Efficient Suboptimal Detectors for Maritime Surface Surveillance High-Resolution Radar

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***Abstract*— This paper presents some efficient suboptimal detectors, based on statistical descriptors, which take advantage of the high-resolution characteristics of the high-resolution radars (HRR). Which are one of the first stages of the sensor-based localization and tracking technologies. The detection performance has been studied under noise and sea clutter conditions, with non-coherent data from both real and synthetic extended targets. We have also made an adaptation of the classical moving window detection technique for the high-resolution radars, making use of it as a reference technique to evaluate the results obtained with the detection techniques that we present. The experimental results were obtained with the ARIES radar, a maritime surface surveillance LFM-CW HRR operating in X-band.**

Keywords-HRR radar; detectors; statistical descriptors.

I. INTRODUCTION

The specific characteristics of high-resolution radars (HRR) [1] suggest the interest to analyze the possibilities of new detection algorithm for global detection purposes of the extended targets (composed of a number of scatterers, where the target extent in any dimension is greater than the radar resolution in that dimension) [2]. This means, the development of detection algorithms oriented to the radar images, and not just to perform the detection process in each one of the resolution cells, as conventional radar detection techniques do. This paper presents detectors based on statistical descriptors, widely used in the field of digital image processing [3].

Nowadays, the operating HRR typically have the sliding window technique built in [4], [5], (also called moving window, depending on the references) originally developed for conventional radar, without any adaptation to the characteristics of the high resolution. The sliding window detector [4], [5] has been chosen as reference in this paper to compare with the results provided by the proposed algorithms.

In order to explore the possibilities for some of these detectors, a comparative study has been obtained in terms of probability of detection (P_d) for a given probability of false alarm (P_{fa}) using the of Neyman-Pearson criterion [6], widely accepted and widely used in radar. This work has been carried out through a theoretical and experimental analysis with real and synthetic targets. Since from the operational point of view, the significant parameter is the time between false alarms (the inverse of the product of the P_{fa} by the number of decisions per second the sensor should take), image sensors work with probabilities of false alarm several orders of magnitude higher than the pixel-oriented sensors, as a direct result due to the fact that the radar requires a smaller number of decisions made per second.

Some synthetic targets have been generated to verify the quality of the presented algorithms in this article for the detection of extended targets in two dimensions. The HRR targets have multiple scattering (individual targets) not fluctuating. Each resolution cell (or pixel, in the radar image) is well defined by its Cartesian coordinates (x, y), and its amplitude level. Thus non-fluctuating targets have been modelled (according to bibliography: Marcum model, or Swerling 5 or 0) [7], which correspond with the HRR real targets. In addition, in order to corroborate the reliability of the algorithmic developed operating in real-world scenarios, real targets have been processed, which have been captured with the ARIES HRR [8], a maritime surface surveillance linear frequency modulated continuous wave (LFM-CW) HRR, operating in X–band, in scanning mode, and non-coherent detection, which data are range–azimuth matrices.

In this paper, first the problem statement is presented, then the suboptimal efficient detectors based on statistical descriptors for HRR are introduced, after that the results vs. noise and results vs. clutter are described and finally the conclusions are exposed.

II. PROBLEM STATEMENT

Based on the classical statement of the problem, the problem is dealt starting with the analysis of a point target (where the size of the target is smaller than the resolution cell of the radar system). The second step of the analysis deals the generalization for extended targets.

In order to provide a comparison of the results provided by the techniques presented in this article, we make use of the sliding window detector as a reference technique [7], which has been adapted to the HRR characteristics. This paper presents the results obtained with three significant targets:

- Point target: the Fig. 1 shows the range–azimuth matrix obtained at the envelope detector output in conventional surveillance radars, in which the size of the target is smaller than the range resolution cell. The level of the clutter considered is far below the thermal noise of the system. This assumption is a quite common situation and it is according to the real operation of the HRR, due to the small surface inside the considered resolution cell. In most of the resolution cells the radar signal is a Rayleigh random variable [7]. The target amplitude shape is affected by the antenna radiation pattern, which can be considered as a Gaussian distribution.

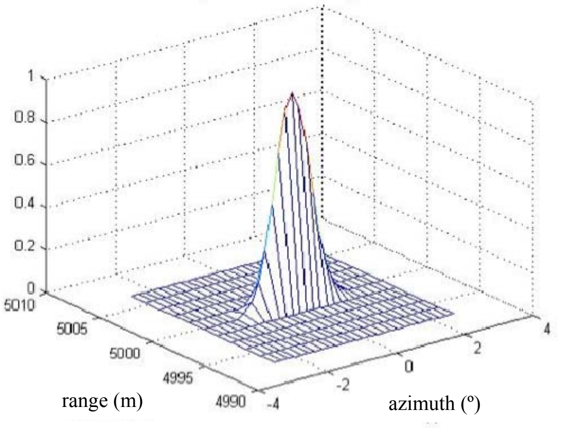

Figure 1. Range–azimuth data matrix of a synthetic point target, synthesized according to the operating parameters of the ARIES radar

- Extended targets: Fig. 2 presents the range–azimuth data matrix from a HRR for a simple model of extended target, a linear target. Fig. 3 shows a real extended target (with a high enough signal-to-noise ration, SNR, and also large enough) captured with the ARIES HRR, which demonstrates the extended targets can be considered as a collection of single point targets, provided that the range resolution cell is small enough (e.g. close to 1 m), compared to the size of the target.

In all considered cases, the data matrices, containing each of the targets, are of the same size, and have a large enough number of bins in order to have a sufficient statistic [9], in order to provide an accurate results.

The main ARIES radar operating parameters for both real and synthetic targets are shown in Table I. The specific parameters to synthesize the point target and the linear extended target, Fig. 1 and Fig. 2, are shown in Table II.

The simulation results were obtained making use of the Monte Carlo method, widely accepted in the radar simulation field [10]. The adopted relative accuracy was 10% to reach probabilities indicated in each case.

The thermal noise model is an additive white Gaussian noise (AWG) with zero mean. Therefore, it can be calculate the receiver operating characteristics curves (ROCs).

TABLE I
MAIN ARIES RADAR OPERATION PARAMETERS

Parameter:	**Value:**
Center frequency:	9 GHz
Period of the sawtooth wave (also can be considered as 1/PRF for pulsed radars):	2,0384ms
Angular velocity of the antenna:	15 rpm
-3 dB antenna beamwidth:	1,2º
Azimuth resolution:	0,2º
Antenna beam shape:	Gaussian distrib.

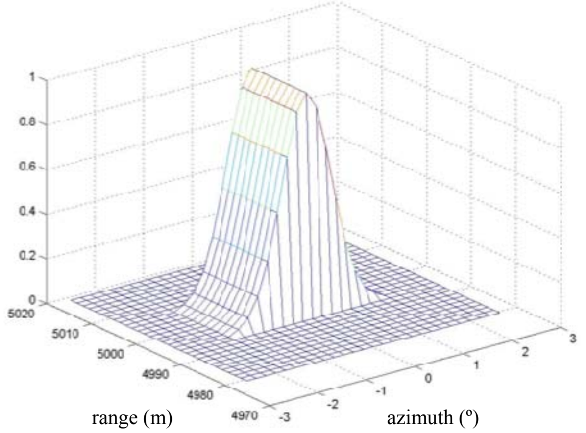

Figure 2. Range–azimuth data matrix of a synthetic linear extended target, synthesized according to the operating parameters of the ARIES radar

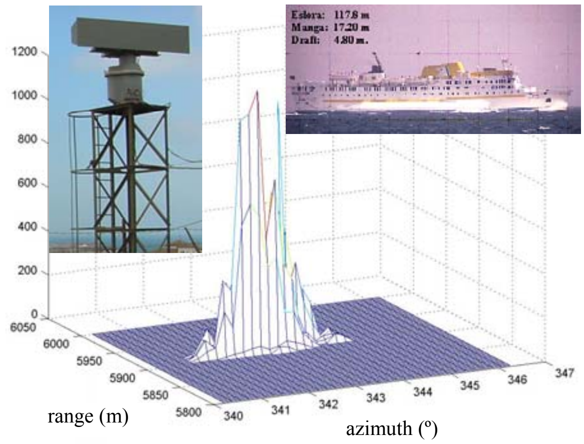

Figure 3. A real extended target, the Boughaz ship: raw range-azimuth data matrix, and the photo (inset right). Inset left: radar ARIES

Many models of sea clutter statistical distributions have been considered over the years, including Weibull, K distribution, etc. [11]–[15]. Experimentally, for the operation parameters used in the capture of targets with the ARIES radar, and for moderate sea conditions, the best suited statistical model of this sea clutter has been a log-normal distribution with a shape factor $\sigma = 0.8$ (standard deviation), which corresponds to the 3 Beaufort number, on the Beaufort scale, according to [16]. This result is consistent with [13]. In this way, the ROC, P_d against signal to clutter ratio (SCR) have been computed.

TABLE II
SPECIFIC RADAR PARAMETERS FOR THE SYNTHESIZED TARGETS

Parameter:	Value:
The operation range of the ARIES radar:	11112m (6nmi)
The target's position in range:	5000m
The target's position in azimuth:	0º
Aspect angle:	0º
Maximum target relative amplitude:	1

III. SUBOPTIMAL EFFICIENT DETECTORS BASED ON STATISTICAL DESCRIPTORS FOR HRR

The vast amount of information obtained by the HRR, leads to develop simple detectors which are able to work with 2-dimensional image (2D), instead of analyse pixel by pixel, and they must also computationally very efficient, producing results in the extended target detection at least comparable with conventional techniques working with point targets. Based on this goal, we have developed the detectors shown in the Fig. 4. This group of techniques process 2D radar raw images, instead of processing each range profile individually (in contrast to classical techniques). Basically the input data to the proposed detectors directly are the range–azimuth matrices of raw video from the output of the FFT stage of the FM–CW radar sensor. The proposed techniques can be applied to any other type of HRR, and even to other kind of sensors.

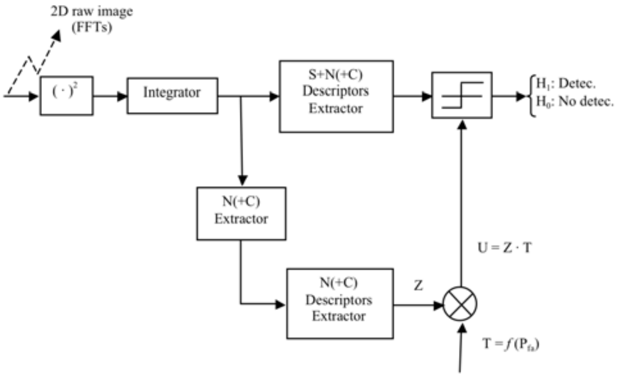

Figure 4. Block diagram of the detectors based on integration and descriptors extraction

For each range row the *Integrator* performs a sum of all resolution cells in azimuth weighted by the considered number of elements, resulting in an improved signal to noise ratio (in other words, it is possible to detect a target with a lower level of SNR, with the same P_{fa} and the same level of the P_d), and causing the clutter becomes Gaussian.

From the resulting vector, the *Descriptors Extractor* gets the statistical descriptor, which compares with a threshold descriptor (U) in the *Comparator* block, which carries out the detection of the target. According to [7], the threshold descriptor is calculated to ensure a detection process with a constant probability of false alarm.

The integrator used is not the optimal one and there is a loss (i.e. it is needed a higher value of SNR to detect a target) due to the shape of the antenna radiation pattern. A real system, in which is known the shape of the beam, makes use of an integrator well matched to it to minimize such loss. Thus, the optimal integrator has not been introduced into the simulation model because it does not provide additional information for the intended purpose: to compare the characteristics of different detectors. In any case it should be noted that the antenna radiation pattern is a given parameter in many applications and it should be considered.

Among the evaluated descriptors have been found to have a performance suitable for use as detectors: the mean (*Med*), the contrast (*Con*), the fourth-order central moment (*M4O*), and the entropy (*Ent*). The analytical expression of the mean and the fourth-order central moment descriptors can be found in [3], and the equations for the contrast and the entropy descriptors are presented in [17].

IV. RESULTS VS. NOISE

Fig. 5 shows the comparative results of the behaviour of the proposed detectors vs. the Sliding Window detector, in terms of the P_d and under conditions of zero-mean AWG noise for each one of the targets presented above. The results are presented separately for each of the two considered P_{fa} (10^{-3} and 10^{-4}).

Under noise conditions, the behaviour of the detectors, based on integration and extraction of descriptors, is nearly identical to the behaviour of the sliding window technique. This statement is well suited in the cases of the detectors based on the contrast descriptor and based on the fourth-order moment descriptor, and this is not true in the case of the mean descriptor. This latter is sensitive in both cases the point target and the extended targets. Thus, for point targets, the mean descriptor works worse than the sliding window detector. This is a reasonable fact since the mean detector integrates all of the noise of an image in which there are very few cells containing the target. On the other side, this is not consistent with the fact of working with HRR systems.

Assuming the situation of working with extended targets, the detector based on the integration and the extraction of the mean descriptor, is better because of its extreme simplicity and computational efficiency (about one order of magnitude). Although the results provides by this detector are worst than the results obtained with the sliding window detector (between -2dB and -5dB, depending on relative size of the target with regard to the image size), the proposed detector is well suited for some applications where the aforementioned limitations are not significant.

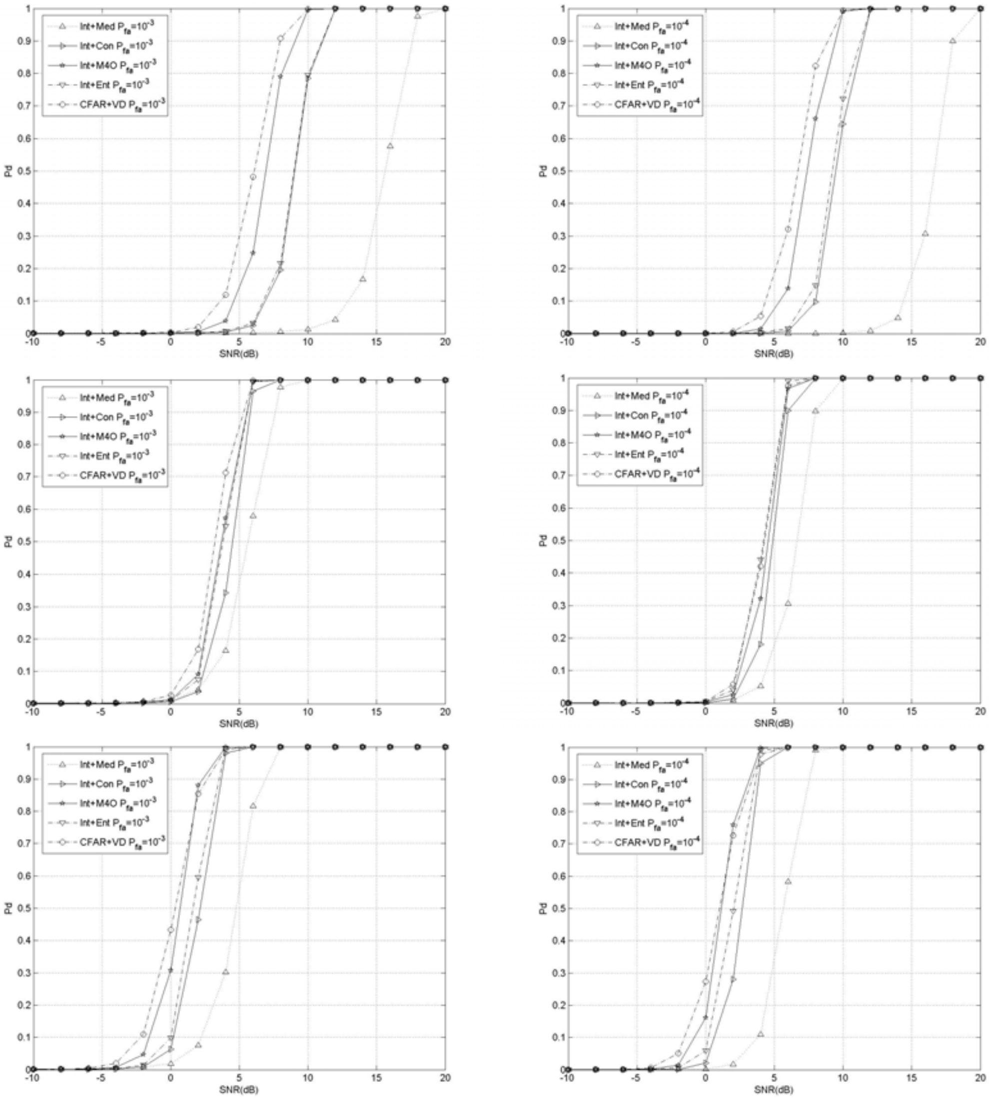

Figure 5. Sliding window (CFAR+VD) vs. presented detectors (Int+: Med, Con, M4O, Ent), under noisy conditions. On the top: for the point target; on the middle: for the linear extended target; on the bottom: for the real extended target, the Boughaz ship. Left side: for a $P_{fa} = 10^{-3}$; and right side: for $P_{fa} = 10^{-4}$.

V. RESULTS VS. SEA CLUTTER

The performance of the presented descriptors under high-resolution sea clutter conditions has been evaluated in the same way as the sliding window with a lognormal distribution with shape parameter σ=0.8, previously indicated.

Fig. 6 shows the comparative results of the behaviour of the proposed detectors vs. the Sliding Window detector behaviour, in terms of the P_d, under sea clutter conditions, for each of the three targets. The results are presented separately for each of the two considered P_{fa} (10^{-3} and 10^{-4}).

Under sea clutter environments, the effect of the *Integrator* block is a significant performance improvement of all descriptors, and corrects the malfunction of some descriptors in these settings, as the case of the contrast descriptor. This is a direct result of increasing its near-Gaussian shape of its statistical distribution obtained from the statistical distributions of the sea clutter at the output of the Integrator stage. Moreover, for all the descriptors, the integrator makes comparable the number of false alarms to that number obtained with the sliding window detector, being slightly worst to the case of the entropy descriptor.

In all cases, the number of false alarms increases rapidly, in sea clutter environments. Obviously, in the presence of impulsive clutter, such as modelling, you cannot keep the detection thresholds (in order to maintain a constant values of P_{fa} and P_d), but they should be amended to set the detector into reasonable rates of false alarms. If this is done, it is straightforward to check that the mean descriptor is the best one (with a loss of 3 dB with respect to sliding window detector, while maintaining an approximately equal P_{fa}).

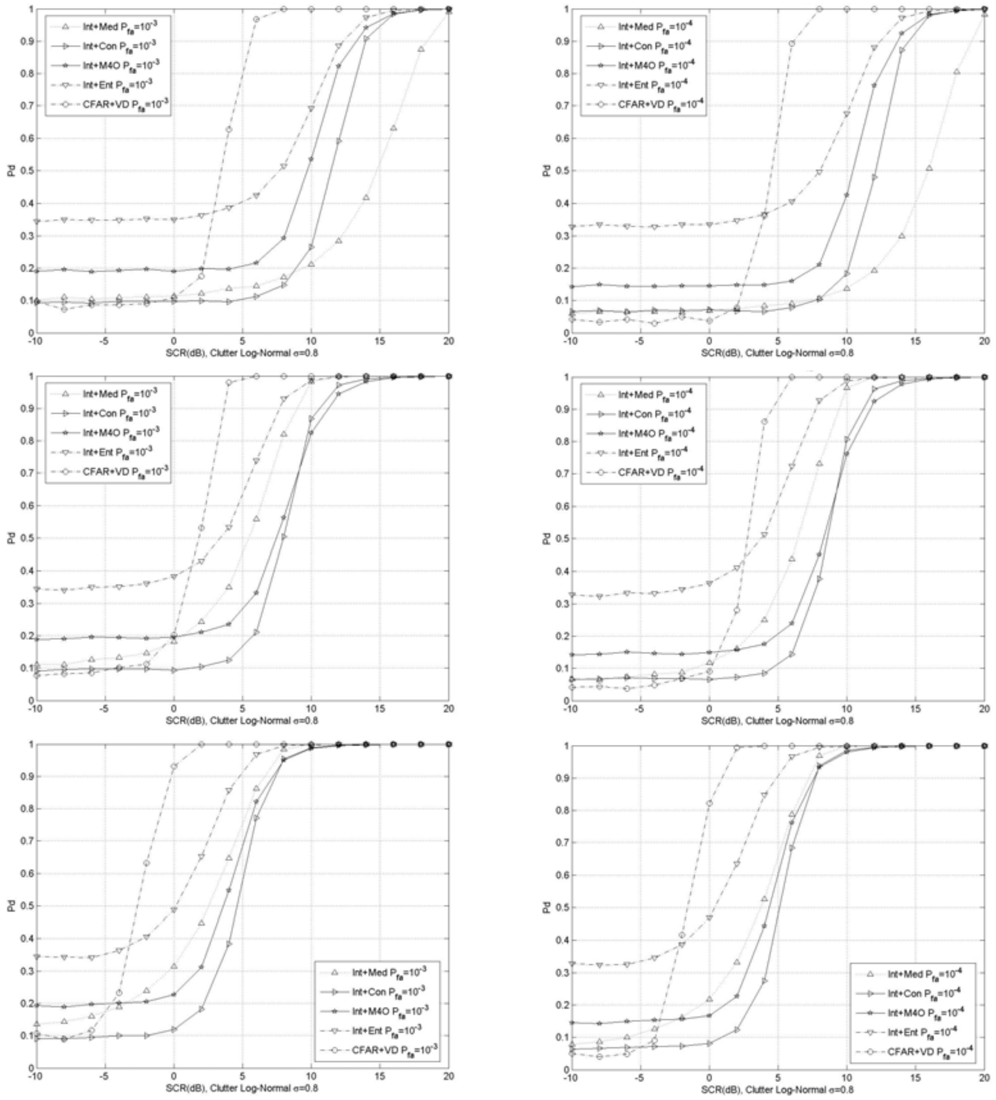

Figure 6. Sliding window (CFAR+VD) vs. presented detectors (Int+: Med, Con, M4O, Ent), under sea clutter conditions. On the top: for the point target; on the middle: for the linear extended target; on the bottom: for the real extended target, the Boughaz ship. Left side: for a $P_{fa} = 10^{-3}$; and right side: for $P_{fa} = 10^{-4}$.

VI. CONCLUSION

It has been demonstrated that the efficiency of presented detectors in terms of P_d, for a given P_{fa}, depends on the relative area occupied by the target within the image, confirming they are particularly suitable for large extended targets. These algorithms have a lower computational burden than the conventional sliding window, allowing to maintain existing radar coverage even when is increased by several orders of magnitude the number of resolution cells, as is the case of HRR systems, in which the technological developments (with the ability to transmit and process the higher bandwidth RF signals) involves reducing the size of the resolution cells in range, and therefore increasing the size of processed matrices.

The used clutter model is especially difficult for the parametric detectors, which are matched to the thermal noise, due to the strong impulse (spiky, typically) character of the clutter, characteristic of HRR's real operation scenarios. Furthermore, one of the main characteristics of the HRR systems that the cell resolution is much lower than in a conventional radar, which means that the received clutter levels are much lower, in many situations below the level of the noise of the system itself. In summary, the curves shown above have been obtained as a function of the SCR, and our experience is that the HRR systems easily handle high SCRs for most of the targets.

Finally we must remark that the techniques discussed in this paper can also be applied, with minor adjustments, to range-Doppler radar images, which are not affected by the shape of the antenna radiation pattern, and the most significant difference, due to its operating principle, is that they are able to separate the targets from the clutter, so that the presented detectors may offer, in any real situation, similar results to the sliding window detector, providing computational advantages.

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