A Modified Hough Transform TBD Method for Radar Weak Targets Using Plot's Quality

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Abstract. In this paper, we propose a modified Hough transform based TBD detection algorithm for radar weak targets using radar plot quality information. Firstly, a general description of the proposed method was presented. And then the quality of radar raw plots was redefined and its calculation algorithms were discussed in detail. Finally, a modification of traditional Hough transform using plot's quality information was applied and more credible peak detections were conducted and outputted. The effectiveness of the proposed method especially in heavy clutter conditions was verified by simulation experiments.

Keywords: TBD · Hough transform · Plot quality · Radar weak target detection

1 Introduction

The detection of low observable targets by radar in marine environment is widely concerned for several decades. To solve this problem, it was acknowledged by most radar researchers that the track-before-detect (TBD) technology is quite useful [1]. Different form traditional detect-before-track (DBT) procedures, TBD outputs the detections and tracks simultaneously after a quite long time non-coherent integration within consecutive radar scans. There are several kinds of algorithms presented to implement the TBD technology including 3D matched filter, Hough Transform (HT), particle filter, dynamic programming and etc. [2–5]. Among these algorithms, the HT based TBD method was specially focused for its great advantage of insensitivity to local missing and strong anti-jamming ability.

Hough Transform was presented by Hough in 1962 for the detection of straight lines in images. In the year of 1994, Carlson [3] first introduced HT for radar weak target detection. Since then, many research works dealing with the improvement and modification of HT-TBD have been proposed [6–14]. However, in most of the existing works, all the suspect radar plots were equally treated or at most only the amplitude information was used. In fact, different plots have different qualities, especially nowadays more and more coherent radar systems are applied for getting a better performance in clutter backgrounds. These radar plot quality (PQ) information should also be adequately used to extract real targets form massive false alarmed detections.

In this paper, we present a novel HT-TBD approach using radar raw plot's PQ information. Firstly, the PQ of a radar suspect plot was redefined which was suitable for

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both coherent and non-coherent radars, and the calculation algorithms for the radar PQ and its four different component indexes were given. Then a modification of standard HT was present to implement PQ integrations and peak detections. Finally, simulations were conducted to evaluate the performance of the proposed approach in K-distributed sea clutter environment.

2 General Description of the Proposed Method

Figure 1 shows the basic flow chart of the presented novel HT-TBD method.

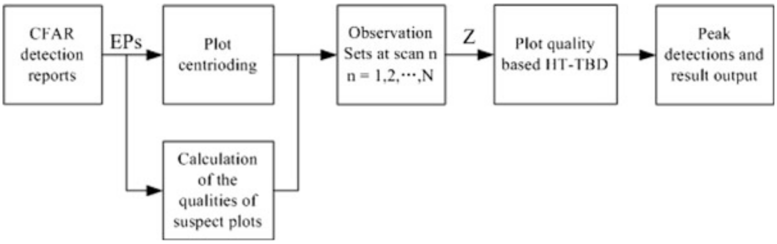


Fig. 1. Flow chart of the proposed algorithm

The inputs of the improved method are the constant false alarmed rate (CFAR) detection reports named as EPs (Echo Presence). The threshold of CFAR detection usually called as the first threshold which should be set enough low as to ensure weak target echoes can pass through, and the final false alarm rate can be controlled by the TBD. After CFAR detection, all EPs are condensed to several suspect plots through a traditional plot centroid technology; meanwhile at this stage, the PQ of each suspect plot was calculated using an algorithm which will be given in detail in Sect. 3.

Then we get the radar's suspect plot observation set of N scans denoted as

$$\mathbf{Z} = \left\{ Z_i^n \middle| i = 1, 2, \ldots, M_n,\ n = 1, 2, \ldots, N \right\} \tag{1}$$

where $Z_i^n = [x_i, y_i, n, Q_i]$, (x_i, y_i) are respectively the Cartesian coordinates of suspect plot i, M_n is the total number of suspect plots in scan n, Q_i is the plot's quality which in standard Hough transform (SHT) algorithm is exactly the amplitude.

Hough transforms map points in Cartesian space to curves in parametric space by using the following parametric equation

$$\rho = x \cos\theta + y \sin\theta \tag{2}$$

In which ρ is the distance between origin and a line that contains point (x, y), and $\theta \in [0, \pi]$ is the angle between the line and x-axis. Usually an accumulator Matrix H defined on the parametric space is used to record the integrated values. In SHT applications, the value is plot's amplitude. However, for the detection of weak radar targets submerged in strong clutters, amplitude or energy is not so creditable. As a modification of the SHT, here we propose to use the plot's quality as instead.

After using the modified HT towards **Z**, peak detections will be made in matrix H and a final detection and track reports will be outputted.

3 The Definition and Calculation of Radar Plot Quality

3.1 The Definition of Radar Plot Quality

In this paper, we say that the quality of a suspect plot was decided by four different kind factors which are the EP numbers, the local signal noise ratio (SNR), the range/azimuth match degree and the Doppler match degree. The composite influence of the four factors was described as the average quality of the suspect plot, which was denoted as

$$\bar{q} = Average(q_{EP}, q_{SNR}, q_{RA}, q_D) \tag{3}$$

where q_{EP}, q_{SNR}, q_{RA} and q_D are respectively the quality decided by EP numbers, local maximum SNR, range/azimuth match degree and Doppler match degree. All the four special kind quality index ranged in [0, 1]. For non-coherent radar applications, just q_{EP}, q_{RA} and q_E will be used.

To enhance the disparity between high quality plots and low quality plots, a nonlinear function $g(\cdot)$ was designed to map $\bar{q}$ to the total PQ of the suspect plot Q

$$g(\cdot): \quad Q = \begin{cases} \sqrt{\bar{q}} & \bar{q} > q_{th} \\ \bar{q}^2 & \bar{q} \le q_{th} \end{cases} \tag{4}$$

where q_{th} is the threshold for the partition of high PQ and low PQ plots, commonly in coherent radar cases we define $q_{th} = 0.5$ and in non-coherent radar cases we define a bigger q_{th}. Both the domain and range of $g(\cdot)$ are within $[0,\ 1]$.

3.2 The Calculation Algorithm of Plot Quality

Now we consider in detail the calculation algorithm of q_i for all suspect plots, assuming that target is point-like and non-fluctuant in the coherent process interval (CPI).

3.2.1 The Calculation of q_{EP}

The total number of EPs being used in the centroid procession of a suspect plot can somehow reflect the plot's reliability. Actually the more a suspect plot contains EPs, the more likely it was from a real target.

The EP numbers decided plot quality index q_{EP} was given here as

$$q_{EP} = \frac{N_{ep}}{N_d} \tag{5}$$

in which N_p is the EP numbers and N_d is the total detection times of the plot.

3.2.2 The Calculation of q_{SNR}

Denote the maximum amplitude of the suspect plot's EPs as A_{EP} and the corresponding CFAR threshold as V_T, the quality of SNR q_{SNR} was given as

$$q_{SNR} = \max_{1 \le i \le N_p} \left(\frac{A_{EP} - V_T}{A_{EP}} \bigg|_i \right)^2 \tag{6}$$

The search of maximum value was conducted among all the EPs of the suspect plot. In radar CFAR detection, V_T is subjected to mean power of the local noise or clutters. For all the suspect plots, q_{SNR} is ranged from 0 to 1 since A_{EP} is always bigger than V_T. The more A_{EP} exceeds V_T, the bigger will q_{SNR} be valued, which can be an instruction of plot quality related to local SNR.

3.2.3 The Calculation of q_{RA}

The echo of a real target has its own particular range and azimuth extension features, which are quite different from that of clutter or jamming. These features are actually decided by the radar's match filter designation and antenna gain function.

Here we design q_{RA} as the match degree of the range azimuth extension (RAE) feature between the suspect plot and an ideal point-like target. Denoting the RAE function of an ideal point-like target as $\mathbf{E}_{IT}$ and the RAE function of a suspect plot as $\mathbf{E}_{EP}$, then q_{RA} can be defined as follow

$$q_{RA} = \frac{\|\mathbf{E}_{IT} \cdot \mathbf{E}_{EP}\|^2}{\sqrt{\|\mathbf{E}_{IT}\|^2} \cdot \sqrt{\|\mathbf{E}_{EP}\|^2}} \tag{7}$$

where

$$\mathbf{E}_{IT}(r, \phi) = H_R(r) \cdot H_A(\phi) \tag{8}$$

In which $H_R(r)$ and $H_A(\phi)$ are respectively the radar's match filter responding function and the antenna's round trip gain function towards an ideal point-like target. Both $H_R(r)$ and $H_A(\phi)$ are only subject to radar itself, and can be acquired by actual measurements. $\mathbf{E}_{EP}(r, \phi)$ is the measured RAE and can be calculated from the suspect EPs' amplitude and position. If in a particular (r, ϕ) cell, an EP does not exist; then we just simply set the value of this cell to be zero.

3.2.4 The Calculation of q_D

As to talking about coherent radar applications, there exists additional Doppler information that can be used for plot quality calculation. In coherent radar signal processing, traditionally moving target detection (MTD) technology was used to suppress clutter, and then CFAR was implemented upon ranges for each Doppler channel. When a moving real target with identifiable radial velocity exists, special peaks will occur in corresponding adjacent channels and present a Sinc-function like amplitude Doppler spectrum feature.

We present here to define a suspect plot's Doppler quality index q_D by using the match degree of the plot's measured Doppler spectrum towards real target's theoretical spectrum. Denoting the Doppler spectrum of the suspect plot measured in a CPI as $S_d(f)$ and the expected target's theoretical spectrum as $S_{ref}(f)$, then q_D was given by

$$q_D = \frac{\int S_d(f) \cdot S_{ref}(f) df}{\sqrt{\int S_d^2(f) df} \cdot \sqrt{\int S_{ref}^2(f) df}} \tag{9}$$

If the MTD was implemented by the fast Fourier transform (FFT) algorithm, then the discrete analytic expression of $S_{ref}(f)$ can be given as

$$S_{ref}(n) = \frac{\sin[\pi N(f_d/f_r + m/M)]}{\sin[\pi(f_d/f_r + m/M)]} \tag{10}$$

This is directly the magnitude response of the m-th Doppler filter channel of FFT based MTD, where M is the numbers of Doppler channels.

4 Simulation and Results Analysis

To validate the proposed method and evaluate its performance, Monte Carlo simulations were made considering a K-distributed sea clutter environment.

4.1 The Generation of K-Distributed Sea Clutter

Firstly, K-distributed temporal-spatial correlative sea clutter was generated using the famous SIRP method given in detail by reference [15]. Main parameters of the simulated sea clutter were shown in Table 1. Figure 2 shows an example of the simulated coherent sea clutter's amplitude and its fitting probability density compared with a theoretical K distribution of exactly same parameters, which demonstrates that the simulation method works well.

Table 1. Main simulation parameters of the sea clutter

Simulation parameters	Value
Shape factor	1.71
Scale factor (*b*)	3.52
Radar direction towards wind	0°
s.t.d of clutter spectrum spread	66.67 Hz
Wind speed	10 m/s

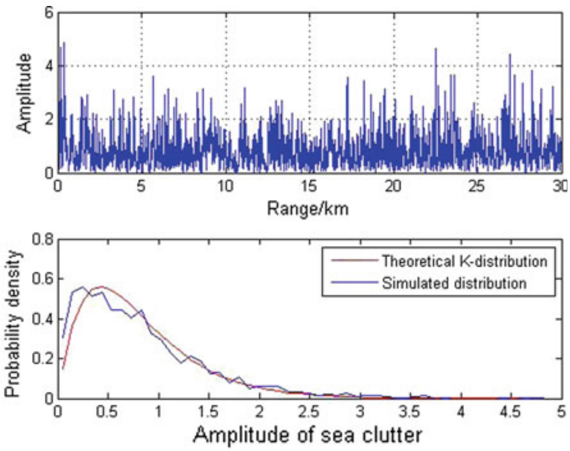


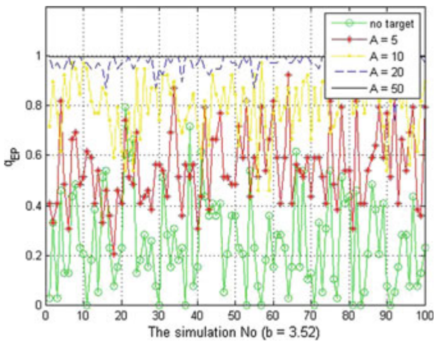
Fig. 2. The simulated K-distributed sea clutter

4.2 The Validation of PQ Calculation Algorithms

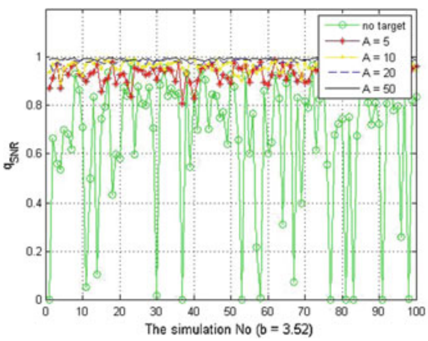
Then we consider a marine target with a radial velocity of 4 m/s observed by coherent radar in K-distributed sea clutter environment. The simulation parameters of sea clutter is same as Sect. 4.1 and the simulation parameters of radar was set as follow: the wavelength $\lambda = 3\,\text{cm}$, the PRF is 1000 Hz, the 3 dB beam width is 1.8°, the range resolution is 15 m, and the scan period is 2.5 s. A sixteen point FFT algorithm was used for MTD and CA-CFAR algorithm with a normalization factor of 2 was used for CFAR detection. The amplitude of simulated target coherent echo is defined as A, and A/b decided the SNR of the input echoes. The simulation was done for 100 times.

The calculation results of component PQ index q_{EP}, q_{SNR}, q_{RA}, q_D using the simulated target and clutter data under different input SNR conditions were given in Fig. 3, and the calculation results of total PQ for non-coherent and coherent radar applications were given in Fig. 4.

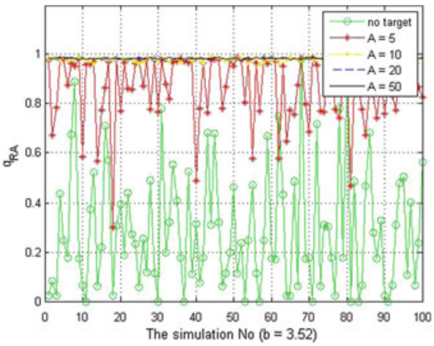
From the results shown in Figs. 3 and 4, we can conclude that: (a) As far as the input SNR is not too low, in this simulation case such as $A/b \geq 10/3.52$ was satisfied, all the four presented quality indexes can successfully distinguish real target plots from clutter induced false alarm plots. (b) Among the four different quality indexes, especially in low input SNR conditions, q_D has the best performance and q_{EP}, q_{SNR} are more or less confusing, which means that the introduction of q_D made great difference. (c) The designed calculation algorithm for Q is quite effectual and robust, which was shown in Fig. 4, even in quite low input SNR conditions, target and clutter are still mainly distinguishable.



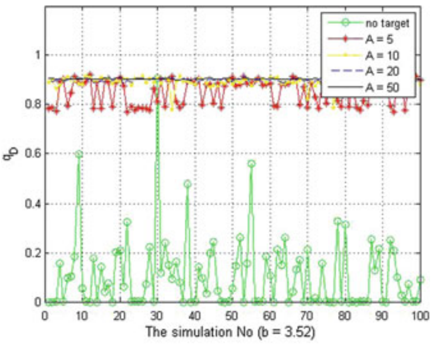
(a)The calculation results of q_{EP}



(b) The calculation results of q_{SNR}

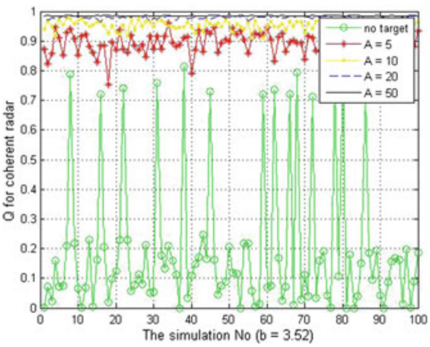


(c) The calculation results of q_{RA}

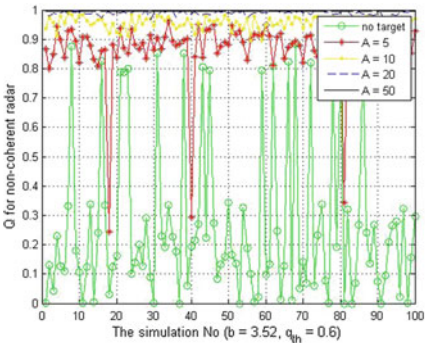


(d) The calculation results of q_D

Fig. 3. The calculation results of q_i



(a) Coherent radar case

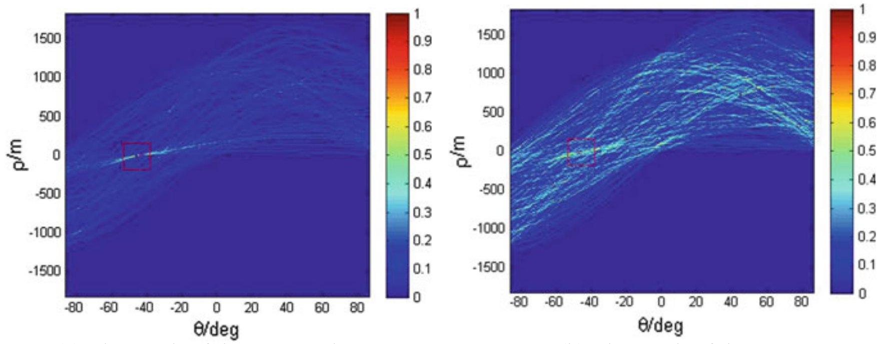


(b) Non-coherent radar case

Fig. 4. The calculation results of Q for coherent and non-coherent radars

4.3 The Performance of the PQ-HT TBD Method

Assuming a marine target started from $(0\,\mathrm{m},\ 0\,\mathrm{m})$ sailing with the speed of $(3\,\mathrm{m/s}, 3\,\mathrm{m/s})$ and seven scans radar observations were integrated. The number of false alarm plots per scan is controlled to be random variable uniformly distributed in the range of [40, 45]. Other simulation parameters are set as same of Sect 4.2. Figure 5a gives the results of the proposed PQ-HT algorithm in the condition of A = 3, as a comparison the results of SHT with magnitude accumulation was given in Fig. 5b, in which the red square indicates the position of the real target and all the values are normalized by the maximum peak.



(a) The result of the proposed PQ-HT (b) The result of the SHT

Fig. 5. Results comparison between the PQ-HT and SHT

Let the threshold of peak detection to be 0.8 (H has been normalized), Table 2 gives the mean false alarm numbers n_{fa} of the two algorithm with different input SNR conditions. For each input SNR condition, Monte Carlo simulation was done for 50 times.

Table 2 Mean false alarm numbers of PQ-HT and SHT

$A(b = 3.25)$	1	1.5	2	3	4	5
n_{fa} (PQHT)	8.04	5.04	0.9	0.02	0	0
n_{fa} (SHT)	20.2	17.4	14.58	13.15	6.02	2.02

The results given by Fig. 5 and Table 2 show a significant advantage of the proposed PQ-HT compared with SHT in low SCR applications.

5 Conclusion

In this paper we introduced a new definition and calculation algorithm for the radar plot's quality, and then presented a modified HT based TBD method for radar weak targets in strong sea clutter using the defining plot quality information. Results of Monte Carlo simulations show the advantage of the proposed method.

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