International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-9 Issue-4, February 2020

New Side Lobe Cancellation Method of Linear Frequency Modulated Radar Signals

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Abstract; Pulse Compression (PC) technique has many advantages in signal processing of radar systems which enhances the radar performance. For a long pulse, the range detection capability can be increased with PC while maintain the advantage of resolution in range for uncompressed pulse. There are many PC techniques such as Binary and Linear Frequency Modulation (LFM) Codes, which can be utilize in radar. The radar detection performance is affected by unwanted signals, which called side lobes that may mask the weaker useful signals, which are present near to strong signals. Pulse compression that uses LFM code is discussed and contrasted with matched filter keep tracked of Hamming windowing filter technique to eliminate the level effect of side lobes. In the present paper, a proposed optimum filter is introduced to enhance both the radar detection capability and resolution in range. The proposed optimum filter representation is evaluated and compared with the classical matched filter response associated with Hamming windowing filter according to the representation of radar detection through Receiver Operating Characteristics (ROC) curves and resolution performance.

Keywords: Pulse compression, LFM signal, Optimum filter, Range resolution, Side lobe cancellation.

I. INTRODUCTION

The techniques of pulse compression (PC) are used in radar systems to achieve long-range detection and good resolution simultaneously. Many PC mechanisms in radar are used to achieve these requirements such as Polyphase, Bi-phase and LFM Codes. PC process is achieved by modulating the transmitted carrier waveform of single frequency in either phase or frequency to achieve wide bandwidth [1]. The received compressed signal is processed by matching filter which its output has a maximum signal-noise ratio (SNR). The resolution in range direction can be resolved according to the width of the main or central lobe associated with the minimum the levels of side lobe, which are the main disadvantages of PC. These sidelobes are highly undesirable because they may mask the appearance of weak useful signal. Many methods are used to eliminate these levels of side lobe and consequently enhance response of the identified or matched filter such as weighting filters or windowing [1], mismatching filter [2], adaptive filtering and optimization techniques. PC permits the radar to employ a pulse with long duration to fulfill large radiated power, but together to attain high resolution of pulse with short duration. In transmitted pulse, due to the limitation on peak power, the pulse has a long duration with low peak power for long-range detection.

Revised Manuscript Received on February 28, 2020.
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In LFM radar, the range resolution relies on the signal bandwidth as illustrates in the following relation:

$$\delta R = \frac{c\tau_o}{2} = \frac{c}{2B} \qquad (1)$$

Where, c is light speed, δR is the resolution in range, τ_o is compressed pulse duration and B is the bandwidth.

As seen in Eq. (1) as the bandwidth increases, the resolution in range direction improves and the Pulse Compression Ratio (PCR)must be very high as defined in Eq. (2).

$$PCR = \frac{width\ of\ the\ pulse\ before\ compression}{width\ of\ the\ pulse\ after\ compression} \qquad (2)$$

Modulation in frequency or in phase is applied to the radar signal before transmission to enhance the resolution compared to unmodulated signals. After compression and matched filter, many unwanted lobes are generated which degrades the performance of the radar capability due to masking or hidden of small targets [3].

ThePeak of Sidelobe Level (PSL) is defined as:

$$PSL(dB) = 20\log\frac{Amplitude\ of\ peak\ sidelobe}{Ampolitude\ of\ mainlobe} \quad (3)$$

Many kinds of modulation in radar that used for pulse compression such as the phase-coded and LFM pulse, which is the most widely, used [4]. Many papers introduced the pulse compression advantages in radar systems such as Susaki, in [5], which a new manner of pulse compression is illustrated for simple pulse.The desired signal waveform has frequency characteristics, which selected to get low peak side lobe level. In [6], a proposed phase coded pulse compression mechanism is presented to explain the weather targets return. A performance comparison of various filters and inverse filters used to suppress the unwanted side lobe setup on the integration of sidelobe level and the sensitivity of Doppler is achieved. Different suppression methods of LFM side lobes are introduced in [7], which introduces the comparative behavior of LFM and NLFM waveform with low pulsecompression ratio. Convolutional window in time domain is used to LFM sidelobe suppression to get a lower side lobe level as discussed in [8].Xi. Liu, Yixin Yang, and JieZhuo [9] illustrates side lobe reduction levels for sonar imaging using stepped -frequency pulses. In the present paper, a new optimum filter is suggested to completely cancel the levels of side lobes in radar systems compared with that of the matching filter response based on LFM pulse compression.

However, reduction in side lobes in the traditional matched filter response is achieved using weighting function or window such as Hanning or Hamming windowing filter, the proposed optimum filter output can completely cancel or reject the levels of side lobes after the traditional matched filter without any window function.

The organization of this paper is presented as follows; after introduction section 2 allows the spectrum response of the matched filter and reduction levels of side lobe using window function. Section 3 presents the proposed optimum filter structure. Performance estimation of the suggested optimum filter response in LFM radar signal compared with windowed matched filter response is provided in section 4. Finally, conclusion comes in section 5.

II. MATCHED FILTER RESPONSE WITH WEIGHTING FUNCTION

LFM waveform of a single pulse has a rectangular amplitude modulation with pulse width (T)and swept bandwidth (B) can be described by [10]:

$$x(t) = A\, rect\left(\frac{t}{T}\right) \cos\left[2\pi f_o t + \pi \alpha t^2\right] \qquad (4)$$

Where T is the pulse width, fo is the carrier frequency, α is the LFM slope, and the rect function is defined as:

$$rect(x) = \begin{cases} 1, |x| < 1/2 \\ 0, |x| > 1/2 \end{cases} \qquad (5)$$

The LFM slope is specified by $\alpha = \pm B/T$, where the positive sign utilizes for up LFM slope (up chirp) and negative sign used for a down LFM slope (down chirp). The amplitude modulation is $\alpha(t) = A\, rect(t/T)$ and the phase modulation is represented as a quadratic function of time as [10]:

$$\emptyset(t) = \pi \alpha t^2 \qquad (6)$$

The frequency modulation, defined as the immediately frequency deviation from the carrier frequency (fo) is expressed in terms of the phase as described by:

$$f_i(t) = \frac{1}{2\pi}\frac{d\emptyset}{dt} \qquad (7)$$

The frequency modulation for a LFM waveform is linear with slope equal to (α)

$$f_i(t) = \alpha t = \pm\left(\frac{B}{T}\right) t, \quad |t| \le T/2 \qquad (8)$$

LFM waveform envelope is complex and can be specified as [10]:

$$u(t) = A\, rect\left(\frac{t}{T}\right) e^{J\pi\alpha t^2} (9)$$

The matched filtering response is mainly based on FFT as shown in Figure 1.

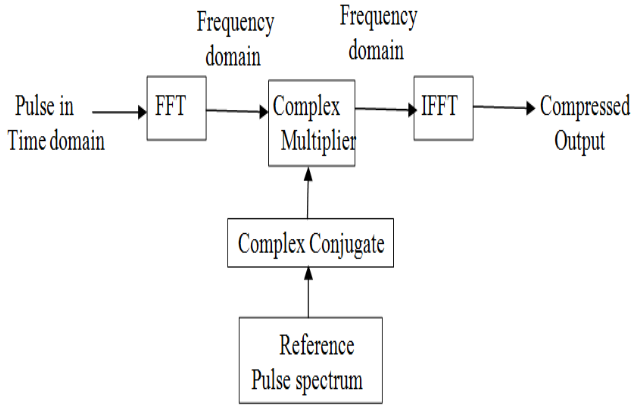


Fig. 1 Matched filter components in the frequency domain [10]

The impulse response of matched filter is described by [11]

$$H(f) = CX^*(f)e^{-j2\pi f t_{op}} \qquad (10)$$

Where C is a constant, $X^*(f)$ is the spectrum complex conjugate of the input signal x(t) and top is the optimum time of the received signal. So, the spectrum of the matched filter output after pulse compression is allowed by

$$Y(f) = H(f)X(f) \qquad (11)$$

$$\text{Or}\, Y(f) = CX^*(f)e^{-j2\pi f t_{op}}X(f) \qquad (12)$$

A window uses after the matching filter to eliminate the impact level of side lobe, which are generated at the filter output. There are many window techniques used in side lobe elimination or reduction such as Hamming, Hanning, Flattop, and Blackman windowing filter. In [12], it is illustrated that, Hamming windowing has a better performance among the above filter techniques according to resolution and peak of side lobe level.

III. THE PROPOSED OPTIMUM FILTER STRUCTURE

Theproposed optimum filter is designed to completely cancel the levels of side lobe at the matching filter response for LFM signal as clarified in Figure 2.

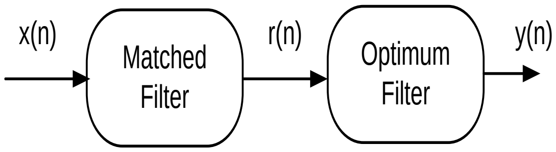


Fig. 2 Optimum filter for side lobe cancellation

The general form of a single-pulse LFMsignal in digital form of Eq.(10) can be expressed as:

$$s(n) = Ae^{J(w_o n + k\pi n^2)}, \quad 0 \le n \le N-1 \qquad (13)$$

Where A is the amplitude,fsis the sampled frequency required, ωo is the angular frequency, $k = B/(Nf_s)$ which is LFM coefficient and (N) is the total samples (integer value) which may be even or odd. So, two cases of optimum filter construction can be achievedaccording to the value of integer (N). The matched filter autocorrelation function can be explained as:

$$x_N(l) = \sum_{n=-\infty}^{\infty} s_N^*(n) s_N(n+l), \quad 0 \le l \le N-1 \qquad (14)$$

Where the asterisk (*) indicates complex conjugation.
TheDiscrete Fourier Transform (DFT) of autocorrelation signalfor odd number of samples (let N=5) can be expressed as:

$$X_5(\omega) = \sum_{l=0}^{M-1} x_5(l)\, e^{-j\frac{2\pi l \omega}{M}} \qquad \text{where} \quad M = 9$$

$$\begin{aligned} &= e^{-j4(k\pi+2\omega+\omega_o)}\Big\{e^{j4(k\pi+2\omega)} + 5e^{j4(k\pi+\omega+\omega_o)} + e^{j2(3\omega+\omega_o)} + e^{j2(2k\pi+3\omega+\omega_o)} + \\ &e^{j2(4k\pi+3\omega+\omega_o)} + e^{j(k\pi+7\omega+\omega_o)} + e^{j(7k\pi+7\omega+\omega_o)} + e^{j4(k\pi+2\omega_o)} + e^{j2(\omega+3\omega_o)} + \\ &e^{j2(2k\pi+\omega+3\omega_o)} + e^{j2(4k\pi+\omega+3\omega_o)} + e^{j(k\pi+5\omega+3\omega_o)} + e^{j(3k\pi+5\omega+3\omega_o)} + \\ &e^{j(5k\pi+5\omega+3\omega_o)} + e^{j(7k\pi+5\omega+3\omega_o)} + e^{j(k\pi+3\omega+5\omega_o)} + e^{j(3k\pi+3\omega+5\omega_o)} + \\ &e^{j(5k\pi+3\omega+5\omega_o)} + e^{j(7k\pi+3\omega+5\omega_o)} + e^{j(k\pi+\omega+7\omega_o)} + e^{j(7k\pi+\omega+7\omega_o)}\Big\} \end{aligned} \qquad (15)$$

The output response in time domain, y(n), for *N*= 5 samples is set as:

$$y_5(l) = \{0,0,0,0,5,0,0,0,0\} \qquad (16)$$

The spectrum of the output response (Eq.(16)) can be rewritten as:

$$Y_5(\omega) = 5e^{-j4\omega} \qquad (17)$$

International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-9 Issue-4, February 2020

The proposed optimum filter transfer function for 5 samples and its simplified form in frequency can be fulfilled as in Eq.(18) and Eq.(19) respectively.

$$H_5(\omega)=\frac{Y_5(\omega)}{X_5(\omega)}$$

$$=\frac{5}{\left\{\begin{array}{l}5+2\cos\left(4(\omega-\omega_o)\right)+2\cos\left(3(k\pi+\omega-\omega_o)\right)+\\ 2\cos\left(3(k\pi-\omega+\omega_o)\right)+2\cos\left(2(2k\pi+\omega-\omega_o)\right)+\\ 2\cos\left(2(2k\pi-\omega+\omega_o)\right)+2\cos\left(2(\omega-\omega_o)\right)+2\cos(k\pi+\omega-\omega_o)+\\ 2\cos(k\pi-\omega+\omega_o)+2\cos(3k\pi+\omega-\omega_o)+2\cos(3k\pi-\omega+\omega_o)\end{array}\right\}} \quad (18)$$

$$H_5(\omega)=\frac{5}{\left\{\begin{array}{l}5+4\left[\cos(k\pi)+\cos(3k\pi)\right]\cos(\omega-\omega_o)+\\ 2\left[1+2\cos(4k\pi)\right]\cos\left(2(\omega-\omega_o)\right)+\\ 4\cos(3k\pi)\cos\left(3(\omega-\omega_o)\right)\end{array}\right\}} \quad (19)$$

The transfer function H(Z) of the optimum filter for 5 samples is:

$$H(Z)=\frac{5Z^{-4}}{\begin{array}{c}(2\cos k\pi+2\cos 3k\pi)(Z^{-3}+Z^{-5})+(2\cos 4k\pi+1)\\ (Z^{-2}+Z^{-6})+2\cos 3k\pi(Z^{-1}+Z^{-7})+1+Z^{-8}+5Z^{-4}\end{array}} \quad (20)$$

Similarly, the proposed optimum filter transfer functionfor 7 samples can be simplified as:

$$H_7(\omega)=\frac{7}{\left\{\begin{array}{l}7+4\left[\cos(k\pi)+\cos(3k\pi)+\cos(5k\pi)\right]\cos(\omega-\omega_o)+2\cos\left(6(\omega-\omega_o)\right)\\ 2\left[1+2\cos(4k\pi)+2\cos(8k\pi)\right]\cos\left(2(\omega-\omega_o)\right)+\\ 4\left[\cos(3k\pi)+\cos(9k\pi)\right]\cos\left(3(\omega-\omega_o)\right)+\\ 2\left[1+2\cos(8k\pi)\right]\cos\left(4(\omega-\omega_o)\right)+4\cos(5k\pi)\cos\left(5(\omega-\omega_o)\right)\end{array}\right\}} \quad (21)$$

So, the proposed optimum filter transfer function general form for (N) odd samples is written as:

$$H(Z)=\frac{NZ^{-(N-1)}}{\begin{array}{c}\sum_{i=1}^{\frac{N-1}{2}} 2\left[\sum_{j=1}^{\frac{N-1}{2}-(i-1)} \cos\left((2i-1)(2j-1)k\pi\right)\left(Z^{2i-N}+Z^{-2i-N+2}\right)\right]+\\ \sum_{i=1}^{\frac{N-1}{2}-1}\left[\sum_{j=1}^{\frac{N-1}{2}-i} 2\cos(2i(2jk\pi)+1)\left(Z^{2i-(N-1)}+Z^{-2i-(N-1)}\right)\right]+\\ 1+Z^{-2(N-1)}+NZ^{-(N-1)}\end{array}} \quad (22)$$

The proposed optimum filter transfer function for even samples (*N=6*) can be simplified as:

$$H_6(\omega)=\frac{6}{\left\{\begin{array}{l}6+2\left[1+2\cos(2k\pi)+2\cos(4k\pi)\right]\cos(k\pi+\omega-\omega_o)+\\ 4\left[\cos(2k\pi)+\cos(6k\pi)\right]\cos\left(2(k\pi+\omega-\omega_o)\right)+\\ 2\left[1+2\cos(6k\pi)\right]\cos\left(3(k\pi+\omega-\omega_o)\right)+\\ 4\cos(4k\pi)\cos\left(4(k\pi+\omega-\omega_o)\right)+2\cos\left(5(k\pi+\omega-\omega_o)\right)\end{array}\right\}} \quad (23)$$

Similarly, the transfer function general form for even samples (*N*) can be expressed from Eq.**Error! Reference source not found.** as:

$$H_{N_e}(\omega)=\frac{N_e}{\left\{\begin{array}{c}N_e+\sum_{i=1}^{\frac{N_e-1}{2}} 4\left(\sum_{j=1}^{\frac{N_e}{2}-i}\cos\left(2i\left((2j-1)\pi k\right)\right)\right)\cos\left(2i(k\pi+\omega-\omega_o)\right)\\ 2\cos\left((N_e-1)(k\pi+\omega-\omega_o)\right)+\\ \sum_{i=1}^{\frac{N_e-1}{2}}\left(2\sum_{j=1}^{\frac{N_e-1}{2}-(i-1)}\cos\left((2i-1)\left((2j)\pi k\right)\right)+1\right)\cos\left[(2i-1)(k\pi+\omega-\omega_o)\right]+\end{array}\right\}} \quad (24)$$

IV. RESULTS ANALYSIS

The performance of the suggested optimum filter is achieved using Matlab. The base band of the radar signal is generated with processed total range samples is supposed to be 1024 samples with 120MHz sampling frequency and 100MHz bandwidth. It is assumed that, radar simulation representation is estimated with known return of target and with White Gaussian as a thermal noise with zero mean and unity variance. The performance is predestined by comparing the levels of side lobe reduction of the suggested optimum filter with that of Hamming windowing filter. Besides, the detection probability and range resolution are take into consideration as presented in Figure 3.

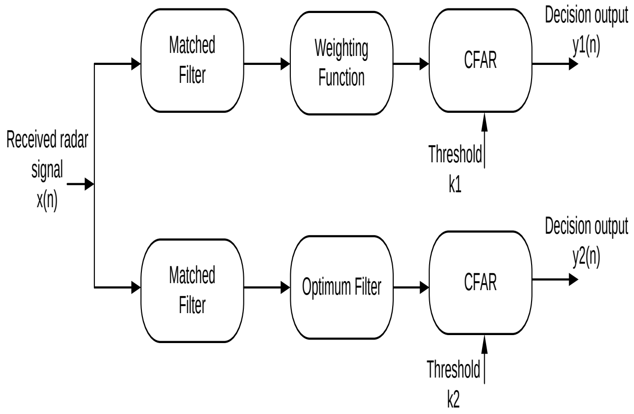
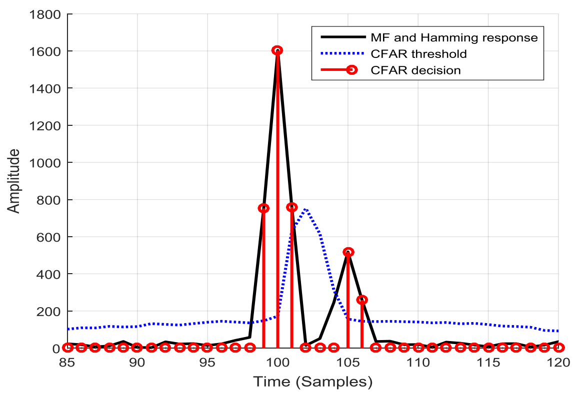


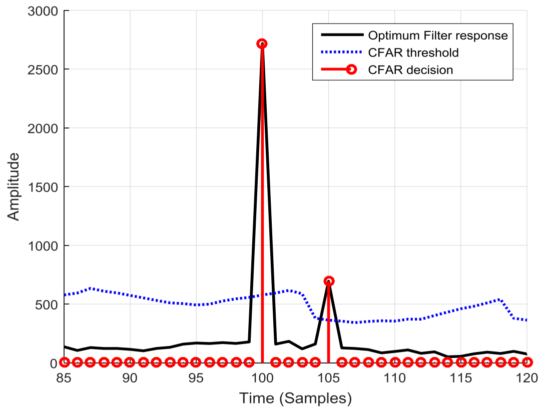
Fig.3 Performance evaluation setup of the suggested optimum filtercompared to the weighting filter

A. Detection Evaluation

Detection performance evaluation is achieved for both the suggested filter with the matched and with Hamming windowing filter through ROC under certain false alarm probability (P_{fa}) and the detection probability (P_d) is calculated using the Cell Average Constant False Alarm Rate (CA-CFAR) processing of both the matched filter and Hamming windowing filter output. The detection evaluation is performed using single target at range cell number (100) for both the proposed optimum filter output and hamming windowing filter response.



(a)



(b)

Fig. 4 CFAR detection for two targets at $P_{fa}=10^{-6}$and (SNR =10dB and 5dB) (a) Hamming windowing filter (b) Optimum filter

It is clear that, the matched filter detection performance with Hamming window has a bad response compared with that of the suggested filter due to high levels of the side lobes in the matched filter. From these figures, it is found that, there are many targets, which are detected due to low SNR. These targets results in false detection as presented in Fig.(4-a). But in case of optimum filter response, as in Fig.(4-b), the known targets are clearly detected which indicates to the better estimation of the suggested filter detection than that of the matched windowing filter. The detection performance through ROC curve of both the proposed optimum filter and the matched with Hamming windowing filter is evaluated at 10-6Pfa as explained in Figure 5.

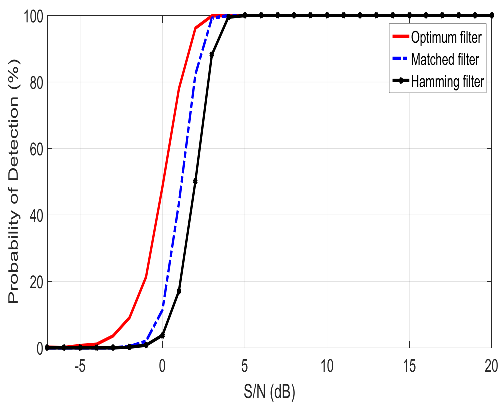


Fig.5 ROC of the proposed filter compared with the Hamming matched filter atP_{fa} = 10^{-6}

It is clarified that, the optimum filter detection performance is outperforms the response of the matched filter by approximately 2.5dB and outperforms the Hamming windowing filter response by approximately 3dB.

B. Resolution Performance

The resolution of the suggested optimum filter in range domain for LFM radar signal is evaluated and compared with that of the matched and Hamming windowing filter. The range resolutionis evaluated by simulating two close targets at two range cells number 100 and 102 respectively which practically are separated by one range cell. CFAR detection output of these targets in range domain at several SNRs (10 dB and 15dB) and$P_{fa}$of 10-6 are discussed. Figure (6-a) represents the CFAR detection for the matched filter response only without window in which, it is found that, bad resolution is obtained and the matched filter response cannot discriminate between these two targets. Hamming windowing filter effect after the matched filter is described in Figure (6-b) where worst resolution is obtained due to the impact of window which reduces the levels of side lobes only but the resolution is degraded.CFAR detection of the suggested filter is shown in Figure (6-c) where the two targets appear clearly which indicates that, better resolution is achieved from the proposed filter response.

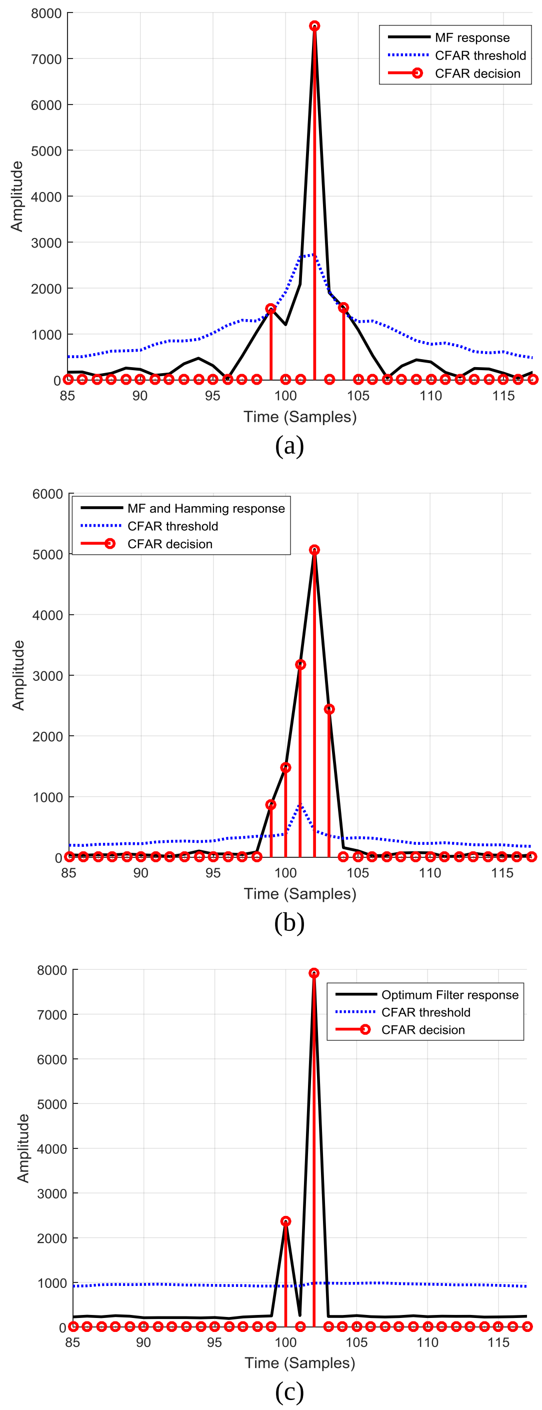


Fig. 6 CFAR detection for two close targets at $P_{fa}=10^{-6}$ and (SNR =10dB and 15 dB) for (a) Matched filter only (b) Hamming windowing filter (c) The suggested filter

From these figures, it is found that; the resolution of the proposed optimum filter has a better performance than that of the matched associated with the Hamming windowing filter, which is the main advantage of the proposed filter than the other filters.

C. Peak Sidelobe Reduction

The proposed optimum filter has a PSLR which outperforms that of the other filters due to absence of all side lobes. For the matched and Hamming windowing filters, as the S/N increases the level of sidelobes decreases with our proposed optimum filter, the PSLR is almost linearly decreases with the increase in S/N above 10 dB where approximately none side lobes as illustrated in Figure 7.From these results, it is clear that, the suggested filter outperforms the matched and Hamming windowing filter according to PSLR and range resolution.

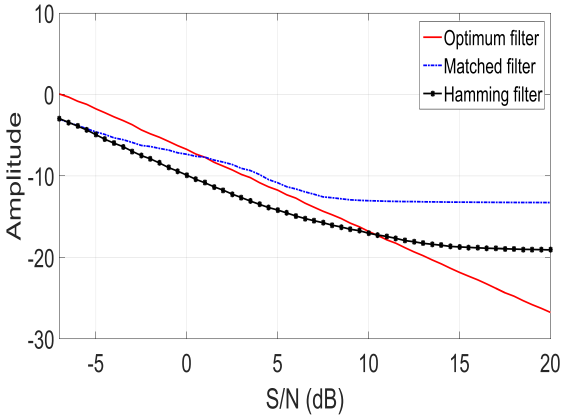


Fig. 7 Effect of increasing SNR on the PSLR using optimum filter compared to the matchedfilter and Hamming windowing filter

To resolve the optimum filter response, many parameters should be taken into consideration such as peak to side lobe ratio (PSLR) and resolution. These parameters of the suggested optimum filter are compared with that of matched and Hamming windowing filter at 10dB SNR and 120MHz sampling frequency as discussed in Table1.It is found that, the suggested optimum filter has a better performance than that of both the matched and Hamming windowing filter.

Table 1.Comparison between the proposed optimum filter, the matched and Hamming windowing filter for LFM signal

Filter	PSLR (in dB)	Resolution (m)
Matched Filter alone	-23	1.091
Hamming windowing filter	-39	2.325
Proposed Optimum Filter	-140	0.456

V. CONCLUSION

In the current paper, a filter has been suggested to completely reject the levels of side lobe in LFM radar signals. The interpretation of the suggested optimum filter has been estimated and analyzed compared to that of the matched filter associated with Hamming windowing filter through ROC curves. The proposed optimum filter has a good detection performance above 10dB of SNR because the sensitivity of noise. The proposed optimum filter outperforms the matched associated with Hamming windowing filter in side lobe reduction where the proposed optimum filter has a better side lobe cancellation compared with that of the Hamming windowing filter response. Resolution of the suggested optimum filter in range has a better performance compared with that of both the matched and Hamming windowing filters.

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