Optimised Scan-to-Scan integration techniques for low observable target detection in sea clutter

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Abstract— **Detection of low RCS (Radar Cross section) targets (e.g small boats) immersed in Sea clutter has always been a challenge, but with a critical detection requirement. Apart from small boats entering into the territorial waters, Unmanned Aviation Vehicles over land and sea that are involved in EW assignments and also submarine periscopes are targets of interest. Such targets have weak reflected/scattered power, masked by strong correlated sea clutter and ground clutter returns. Extracting such weaker and unstable target returns requires efficient, reliable and robust Target detection methods and techniques. One of the detection methods viz Scan to Scan integration and their enhancement, exploiting the decorrelation properties of sea clutter over several antenna scans, will be analysed in this paper, with appropriate illustrations.**

Keywords—sea clutter, scan-to-scan integration, small targets

I. INTRODUCTION

Small surface targets like the small boats, buoys, low-flying aircraft etc are not detected optimally by current marine navigation (and other) radar systems because the detection process has to compete against severe land and sea clutter. Moving target detection processes that are used for air targets generally, are impractical for a sea surveillance system because (a) the length of the dwell required to obtain sufficient Doppler information is prohibitive and (b) the Doppler frequency range of the sea surface covers the same velocity range as the targets of interest. Potentially, the polarization processing could be a discriminator between the sea surface and many types of small boats, but this would require the implementation of additional RF hardware with associated increase in system costs. Potentially, we can exploit the persistence of surface targets to enhance the detectability of these targets, by using a motion compensated track before detect system.

The sea clutter returns encountered by the radars are very much dependent on the sea state, radar grazing angle, wind velocity and direction. Furthermore, sea returns generally present sea spikes, which will impact on the target detection performance, especially for the targets of slow speed and low RCS. The detection of such targets become *more* difficult, when a) the grazing angle of radar is lower than 3 degrees, b) the lengths of these targets become *smaller* than 30m and c) the height of these targets being low, such as growlers, buoys, and small boats. The power levels of the radar returns from these small targets are equal or less than those of clutter peaks.

Conventional Scan-to-scan integration techniques for detecting small target have been discussed in the literature [1][2]. This paper investigates an optimized and enhanced scan-to-scan integration of the sea returns for detecting targets of small RCS and low signal-to-clutter ratio. The discussions and analysis in this paper are based on the data collected from a X-band marine navigational radar that was operating in a small target environment around northern parts of Australia.

This paper is organized as follows: In section II, the scan-to-scan integration techniques and the associated parameters and their variation and effects on the integrated signal are presented. Also the characteristics of collected data i.e., the signal strength of the video samples at each of the range and azimuth cells of the individual scans are analysed in section II. In section III, the results of enhanced scan-to-scan integration that includes various constant false alarm rate (CFAR) algorithms and binary integration processes on the integrated signal for clean removal of residual clutter components are presented. Lastly, results obtained with these algorithms and future scope of work are discussed.

II. SCAN -TO- SCAN INTEGRATION METHOD

A. Algorithm development

Scan-to-scan integration for non-coherent radar exploits the use of consecutive radar scans (one full rotation of the antenna) to enable detection of small targets in the presence of severe clutter background [1]. For instance, the radar returns corresponding to the polar coordinates viz Range (R) and Azimuth (ø), in a typical plan position indicator (PPI) display, are stored as a 2-D matrix (Azimuth angle and Range). Then, the scan-to-scan integration algorithm applies a weighting factor (α) to the video amplitudes at each of the range and azimuth outputs of each scan as per the expressions below:

$$\boldsymbol{B}_k = \alpha \boldsymbol{A}_k + (1-\alpha)\boldsymbol{B}_{k-1},$$

and

$$\boldsymbol{B}_1 = \boldsymbol{A}_1;$$

Where $\boldsymbol{A}_k$ is the output of the current scan
$\boldsymbol{B}_{k-1}$ is the output of the previous scan and
α is a variable parameter between 0 and 1

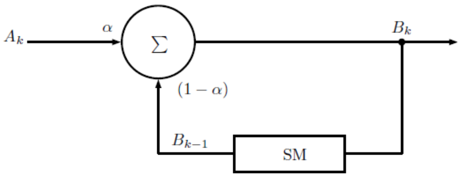

Fig 1. Scan-to-Scan Integration process

Thus $\boldsymbol{A}_k$ is a 2-D matrix representing the returns at k^{th} scan and α is a scalar number representing the weighting factor. If alpha is unity then the integrated value is the same as that of the amplitude of the current scan. If alpha is zero then the integrated value is the amplitude of the previous scan. So the integrated value varies between the current or the past based on the value of alpha.

If K is the number of scans to be integrated and $k = 2, \dots, K$ is the scan index, $\boldsymbol{B}_K$ gives the integrated result of the amplitudes of the specific range-azimuth sample.

The notable effect of the integration over several scans is seen as the reduction of the uncorrelated clutter magnitude, whilst the levels of the targets are maintained.

Refer to Fig. 2 for a typical B Scope plot of detection range (x-axis) against the azimuth angle (y-axis) of a single scan output.

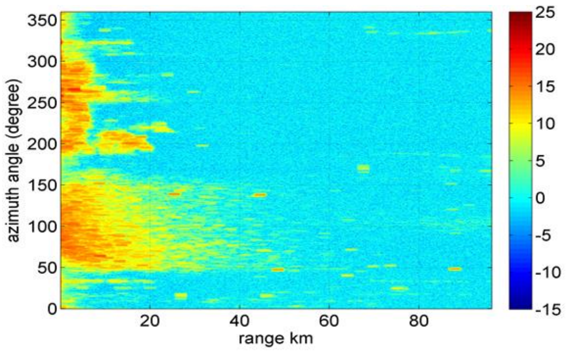

Fig. 2. Azimuth vs Range plot of single scan output

Refer to Fig 3 for the integrated output over 20 consecutive scans where α is set at 0.06.

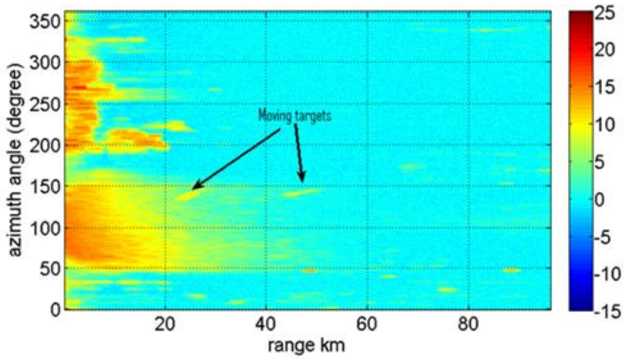

Fig. 3. Scan to scan integrated output for $K = 20, \alpha = 0.06$

The two moving targets seen at approximately ~150 degress azimuth in Fig. 2 has a tail (long echo) as the past scan values are retained. The uncorrelated sea clutter returns are seen reduced in the integrated signal (between 20 and 40 km range, 50 and 150 degrees in azimuth).

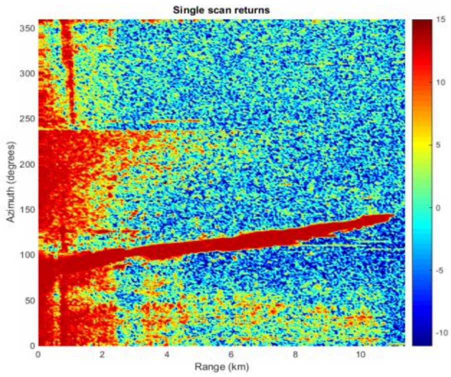

Fig 4. B Scope display of single scan output

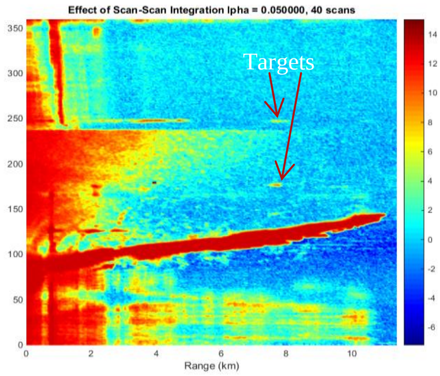

Fig 5. B Scope display of integrated output (after 40 scans)

Refer to Fig 3 above for the Range –Azimuth video display after a single scan and Fig 4 above for the integrated output after processing 40 scans of data with α = 0.05, in a combined sea clutter plus land clutter background. It could well be seen that the uncorrelated sea clutter returns have been reduced considerably and the targets detected well amidst the clutter.

B. *Data Structure*

The captured radar data is stored in three files, viz video file, trigger file and heading file. The video file has the data stored in a binary file in such a way that each data sample is a 16 bit signed integer. The trigger file stores an array of indices, which represents the time instance at which the radar starts receiving target returns. Each index is an 32 bit integer. The heading file stores an array of 32 bit indices each sample index relating to the start of a new scan. Each scan represents a full 360 degrees in azimuth.

The radar that was used to capture data from the sea for all the above analysis was a magnetron based Furuno X band marine navigational radar with the following key parameters.

Transmit (peak) power: 25 kw

Antenna Beamwidth: 1.8 deg (Az) and 20 deg (Elevation)

Antenna rotation rate: 24 RPM (2.5 sec per scan)

Fig. 1 represents the data collected through 360 degrees of antenna rotation in azimuth. It should be noted that the data is severely contaminated by sea clutter for the range below 10 km.

III. OPTIMISED SCAN- TO- SCAN INTEGRATION TECHNIQUES

Scan-to-scan integration process is further optimised by the sliding window adaptive threshold detection (CFAR processing) followed by post-detection binary integration. This algorithm is tested using injected synthetic targets amidst the real time clutter background.

A. *Target Simulation:*

Synthetic target is modelled as static, Swerling 0 (constant SNR from scan-to-scan and pulse-to-pulse) and uniformly spread over 3 range bins. The mean noise level of the designated region (refer Fig 6) is estimated.

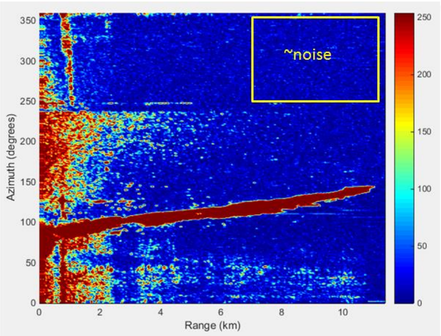

Fig 6. Range – Azimuth plot with the 'noise zone'

Next, the required level of the target corresponding to the desired SNR (Signal-to-Noise ratio) is calculated using the following relationship:

$$P_{Target} = P_{Noise} \times 10^{0.1 \times SNR}$$

Where P_{Target} is the magnitude of the injected target corresponding to the desired SNR.

This target data is inserted in the corresponding indices of the scan matrix, that relates to the desired azimuth and range coordinates. The simulated target data is spread out across three range cells.

B. *Algorithm development*

- CFAR Detection

Sliding window Constant False Alarm Rate (CFAR) adaptive threshold [3] schemes are applied to the output of the Scan-to-Scan Integrated output to test for the presence of spiky target returns. Their implementation includes assessing the magnitude of the reference cells collectively and a threshold multiplier to control the false alarm probability (P_{fa}). A decision rule to test the cell-under-test based on various types of CFAR algorithms is promulgated. The reference window is constructed as a sliding window across the range bins of constant bearing. At each position of the sliding window, a binary decision rule is applied to the Cell under test (CUT). If the magnitude of the CUT is greater than the adaptive threshold the CUT is declared a target; otherwise it is declared as an interference and will be suppressed.

The various CFAR detection schemes that were experimented include Cell averaging CFAR, Order Statistic CFAR, Trimmed mean CFAR and Dual Order statistic CFAR (DO CFAR). Description of these CFAR algorithms are beyond the scope of this paper.

- *Binary Integration*

The final element in the processing chain is the post-detection integration[4] which is a Binary Integration (BI) applied to the CFAR output. Refer Fig 7 for the functional diagram including all the three processes ie. SSI, CFAR and BI.

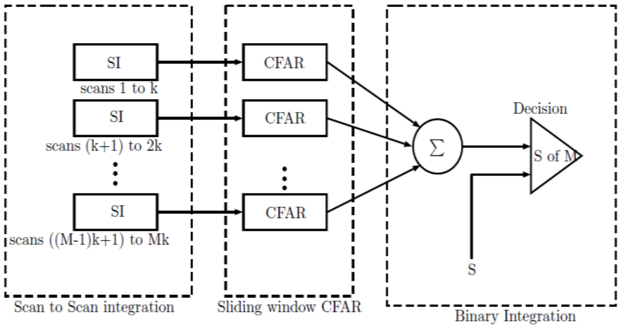

Fig 7. Binary Integration schematic diagram

General applications of Binary Integration aggregate the binary detection results following a series of M independent decisions and if S of M declare targets present, then a target is declared present overall. The optimal choice of S naturally depends on the characteristics (specifically correlation and motion) of the target. If the target fluctuates substantially or moves over the integration period, larger values of S may degrade detection performance. On the other hand, for static targets with constant RCS, larger values of S will greatly improve the performance.

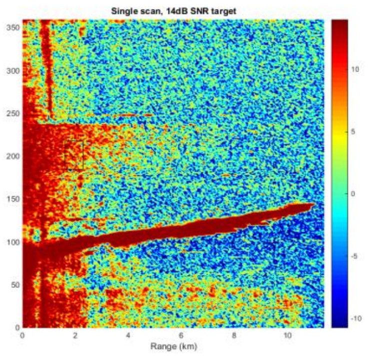

Fig 8. Range - Az display for a single scan

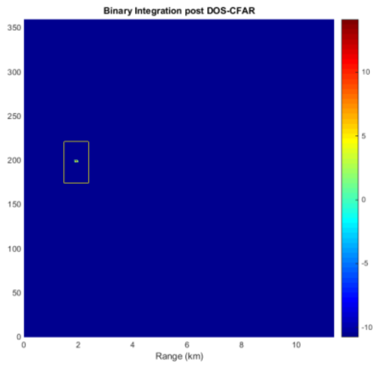

Fig 9. Range – Az display with a detected target

Fig 8 above is the single scan unprocessed video output and Fig 9 is the final output after SSI, CFAR and BI processing detecting only the simulated target.

IV. User Interface

A Matlab GUI was developed which is intended to allow the user to easily and efficiently experiment with the non-coherent detection processes discussed in this paper. We can specify the number of scans for scan-to-scan integration, CFAR parameters, Binary Integration selection criteria etc to test and optimize the detection performance for a given terrain background.

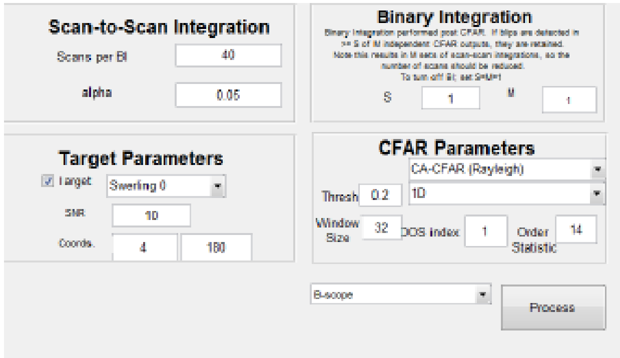

Fig 9. MATLAB GUI for Detection process

V. Results and Discussions

This paper discussed the various aspects of scan- to- scan integration techniques which has considerable reduction of the uncorrelated sea clutter due to the integration process of 40 or 60 antenna scans. This technique was further optimized through various types of sliding window CFAR processes like Cell averaging, Order Statistics, Dual Order Statistics etc and binary integration before declaring the detection of targets. The user can specify no. of trials and success criteria before declaring the detection of targets. We tested the algorithms using a simulated synthetic target of desired SNR injected into the clutter background. The results as shown in the plots were encouraging that the target was detected clean after the suppression of clutter elements. The results demonstrated good detection performance achievable with scan to scan integration followed by appropriate CFAR processes and Binary integration criteria, to detect low observable targets in sea. However, there is good scope for improvement to achieve higher probability of detection.

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