

Enhancement of Matched Filter Response for Chirp Radar Signals using Signal Recovery Technique

Sameh G. Salem



Abstract—The matched filter is one among many effective techniques used to maximize the signal-to-noise ratio (SNR) of chirp radar signals. Besides this enhancement in SNR, it has a drawback due to sidelobe levels which degrade the filter response. There are many additional techniques which reduce these levels such as window techniques and inverse filter. In this paper, a new approach is utilized to completely cancel the level of matched filter side lobes based on the signal recovery of the compressive sensing (CS) theory. The reconstruction process of CS is based on the CAMP algorithm which applied to the response of the matched filter. The recovered chirp radar signals are achieved with completely side lobes cancellation compared to the traditional side lobe reduction technique based on the window method. The comparison between the proposed and traditional methods is achieved according to the detection performance using Receiver Operating Characteristic (ROC) curve. Besides the detection performance, a resolution in the range is another comparison aspect between these algorithms.

Keywords—Pulse Compression, Matched Filter, Chirp signals, Sidelobe levels, Compressive Sensing, Recovery CAMP algorithm.

I. INTRODUCTION

Signal processing of the radar signals is a very significant part of any radar system which enhances the detection of radar capability [1]. There are several techniques used for this purpose such as the pulse compression technique [2]. This compression may be achieved in-phase (Biphase) or frequency such as in Linear Frequency Modulated (LFM) radars. The most widespread application in a radar system is the LFM signal or chirp signal. The response of the matched filter has a formula of sinc function with range sidelobes around the center on both sides. The maximum of these side lobes is nearly less than the peak compressed signal by 13.2dB [3]. Different methods are used to reduce these unwanted signals but on the other hand, degradation on the radar performance will occur. Var. and Thomas [4] presented different sidelobe reduction using LFM signal depending on leakage energy minimization. Also, the behavior of Non-linear LFM is discussed and compared with the LFM waveform. Mudukutore and Ashok., [5] introduced a pulse compression technique in phase to analyze the returned signal from weather targets and produced an achievement on radar detection especially for long pulses. The performance of this paper is compared with other side lobe suppression filters and obtain an acceptable result.

Sahoo and Panda [6] studied the reduction of the LFM waveform side lobe based on the convolution window in time-domain to enhance the detection capability of the radar system. All these focused researches that wanted to enhance the radar performance depending on sidelobe reduction to a lower level as possible. In this paper, the proposed technique is mainly used to remove these side lobes completely using a recovery algorithm which is based on CS theory. The organization of this paper is arranged as follows; after the introduction, section 2 introduces a survey on the sidelobe reduction technique based on the window function. Section 3 focuses on the proposed recovery algorithm features based on CS. Performance evaluation of the suggested algorithm compared to the traditional window technique is presented in section 4. Finally, the conclusion presents in section 5.

II. MATCHED FILTER AND WINDOW TECHNIQUE

The transmitted LFM waveform of a single amplitude-modulated rectangular pulse can be described as [7]:

$$x(t) = A \text{rect}\left(\frac{t}{T}\right) \exp[j(2\pi f_0 t + \pi K_r t^2)] \quad (1)$$

where A is the signal amplitude, T is the pulse width, f_0 is the carrier frequency, $\text{rect}(\cdot)$ is rectangle function, K_r is the chirp rate of LFM signal and its slope can be specified as $K_r = \pm B_r/T$, the positive sign indicates up chirp of LFM slope while negative sign indicates a down chirp. B_r represents the chirp bandwidth.

The received echo signal, $u(t)$, is reflected from a target which can be expressed as:

$$u(t) = A_r \text{rect}\left(\frac{t-\tau}{T}\right) \exp\left[j\left(2\pi f_0(t-\tau) + \pi K_r(t-\tau)^2\right)\right] \quad (2)$$

Where A_r is an attenuated version of the transmitted signal amplitude, τ is the flight time of the target at corresponding range R . Then, τ can be expressed as:

$$\tau = \frac{2R}{c} \quad (3)$$

Where C is the speed of propagation.

The matched filter response in the frequency domain using Fast Fourier Transform (FFT) can be explained as shown in Fig.(1) where $U(w)$ is the spectrum of the received signal $u(t)$, $R_{ref}(w)$ is the spectrum of the reference signal $r_{ref}(t)$, the sign $(*)$ refers to the conjugate of the signal. The compressed signal, $y_m(t)$, can be obtained by an inverse spectrum of the matched filter response, $Y_m(w)$, using IFFT as illustrated in the figure below [7].

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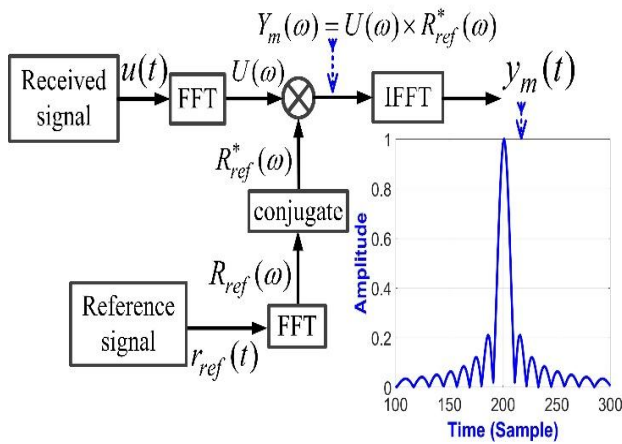


Fig.1 Matched filter response in frequency domain.

From the above figure, the output response affected by sidelobes with the peak level of the first sidelobe is around 20 percent of that the main lobe which degrades the radar performance. The window function is used to enhance the radar performance which reduces these side lobes by 10dB as Hamming or Hanning window [8] but still harms the radar performance as shown in Fig. (2).

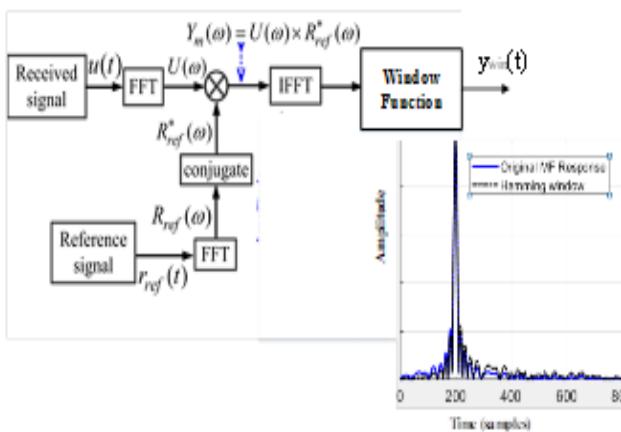


Fig. 2 Matched filter response after the window function.

Enhancement of the radar performance can be achieved by completely remove these side lobes using a recovery technique based on the CS theory as illustrated in the next section.

III. THE PROPOSED RECOVERY ALGORITHM

Signal recovery based on CS is being explored in [9]. The CS states that any signal can be recovered or reconstructed from the original one using a small number of measurement samples under restrictions [10]. The recovered signal can be evaluated using Convex Optimization or Greedy algorithms. Algorithms based on convex optimization require lower measurements than the other algorithms but with higher complexity.

The iterative algorithm as an example of the Greedy algorithms is the simplest one among all the reconstruction algorithms. There are many algorithms are used for signal or image reconstruction with high performance such as Orthogonal Matched Pursuit (OMP) [11], Approximate Message Passing (AMP), and well-known Complex Approximate Message Passing (CAMP) [12]. As illustrated in Fig. (1), the response of the Matched filter is considered as

a sparse signal, which likes to a pulse signal and satisfies the CS recovery operation using a suitable reconstruction algorithm. Lower samples can be selected randomly from this response to generate a compressed measurement vector. The recovered signal can be obtained as shown in Fig. (3).

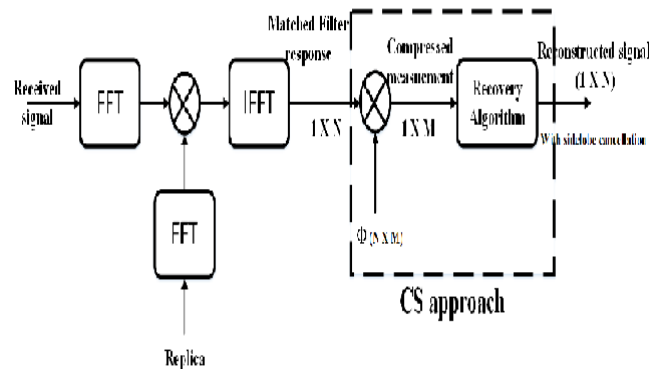


Fig. 3 Block diagram of Side lobe cancellation based on recovery algorithm.

The compressed measurement vector of length M samples will be obtained after multiplying the matched filter response of length N samples with measurement matrix $\Phi (N \times M)$. There are many matrices that are used in the recovery process such as the Gaussian matrix and Fourier matrix. Selection of the Gaussian matrix is done according to its independent and identically distributed (i.i.d.) entries random samples and satisfy the Restricted Isometry Property (RIP) [13] to reconstruct the signal with a high probability according to the following relation [14]:

$$M \geq O(K \log(N/K)) \tag{4}$$

Where K is the number of the significant (nonzero) coefficient. The traditional CAMP is used as a recovery algorithm and its operation will discuss in the next flow chart as shown in Fig. (4).

The recovered signal is firstly estimated as [12]

$$\hat{x}^0 = 0 \text{ and } z_0 = y \tag{5}$$

Where \hat{x}^0 is the initial value of the signal, x , z_0 is the compressed signal at the first iteration and Φ is a Gaussian measurement matrix. The recovered signal \hat{x}^t is computed as

$$\hat{x}^t = A^T z^{t-1} + \hat{x}^{t-1} \tag{6}$$

The threshold (T_1) can be calculated depending on the median standard deviation (σ_t) of the estimated signal \hat{x}^t [10].

$$T_1 = \tau h * \sigma_t, \quad \sigma_t = \sqrt{\frac{1}{\ln 2} \text{median}(|\hat{x}^t|)} \tag{7}$$

Where τh is the gain of the threshold. The measurements will be calculated and prepared for the next iteration for recovering the original signal by using the iterative soft threshold, η [15].

$$\hat{x}^t = \eta(\hat{x}^t; T_1) \tag{8}$$

$$z^t = y - A\hat{x}^{t-1} + z^{t-1} \text{MSE} \tag{9}$$

When the value of Mean Square Error (MSE) becomes less than a certain value (tolerance), the iteration is stopped.

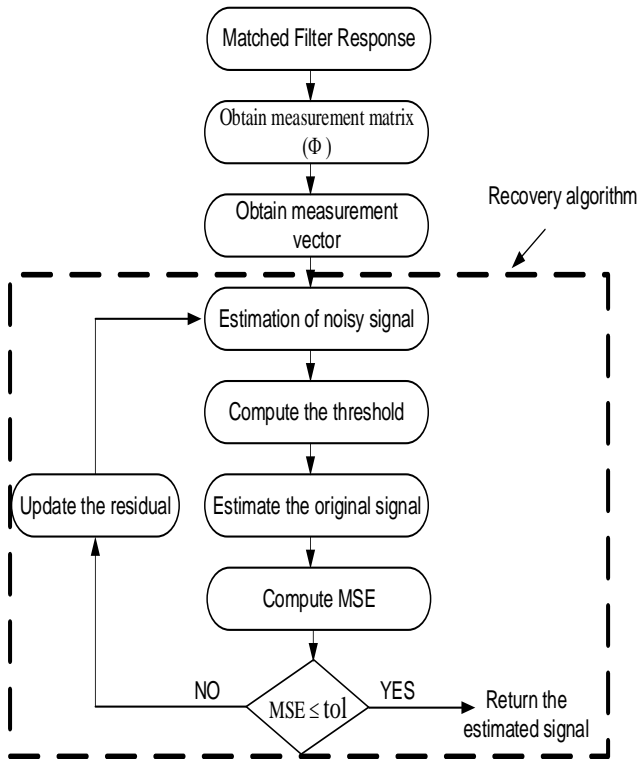


Fig. 4 Flow chart of the CAMP recovery algorithm.

In the present paper, the proposed approach based on CS is compared with that of the traditional one based on window technique after the Matched filter response from point of view of detection capability and resolution in the range as discussed in the next section.

IV. PERFORMANCE EVALUATION

The performance is evaluated between these algorithms using computer simulation based on the Matlab program. The transmitted chirp signal is assumed to be 1024 samples with 120MHz sampling frequency, 10MHz bandwidth with 15 m resolution in range and noise is assumed to be white Gaussian with zero mean and unity variance. Many cases are assumed according to the number of simulated targets which consequently determine the compressed vector length (M) as discussed in Eq.(4). If one target is simulated with a 100 m apart range, the number of nonzeros (K) is assumed to be 10 according to the above signal specifications. The relation between the compressed vector length, the value of nonzero coefficients and the compression ratio ($\delta=M/N$) will be illustrated in Table (1).

The proposed algorithm performance based on CS is achieved and compared with that of the traditional window method as shown in Fig. (5). The comparison between the two approaches will be achieved from point of view detection performance and resolution.

Table 1 Relation among nonzero coefficients (k), compressed vector length (M) and the reduction ratio (δ)

Target No.	No. of nonzeros (K)	compressed vector length (M)	Compression Ratio (δ)
Case 1: One target	10	300	30%
Case 2: Two targets	20	550	50%
Case 3: Three targets	30	700	65%
Case 4: Five targets	50	900	88%

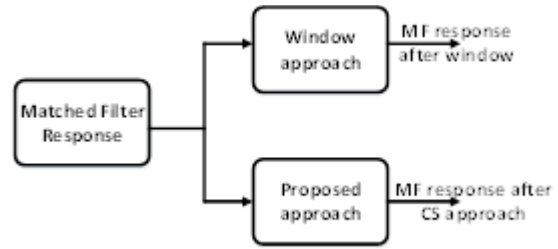


Figure (5) Setup of the simulation comparison between the two approaches.

A. Detection Performance

The detection performance of both algorithms, the proposed one and the traditional, is achieved using the ROC curve at P_{fa} of 10^{-5} under different Signal-to-Noise Ratios (SNR). Three cases are simulated with software according to the number of detected targets which consequently affects the length of the measurement vector as discussed before in Table (1).

Case I: One target is simulated at an expected range of 100 m and with a 30% compression ratio, the detection of this target will be evaluated as shown in Fig. (6) and its range representation is shown in Fig. (7) and Fig. (8) with different SNR.

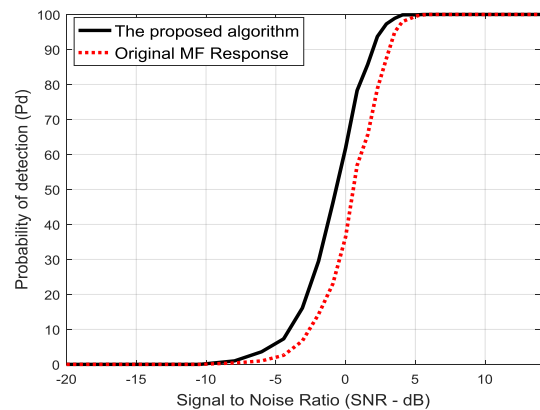


Fig.6 ROC of the proposed approach compared to traditional one for case I at $P_{fa}=10^{-5}$.

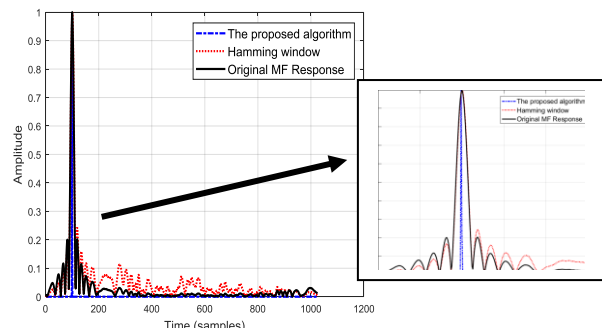


Fig. 7 Range representation for case I, SNR =10dB and $P_{fa}=10^{-5}$.

Case II: Two targets are simulated at expected ranges of 100 m and 400 m with a 50% compression ratio, the detection of these targets will be evaluated in the range representation as shown in Fig. (9).

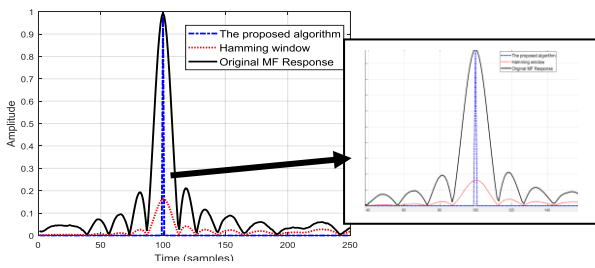


Fig. 8 Range representation for case I, SNR = 5dB and $P_{fa} = 10^{-5}$.

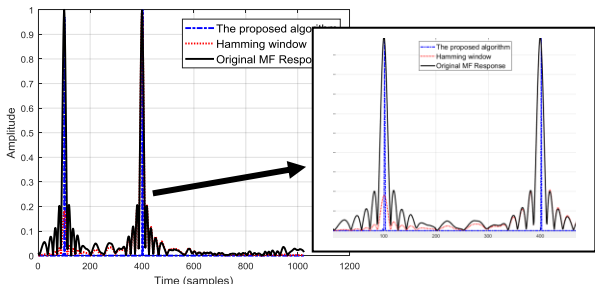


Fig. 9 Range representation for case II, SNR = 10dB and $P_{fa} = 10^{-5}$.

The proposed algorithm detection performance is better than that of the original matched filter by approximately 10dB. This enhancement in detection is obtained due to the sidelobe removal of the proposed algorithm. Case III: Three targets are simulated at expected ranges of 100 m, 300m and 700 m with a 65% compression ratio, the detection of these targets will be evaluated in the range representation as shown in

Fig. (10). From these figures, it is found that the compression ratio relation with the number of expected targets should be met and as the compression ratio decreases, the detection performance degrades. Also, the sidelobe levels in the case of the traditional approach are reduced but still exist. On the other hand, these sidelobes are completely canceled using the proposed approach which is the main object of this algorithm.

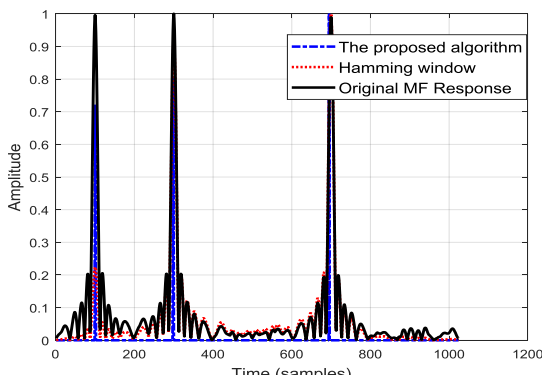


Fig. 10 Range representation for case III, SNR = 10dB and $P_{fa} = 10^{-5}$.

B. Resolution Performance

The performance of range resolution is achieved by simulated two near targets at distances less than 15m according to resolution calculations of the signal parameters. It is assumed two targets at distance 100 m and the other at 108 m range apart with SNR of 10dB, P_{fa} of 10^{-5} and 50% compression ratio as shown in Fig. (11).

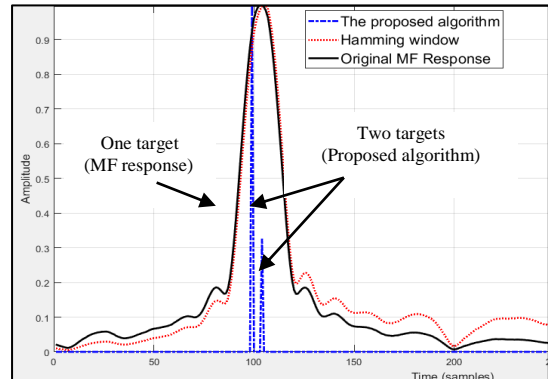


Fig. 11 Range resolution domain of the proposed and traditional algorithms for two targets at 100m and 108m range with 10dB SNR and $P_{fa} = 10^{-5}$.

The resolution of the proposed approach based on signal recovery is better than that of the traditional one based on the windowing technique. The response of the proposed approach has completely removal of sidelobe levels which is the major advantage point of the proposed approach.

V. CONCLUSION

Degradation in radar performance based on matched filter due to the unwanted level of sidelobes which can be reduced using traditional methods such as window function. The Hamming window reduces these side lobes by 10dB of the Matched filter response. This paper has introduced a new method to promote radar performance by completely remove these side lobes using a recovery technique based on CS theory. Traditional CAMP is used as a recovery algorithm based on an iterative soft threshold which estimates the recovered signal using a few samples of the original response of the matched filter. These measurement vector samples should satisfy RIP and sparsity condition to operate successfully. The response of the traditional window function based on Hamming after the matched filter has compared with that of the proposed method based on the recovery technique. The detection of the proposed approach was evaluated using ROC and compared with that of the traditional window response at different SNRs. It is found that the performance of the proposed approach using ROC is approximately 10dB better than that of the traditional one due to the complete rejection of the side lobes in the proposed approach. Another aspect of comparison between these algorithms is the resolution in the range which has an acceptable result of the proposed approach compared with that of the traditional window function.

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Sameh G. Salem received the Ph.D. degree in signal processing and radar system engineering from Military Technical College (MTC), Egypt, in 2015. From 2015 to 2019, he was a Senior Engineer with Technical Research of Electronics Technology in MTC. Since 2019, he has been a lecturer in Egyptian Academy for Engineering and Advanced technology (EAEAT), Egypt. His current research interests

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