutter and Its Applications to Land and Ocean Observations*, Springer, Singapore, 2019.
3. Yang, M. and G. Zhang, "A novel ship detection method for SAR images based on nonlinear diffusion filtering and Gaussian curvature," *Remote Sens. Lett.*, Vol. 7, No. 3, 211–219, 2016.
4. Arwini, K. A. and C. T. J. Dodson, *Information Geometry — Near Randomness and Near Independence*, Springer-Verlag, Berlin, Heidelberg, Germany, 2008.
5. Cao, L., H. Sun, and X. Wang, "The geometric structures of the Weibull distribution manifold and the generalized exponential distribution manifold," *Tamkang J. Math.*, Vol. 39, No. 1, 45–51, 2008.
6. Forbes, C., M. Evans, N. Hastings, and B. Peacock, *Statistical Distributions*, John Weiley & Sons, New Jersey, USA, 2011.
7. Gao, G., S. Gao, J. He, and G. Li, "Ship detection using compact polarimetric SAR based on the notch filter," *IEEE Trans. Geosci. Remote Sens.*, Vol. 56, No. 9, 5380–5393, 2018.
8. Yang, M. and C. Guo, "Ship detection in SAR images based on lognormal ρ-metric," *IEEE Geosci. Remote Sens. Lett.*, Vol. 15, No. 9, 1372–1376, 2018.