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Original Article

Closely Spaced Target Detection and Tracking under Spatial Ambiguity in Marine Surveillance Radar

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Abstract - *Target detection in radar is based on the strength of the received signal. Received echoes are processed to identify the target of interest by comparing the strength of the baseband signal to the surrounding noise. Radar processors will generate two plots for two targets if the radar can resolve both targets. Two closely spaced targets will fall within a beam resolution cell, which results in the generation of a single plot for both targets by radar. In this article, a new centroid algorithm based on the flattening and holding technique is proposed. The received sensor data is processed for each Azimuth Change Pulse (ACP) to identify all possible plots. At this point, the plotted intensity values for the detected targets are identified at individual azimuth angles. The proposed centroid algorithm consists of two stages. In the first phase, a unique averaging process is applied to smooth the intensity curve when two target azimuths have different intensity values. In the second stage, a dynamic threshold is computed and applied to the smoothed curve to identify and extract the original targets along the target spread in the ambiguity region.*

Keywords - *Range and azimuth, Azimuth change pulse, Sensor resolution, Strength averaging, Dynamic threshold.*

1. Introduction

If the surveillance radar has a wide azimuth beam width, then the magnitude of the pulse volume increases with distance in maritime conditions. In scenarios where two or more targets are spatially closely spaced, sensor raw video for those targets will appear within a single beam resolution cell [1]. Any raw video within a resolution cell results in the generation of a single target, and radar cannot distinguish them as multiple targets—detection of two closely spaced targets as a single target results in ambiguous tracking. Target tracking ambiguity leads to wrong estimation of track parameters and changes in track ids for each target. In some conditions where two targets are moving in opposite directions when they cross over each other very closely, they will fall within a single-resolution cell, resulting in the generation of a single target. Because of this discontinuity in plots, the tracker deletes previous traces and creates new traces for these closely spaced targets for a limited number of scans.

In order to avoid the detection ambiguity of two closely spaced targets, a new centroid processing algorithm [2] is proposed. The proposed algorithm is designed to develop a generic centroid [3] and meet the centroiding requirements of all modern radar applications a combination of intensity smoothing and dynamic thresholding techniques used in the algorithm. The proposed algorithm provides a new, efficient approach for tracking two closely spaced targets.

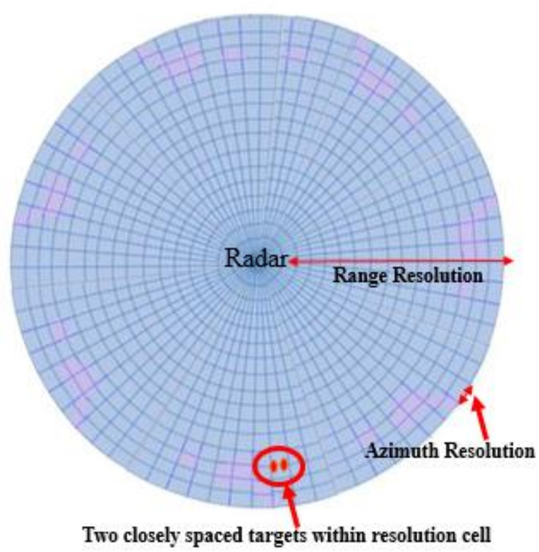

Fig. 1 Radar range resolution with 360^0 radiations

As represented in Figure 1 above, each cell represents the resolution in azimuth and range of the typical surveillance radar. Detections within the resolution cell will be detected as a single target. Even though two targets are present in the resolution cell, radar sensor will detect them as single targets.

2. Working Methodology

2.1. System Working Description

Description of the typical marine radar system processing chain. The Radiofrequency signal received by the antenna is first converted to a lower Intermediate Frequency (IF) for further processing. The signal then undergoes noise suppression with a filter. The Sensitivity Time Control (STC) polynomial curve fitting method is then used to control the system's sensitivity to short-range reflections. The processed data is then sent to the receiving module, where clutter mapping, clutter modeling, and Constant False-Alarm Rate (CFAR) processing are performed. The signal is then further processed on the processing board, the centroid procedure is performed, and the resulting track and detection output is displayed on the target display.

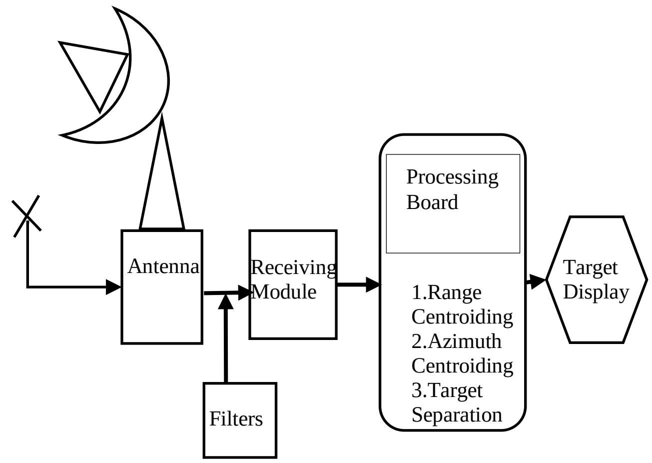

Fig. 2 Block diagram of radar signal processing

Table 1. Typical input data format

ACP.NO/ Range Bin	**Range Bin1**	**Range Bin2**	**Range Bin3**	**....**	**Range Bin4096**
ACP1	1.41732	3.46457	4.64567	**....**	5.19685
ACP2	0.39370	2.3622	4.09449	**....**	5.03937
ACP3	1.41732	3.70079	4.56693	**....**	5.11811
ACP4	2.04724	3.46457	4.56693	**....**	5.27559
ACP5	1.49606	3.30709	4.25197	**....**	5.19685
ACP6	0.55118	1.88976	3.77953	**....**	5.11811
ACP7	1.88978	4.09449	4.64567	**....**	5.35433
ACP8	0.23622	2.20472	3.38583	**....**	5.19685
ACP9	1.5748	3.07087	4.40945	**....**	5.11811
....	**....**	**....**	**....**	**....**	**....**
ACP4096	1.65354	3.46457	4.64567	**....**	5.27559

2.2. Input Data format

Typical input data received by the receive module consists of 4096 ACPs per scan. Each ACP has 4096 range bins arranged in a 4096 x 4096 array for further processing and analysis. Each range bin has an associated intensity value. Intensity values should be based on reflections from real targets or sea clutter.

All ACP data are processed for range detection, and consecutive ACPs are used for azimuth extraction. Each ACP has 4096 range bins per scan, as shown in Table 1; it will be used to detect targets and further apply range approximation to distinguish the two merged targets at their respective ranges and azimuths.

3. Survey of Traditional Methods of Target Detection and Tracking

Range-bearing Centroid Processing of Surveillance Radar [4] reviews several centroid processing techniques and presents a new central mass algorithm implemented using a recursive least squares algorithm.

However, this technique mentioned requires heavy-duty hardware with many vector processing units. Further merged measurements are observed that multiple closely spaced targets appear to be a single target if the space between the targets is less than the range resolution. Range resolution is set constant to avoid computation complexity, but this decreases the accuracy of detecting the target.

In the traditional beam-split algorithm, which uses the classic plot centroid procedures, is straightforward and often used. Its azimuth estimation equation [5] is as follows:

$$\hat{\theta} = \frac{(\theta 1)+(\theta 2-\theta 1)}{2} \quad (1)$$

where $\theta 1$ and $\theta 2$ are the azimuth's starting and ending points, respectively, and is the estimated value of the azimuth. Since this method does not take amplitude information into account, the estimation's departure from the true azimuth can be substantial.

The approximate maximum likelihood estimation is another key component of the “Centroiding process” [6][7]. The following is a representation of the azimuth estimation value derived using the one-dimensional “Centroiding” algorithm:

$$\hat{\theta} = \frac{\sum_{i=1}^{n} Ai\theta i}{\sum_{i=1}^{n} Ai} \tag{2}$$

Where Ai is the plot's amplitude value i, where θi is the azimuth value.

Typically, pulse compression results in echoes of a target higher than the threshold in certain nearby range cells. The azimuth estimate values are calculated in the range cells in accordance with equation (2). These values actually belong to the same target. As a result, the goal of plot centroid is to combine azimuth and range numbers to acquire the target's actual information.

The "Centroiding" methodology uses amplitude information [8]; however, this algorithm trusts all observed plots in a frame. Therefore, it is possible that there are a few strong false plots in the plot group, increasing the estimation divergence.

4. Proposed Algorithm for Closely Spaced Target Detection and Tracking under Ambiguity

To address the problems of conventional techniques, a novel algorithm based on intensity smoothing and dynamic threshold control is proposed.

The algorithm mainly consists of two components:

4.1. Two-Dimensional Intensity Smoothing

4.1.1. Range Spread Measurement

- A weighted area centroiding [3, 9]is performed for all ACP data.
- Allows up to 3 errors to check the continuity of intensity values in each range area. If three consecutive errors are found, consider the next set of intensity values as another target.
- For each target, save important target information such as target intensity for each bin, start range bin, end range bin, and save detected target range and intensity for processed ACPs.
- This range spread measurement [10] is performed on 4096 x 4096 matrix input data. For each range centroid chart, the target range is calculated as follows.,

$$Range = \frac{SR+ER}{2} * RR \tag{3}$$

Here,

SR = Start Range ER = End range

RR = Range Resolution

After this step, Range spread measurements are used for Azimuth spread measurement.

4.1.2. Azimuth Spread Measurement

- Azimuth spreads [11] for consecutive ACP data are measured on the range spread measurements.
- Check for the continuity of range detection across the ACPs. If the range detection is unavailable for two consecutive ACPs, consider next detections as new plots.
- Once the plot is extracted, perform the Azimuth spread measurement process.
- For each plot, store critical target information like Target strength in each bin, Start Azimuth and End Azimuth to get the Target Azimuth of the detected plot.
- For each Azimuth Centroided plot [12, 13], the target azimuth will be calculated as

$$Azimuth = \frac{SA+EA}{2} * AR \tag{4}$$

Here,

SA = Start Azimuth EA = End Azimuth

AR = Azimuth Resolution

Start and end range values start and end azimuth values are updated. Then, the target range and target azimuth values are updated.

After this step, Azimuth spread measurements are used for Intensity normalization.

4.1.3. Strength/Intensity Normalizing

As shown in Figure 3 below, the typical plot strength of the closely spaced targets is asymmetric across the range bins and azimuth angle. Threshold estimation using the conventional method like Constant False Alarm Rate (CFAR) leads to the detection of asymmetric closely spaced targets as single plot detection.

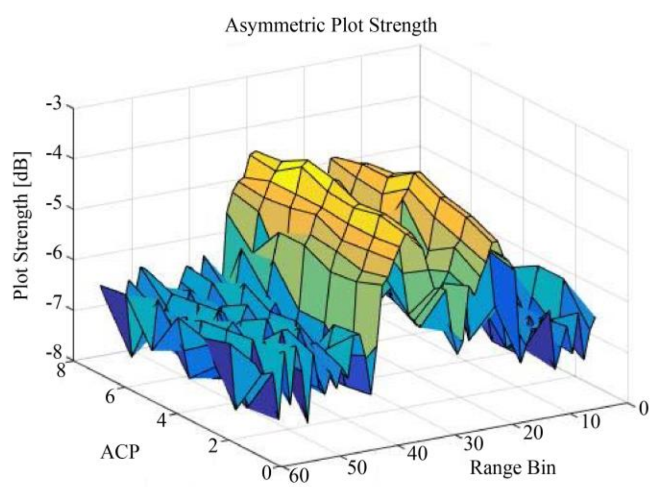

Fig. 3 Original irregular target strength

- In this step of the proposed algorithm, smoothing of the strength value is performed by averaging the consecutive intensity of range bins across all the detected ranges and across all the detected ACP [14] within azimuth spread measurements.
- Normalizing: As range bins of a target have random strength values, strength averaging [15] is performed to get the uniform curve. It is done by taking the average of 3 adjacent values of range bins over the range of the detected target.

$$NS = \frac{\sum(Target[i]+Target[i+1]+Target[i+2])}{3} \quad (5)$$

Here,

NS= Normalized Strength

4.2. Dynamic Thresholding

- This is the second step of the proposed algorithm, in which a threshold will be calculated to distinguish close targets.
- Maximum Strength: Find out the maximum strength [16] value by traversing through the stored target data measurements.
- Thresholding: To find the dynamic threshold value for the target data measurements, use the maximum strength value of the detected plot. Consider the threshold value as 30% of the maximum detected strength. By keeping the threshold value at 30% of the maximum strength, fill all the remaining range bins with zero where its strength value is less than 30% of the maximum value. After finding the dynamic threshold, closely spaced targets are discriminated in the following way.
- Start traversing from the first range bin of the target measurements until the first non-zero value is encountered. Save this range bin value as the target's Starting Range (SR).

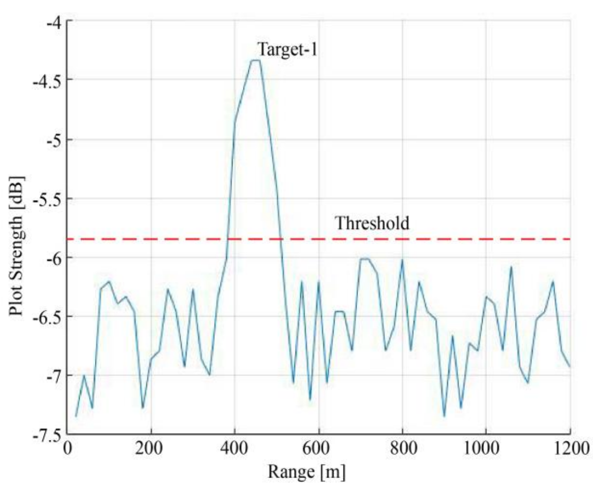

Fig. 4(a) Thresholding in the single target scenario

- Then, proceed until the first zero value is encountered. Save this range bin value as the End Range (ER) of the target.
- Repeat the above two steps until the last bin reaches the end of the measurements.

For a single target scenario like Figure 4(a), the extent of discontinuity in detection was not observed after applying the threshold calculated in the previous step.

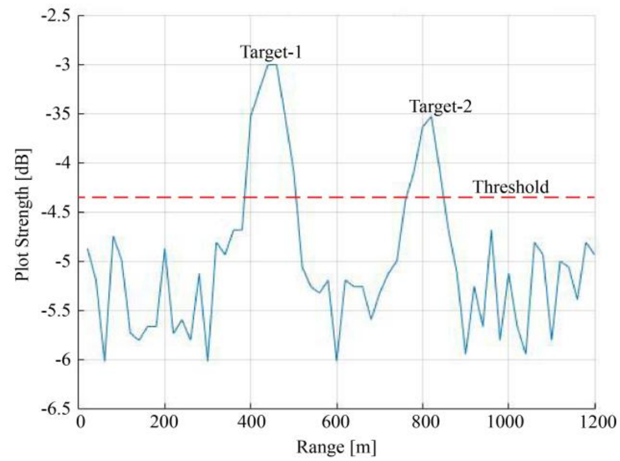

Fig. 4(b) Thresholding in two closely spaced targets scenario

For the scenario where two targets are closely spaced, as shown in Figure 4(b), the range of discontinuities is observed after applying the threshold calculated in the previous step, resulting in the discrimination of the two closely spaced targets.

5. Results and Discussion

The MATLAB analysis of the proposed algorithm showcases target detection, discrimination and tracking with crossover/ closely spaced conditions.

The echo received by the S-band RADAR determines the range and angle at which the object is detected. A specific threshold value is predefined so that environmental disturbances do not lead to false object detection. Threshold values can be changed depending on various factors such as range and magnitude. The peaks correspond to the defined target centers, the point on the target where the radar cross-section is determined to be the highest.

The scenario under discussion occurred on one of the survey routes where two ships were determined to be moving towards each other with very little distance between them.

As shown in Figure 5(a), (b) above, two tracks with track ids T1 and T2 were initiated for both the ships. The target id is consistent when the targets are sufficiently separated and easily distinguished at the plot level.

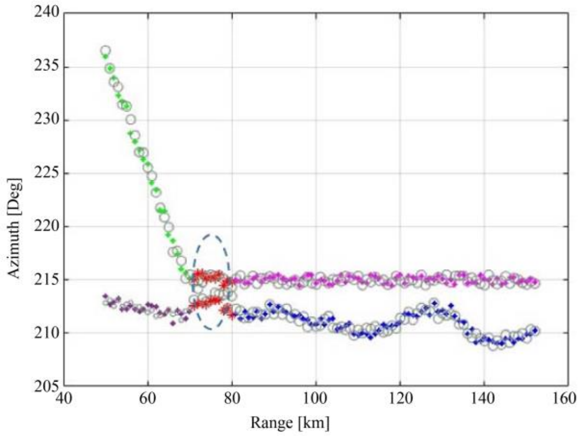

Fig. 5(a) Two targets approaching towards each other with ambiguity

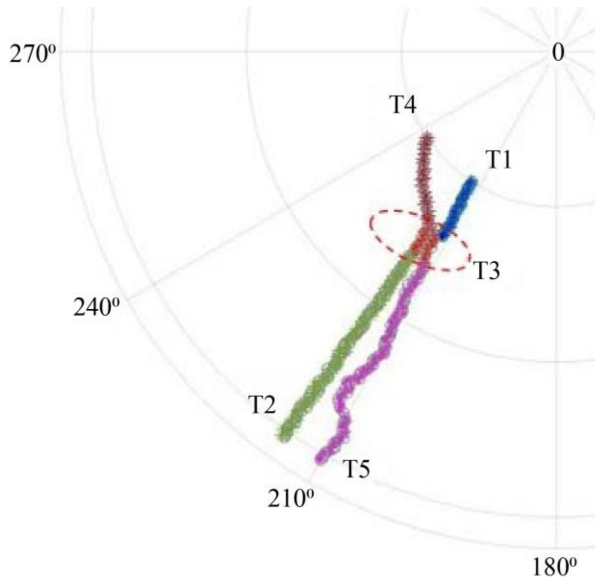

Fig. 5(b) Two targets approaching towards each other with ambiguity (Polar plot)

Table 2. Target 1 and Target 2 parameters

Target 1	Target 2
Outbound target. Track Initiated at 10KM & Bearing of Approx.210° Track ID: T1 before Ambiguity T3 at Ambiguity Region T5 after Ambiguity	Inbound target. Track Initiated at 30KM & Bearing of Approx.203° Track ID: T2 before Ambiguity T3 at Ambiguity Region T4 after Ambiguity

When both the targets come close to each other or even cross over, ambiguity arises in detecting and tracking the targets. In this case, target tracks get distorted, and the target plot merges, showing two targets as a single target with new track id T3.

Again, after crossing the ambiguity region, the new tracks are initiated for both the tracks with new tracks id's T5 and T4, respectively, as shown in Table 2 above.

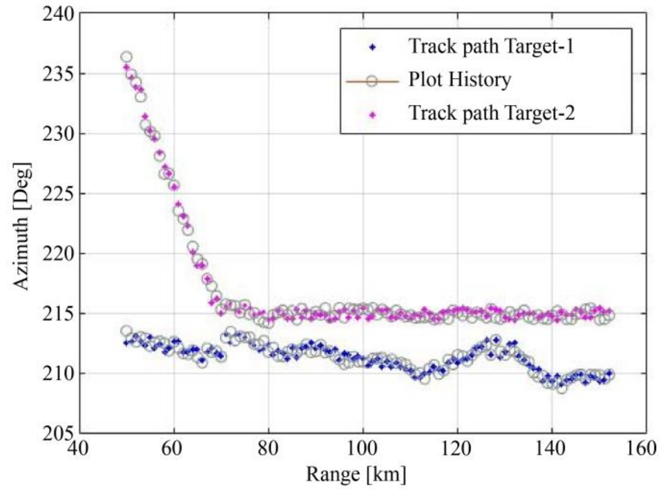

Fig. 6(a) Two crossover targets tracking with the proposed algorithm

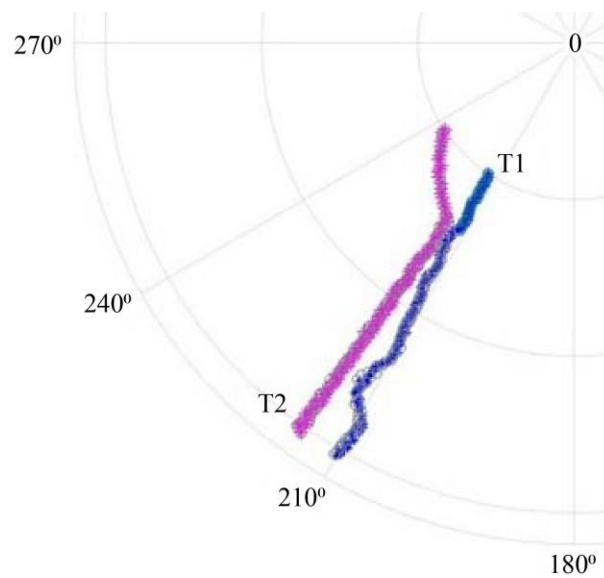

Fig. 6(b) Two crossover targets tracking with the proposed algorithm (Polar plot)

As shown in Figure 6(a), (b) with the proposed algorithm applied to the data set, the approximate size of the target can be determined by observing the threshold crossing points. Thus, it can be concluded that there are two distinct targets.

Target 1 is detected and initiated tracking with track id T1, and Target 2 is detected and initiated tracking with track id T2 even at the ambiguity region, as shown below in Table 3. Therefore, the proposed algorithm generates two distinct target signatures and provides the target size, range and azimuth.

Table 3. Target 1 and Target 2 parameters after the proposed algorithm

Target 1	Target 2
Outbound target. Track Initiated at 10KM & Bearing of Approx.210° Track ID: T1 before Ambiguity T1 at Ambiguity Region T1 after Ambiguity	Inbound target. Track Initiated at 30KM & Bearing of Approx.203° Track ID: T2 before Ambiguity T2 at Ambiguity Region T2 after Ambiguity

The algorithm applies azimuth centroid, range focus, and target separation to improve target recognition and tracking.

5.1. Scenario 1: The Proposed Algorithm is also used on the GUI for Target Detection. Scenario 1 is Drawn before the Proposed Algorithm

Analysis is also performed using Qt GUI (Graphical User Interface), which is used to spot the targets on the display. As shown in Figure-7(a) below, targets are approaching towards each other with track ids 164 and 228. The track id is consistent when the targets are sufficiently separated and are not ambiguous for detection.

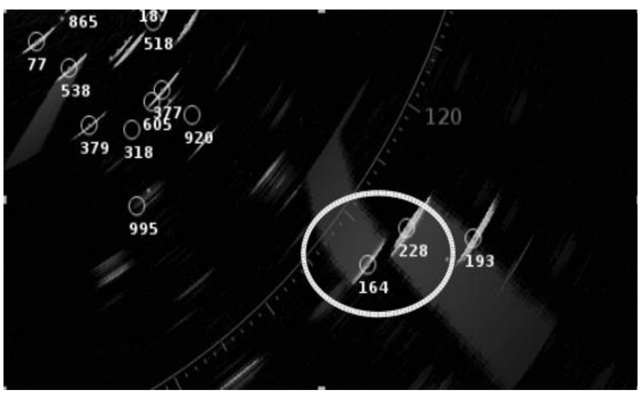

Fig. 7(a) Targets approaching towards each other

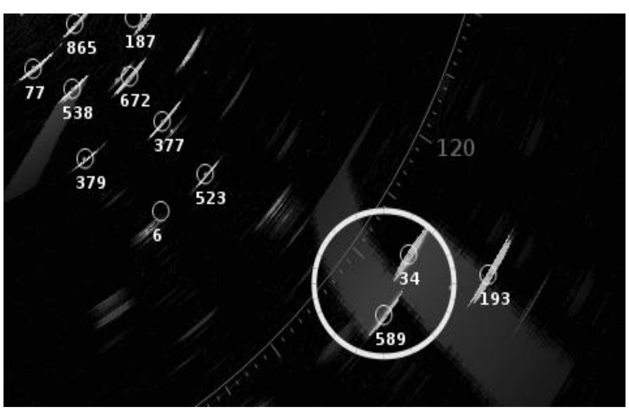

Fig. 7(b) Targets after crossover with the old algorithm

Table 4. Target 1 and Target 2 parameters (Scenario 1)

Target 1 (Outbound Target)	Target 2 (Inbound Target)
Track ID: 164 before Ambiguity Region Track ID: 589 after the Ambiguity Region, a New Track ID is Generated	Track ID: 228 before Ambiguity Region Track ID: 34 after the Ambiguity Region, a New Track ID is Generated

Once both the targets approach nearby to each other, the tracker drops/deletes the current tracks due to ambiguity in detection. After both the targets cross over, the tracker generates new tracks for both targets with new random track ids 589 and 34, as shown in Figure 7(b). The track ids get distorted when the targets come close to each other or even cross over; in this case, the track ids change.

5.2. Scenario 2 is Plotted According to the Proposed Dynamic Threshold Control and Intensity Smoothing Algorithm

When the proposed algorithm is applied, track ids 244 and 1 are maintained, as shown in Figures 8(a) and 8(b) below.

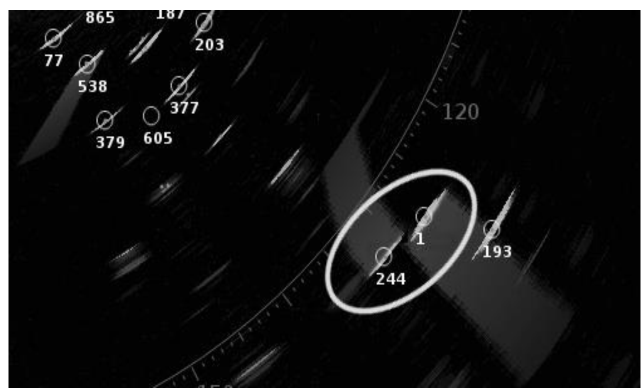

Fig. 8(a) Targets before crossover

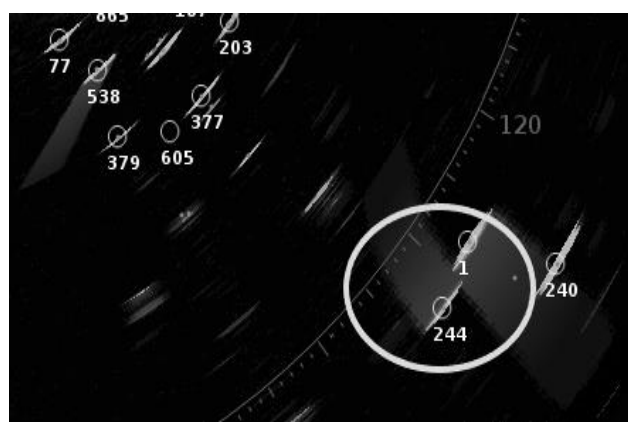

Fig. 8(b) Targets after crossover with the proposed algorithm

When the targets approach each other and cross over, the track ids won't change even in ambiguous regions and mark the targets clearly, hence improving the target identification and tracking. Both targets get detected by applying intensity smoothing and dynamic thresholding for two closely spaced target scenarios

Table 5. Target 1 and Target 2 Parameters after the proposed algorithm (Scenario 2)

Target 1 (Outbound Target)	Target 2 (Inbound Target)
Track ID: 244 before ambiguity region Track ID: 244 after the ambiguity region, the same track id is maintained	Track ID: 1 before ambiguity Track ID: after the ambiguity region, the same track id is maintained

6. Conclusion

The innovative centroid processing algorithm presented in this experiment proved to be a successful solution to the challenges of target detection and tracking of closely spaced targets in oceanographic radar systems. With the conventional center-of-gravity approach, the spread of the radar beam makes it difficult to separate nearby targets. However, new algorithms overcome this problem by incorporating smoothing and thresholding techniques to reduce noise and false targets and improve accuracy.

This algorithm effectively processes the input data by detecting the strength of the received signal and applying a unique averaging process and dynamic thresholds to extract the original target. The result is a robust and efficient target-tracking method that prevents two objects from merging on the tracker.

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