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SideLobe Level Reduction of Compound Barker codes using mismatched filter techniques

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Abstract— The major advantages of pulse compression are low pulse-power which makes it suitable for solid-state devices, higher maximum range, good range resolution and better jamming immunity. The matched filter is the optimal linear filter for maximizing the signal to noise ratio (SNR) in the presence of additive stochastic noise. Pulse compression is an example of matched filtering. But this matched filter output consists of unwanted but unavoidable side lobes. For multiple-target radar, the side lobes of the compressed pulse must be considered in the system design because of the likelihood of false alarms. At the receiver the signal processor uses weighting filters which are not matched to the transmitted waveform. When this filter is not matched to the transmitted waveform then filter output consists of unwanted but unavoidable side lobes. In this paper a new technique is proposed to suppress the side lobes of radar signals that result from standard matched filtering. This technique produces better peak side lobe ratio than all other conventional side lobe reduction techniques. In simulation the results of this filter technique for compound Barker codes is compared with the other side lobe reduction techniques.

Index Terms— Barker code, Compound Barker code, Peak side lobe Ratio, Wiener filter, Amplitude shift code, Cascaded filter..

1 INTRODUCTION

Pulse compression originated with the desire to amplify the transmitted impulse (peak) power by temporal compression. It is a method which combines the high energy of a long pulse width with the high resolution of a short pulse width. Since each part of the pulse has unique frequency, the returns can be completely separated. This modulation or coding can be either FM (frequency modulation) or linear (chirp radar) or non-linear, time-frequency-coded waveform (e.g. Costas code) or PM (phase modulation). The receiver is able to separate targets with overlapping of noise. The received echo is processed in the receiver by the matched filter. The matched filter readjusts the relative phases of the frequency components so that a narrow or compressed pulse is again produced. The radar therefore obtains a better maximum range than it is expected because of the predictable radar equation. The ability of the receiver to improve the range resolution over that of the conventional system is called the *pulse compression ratio* (PCR) [1], [6].

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When a target echo signal is passed through a matched filter and outputs a spike-like main lobe and some unwanted but unavoidable noise-like side lobes. Sidelobes are undesirable because noise and jammers located in the sidelobes may interfere with the target expected in the main lobe. These sidelobes can form spurious targets or mask the main lobe of weak target echo signals at adjacent range cells [5]. To prevent these problems, a binary code has to be designed whose auto correlation function main lobe-to-peak-sidelobe ratio is maximized for a given code length. Enormous efforts have been dedicated to design a good auto correlation function property for binary sequences [2], [3], [4]. Furthermore, we have to employ a sidelobe reduction filter to achieve an adequate main lobe-to-peak-sidelobe ratio. The first method is by using a matched filter to perform the pulse compression correlation and this output of the matched filter is cascaded with the mismatched filter to suppress the sidelobes. In this contest Rihaczek and Golden (R-G) introduced the R-G filter to suppress the sidelobes for Barker codes [2]. But the method suggested in the [2] is not applicable to the binary coded waveforms having negative sidelobes and also not supported with

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optimization. Hua and Oksman[4], and Jung, et al. [7],proposed two separate algorithms to improve the (R-G) filter performance that is called the (R-G)LP and (R-G)LS filters respectively.AmirmokhtarAkbaripourmohammad H.Bastani[8],[10] proposed another algorithm to improve the (R-G) filter performance that is called (R-G) wiener filter.

But this technique was limited to Barker codes whose maximum length is 13. Because of the unique properties of the Barker code, the length should be increased beyond the 13. Another difficulty in the R-G filter there is dilemma in the length of the filter .Whether the length of the filter is number of coefficients or the number of delay elements. Designing complexity is very high in the R-G filter when more stages are increased and also the accuracy may cause due to more delay elements for increased stages. So another technique is used to suppress the side lobes by using cascaded mismatched filter proposed by Indranil Sarkar and Adly T. Fam [9],[11].In this technique they proposed compound barker codes instead of Barker codes.But in the receiver there will be noise present . So in this paper compound Barker codes with Gaussian noise added are used and simulated the results for all these techniques.

2. Barker Coded Waveform:

The binary code consists of a sequence of either +1and -1. The phase of the transmitted signal alternates between 0 and 180° in accordance with the sequence of elements, in the phase code, as shown on the figure1. Since the transmitted frequency is usually not a multiple of the reciprocal of the sub pulse width, the coded signal is generally discontinuous at the phase-reversal points. The selection of the so called random 0, π phases is in fact critical. The binary choice of 0 or π phase for each sub-pulse may be made at random. However, some random selections may be better suited than others for radar application. One criterion for the selection of a good "random" phase-coded waveform is that its autocorrelation function should have equal time sidelobes. The binary phase-coded sequence of 0, π values that result in equal sidelobes after passes through the matched filter is called a Barker code.

3. Compound Barker Code:

Compound Barker Codes is demonstrated using pair wise combinations of Barker Codes of length 13, 11, 7and 5. If a code C_{N1} of length N_1 is compounded with another code C_{N2} of length N_2, the z-domain representation for such compounding is given by

$C_{N1,N2}(z) = C_{N2}(z) \text{ X } C_{N1}(z)$ Where $C_{N1}(z)$ is the outer code and $C_{N2}(z)$ is the inner code. In the time domain, the inner code is repeated a number of times equal to the number of bits in the outer code. In each repetition, the inner code is phase inverted or not depending on whether the corresponding bit in the outer is -1 or +1 respectively. Let us consider the Barker Codes of length 7 and 5 as

$B_7 = \{1\ 1\ 1\ -1\ -1\ 1\ -1\}$ $B_5 = \{1\ 1\ 1\ -1\ 1\}$

Either of these codes could be compounded with the other to produce a code of length 35. If the outer code is length 5 and the inner code is length 7, the compound code is denoted by $B_5 \otimes B_7$ where $\otimes$ represents the Kronecker product.

The compound code is given by {1 1 1 -1 -1 1 -1 1 11 -1 -1 1 -1 11 1 -1 -1 1 -1 -1 -1 -1 11 -1 1111 -1 -1 1 -1}

4. (R-G) filter:

The proposed filter to suppress the side lobes produced at the output of the matched filter is as shown in fig.1

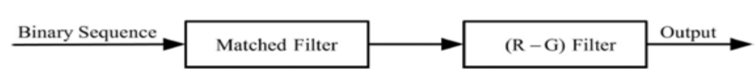

Fig.1

Consider the input wave form at the receiver is x (t) which possesses the auto correlation function R (t)

R (t) =x (t)*x (-t)…………………………….. (1)

Where * indicates time convolution [7]. However R (t) can also be rewritten as two sub functions (R_m (t) and R_s (t)), representing the

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contributions of the main lobe and the sidelobes respectively. By taking Fourier transform of equation (1) and energy spectrum is given as $E(f) = E_m(f)\,Es(f)$………………… (2)

Where

$E_m(f) = \sin^2(\pi fT)/(\pi fT)^2$, $E_s(f) = N-1+\sin(2\pi fNT)/\sin(2\pi fT)$

$E_m(f)$ and $E_s(f)$ represents the spectrum contribution of main lobe and the sidelobes, respectively. It is obvious that to find a network which has a transfer function of $1/E_s(f)$, then the sidelobes in every range cell would vanish. Often it is difficult to synthesize a filter with a transfer function exactly equal to $l/E_s(f)$. But closer the transfer function of the filter approximates $l/E_s(f)$, the lower the peak output side lobe will be. So the inverse of the $E_s(f)$ will be

$H(f) = l/E_s(f) = 1/N-1+\sin(2\pi fNT)/\sin(2\pi fT)$…………. (3)

Equation (3) can be written as

$H(f) = [N-1+\sin(2\pi fNT)/\sin(2\pi fT)]^{-1}$. In conclusion, the higher degree of sidelobe suppression can be obtained by approximating this transfer function.

To analyze filter transfer function, H (f) is approximated as a geometric series and the first four terms of the H (f) are selected as given by

$H(f)=A+B\sin(2\pi fNT)/\sin(2\pi fT)+C[\sin(2\pi fNT)/\sin(2\pi fT)]^2+D[\sin(2\pi fNT)/\sin(2\pi fT)]^3$ where A,B,C,D are coefficients of the (R-G)filter. So the filter transfer function with m coefficients are called as (R-G-m) stage filter. The impulse response of this H (f) is given as

$h(t)=A\,\delta(t)+B\sum_{-(N-1)/2}^{(N-1)/2}\delta(t-2nT)+C\sum_{-(N-1)}^{(N-1)}(N-|n|)\delta(t-2nT)$ ……………..(4)

The sampled sequence for h (t) is a discrete set $\{h_i\}$. However this discrete set $\{h_i\}$ is cascaded with matched filter output .So if the discrete auto correlation sequence is $\{R_i\}$ (matched filter output) for the 13-bit Barker code, the output of the (R-G-2) filter where m=2 stage is obtained by

$\{y_i\}=\{R_i\}*\{h_i\}$ where i=0, 1, 2 … ………… (5)

The output signals of the (R-G-2) filter resulting from convolutions of $\{R_i\}$ with the first term, the second term and the third term of $\{h_i\}$. The unknown filter coefficients are found by using Wiener filtering

4.1. (R-G-m) filter with weighting function:

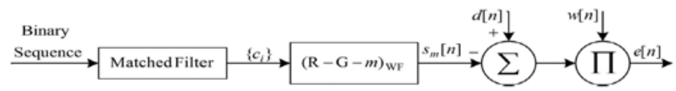

Fig.2

Fig.2 is a diagram of wiener filter with weighting function. The Wiener filter adjusts its weight(s) to produce filter output $s_m[n]$, which would be as close as the noise n (n) contained in the output of the matched filter. Hence, at the subtracted output, the noise is cancelled and the output e (n) contains clean signal. Where d[n] is the desired output and w[n] is the weighting function. The error function e[n] is the difference of the desired output d[n] to the output of the filter s[n] is multiplied by the weighting function w[n] i.e $e[n]=w[n](d[n]-s[n])$ Now, the wiener filtering technique is used to achieve an optimal filter that minimizes the total energy of e[n] .

So the method is to minimize the error signal e[n], to get the desired signal with minimum sidelobe levels.

The Wiener filtering technique is used to achieve coefficients of the filter such that it minimizes the total energy of e[n]. So the method is to minimize the error signal e[n] given as MMSE

$$\sum_{n=-(m+1)(n-1)}^{(m+1)(n-1)}(|e(n)|^2 \quad \text{………………..} (6)$$

The problem is to find the least value of E_{WF}. Because of the symmetry of the discrete set, the output $s_m[n]$ will be symmetric. Hence, the non-positive part of summation in the equation (6) can be discarded. Also, the desired output d[n] may be desirably set to zero everywhere except in the peak location. In other words d[n] = N

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δ[n]. Hence, $\arg_{wk} \min E_{WF} = \arg_{wk} \min (|w[0](N - s_m[0])|^2 + \sum_{n=1}^{(m+1)(N-1)} |w[n]s[n]|^2)$…………………. (7)

The above equation shows an optimization problem. Hence the problem is to solve the set

$$\frac{\partial W_{WF}}{\partial W_K} = 0 \qquad k=0, 1,\text{---------}\ m.$$

The filter coefficients can be normalized so that the main lobe level will be N. the weighting functions can be updated in an iterative manner such that higher side lobes receive greater weights.

Although this optimization reduces the sidelobe levels, the reduction may not be uniform over all sidelobes. To alleviate such non uniformity, the weighting functions can be updated in an iterative manner such that higher sidelobes receive greater weights. Updating the weights by multiplying them with the current filter outputs gives the higher sidelobes greater weights in the next iteration. Therefore, by iterating the algorithm a filter with a relatively flat sidelobe level may be derived, which is called the (R-G-m) WWF filter.

5. Cascading mismatched filter technique:

To analyze the cascaded filters, consider the filter arrangement as shown in figure 3

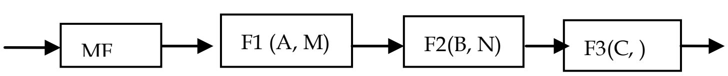

Fig.3

Figure 3 shows three stages cascading mismatched filter. This mismatched filter is aims to suppress the sidelobes that produced at the receiver. The first filter is characterized by the number M of pulses processed and by the weight vector A. The second filter is characterized by the number N of pulses processed and by the weight vector B. The number M is always less than N. The third filter is characterized by the number O of pulses processed and by the weight vector C.

Let us consider the incoming Barker code be $X(z)$. A white noise has been added to this incoming signal. This Barker code with noise is input to the matched filter .Then the output of the matched filter is input to the mismatched filter and that should be designed to suppress the sidelobes at the matched filter. Even though matched filter is the optimal filter to maximize the SNR when an uncorrelated Gaussian noise is present. By designing inverse transfer function of the autocorrelation function of the matched filter then the side lobes can be minimized. So the autocorrelation function of matched filter is given as

$R(z) = X(z)*x(z^{-1})$ this can be written as

$R(z) = N + \sum_{n=1}^{N-1} Sn(z^n + z^{-n})$……… (8)

In equation 8, N is the magnitude of the main lobe and the second term represents side lobes. So to suppress the side lobes the transfer function of mismatched filter is inverse of this. Therefore

$R(z) = N(1 + 1/N \sum_{n=1}^{N-1} Sn(z^n + z^{-n}))$ the transfer function of mismatched filter is

$$h(z) = \frac{N}{R(z)} = \frac{1}{1 + 1/N \sum_{n=1}^{N-1} Sn(z^n + z^{-n})}$$

After rationalizing the transfer function for the number of stages required and optimizing the transfer function for the better sidelobe reduction, the final equation will be

$$F(z) = [1 - 1/N \sum_{n=1}^{N-1} Sn(z^n + z^{-n})]$$
$$[1 + 1/N^2 \{\sum_{n=1}^{N-1} Sn(z^n + z^{-n})\}^2]$$
$$[1 + 1/N^4 \{\sum_{n=1}^{N-1} Sn(z^n + z^{-n})\}^4] \ldots\ldots\ldots\ldots (9)$$

equation 9 is the optimized transfer function for the three stages cascaded mismatched filter .

For a compound Barker codes if B_{N1} is compounded with B_{N2} then the autocorrelation function is denoted as $R_N(z)$ is given by

$R_{N1,N2}(z) = R_{N2}(z).R_{N1}(z^{N2})$

The mismatched filter for compound Barker codes can be implemented by cascading two filters $M_{N1}(z)$ and $M_{N2}(z)$. So the individual mismatched filters are given by

$$M_{N1}(z) = B_{N1}(z^{-1}).F_N(z) \ldots\ldots (10).$$

In equation10 $F_N(z)$ is the transfer function of three stages cascaded mismatched filter. Similarly for $M_{N2}(z) = B_{N2}(z^{-1}).F_N(z)$ where B_{N1} and B_{N2} are the Barker codes.

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The transfer function of the required mismatched filter for the compound code is of the form

$M_{N1,N2}(z) = [B_{N2}(z^{-1}).F_{N2}(z)].[B_{N1}(z^{-1}).F_{N1}(z)]$ ……..(11)

equation 11 can be rewrite by grouping the matched filter terms and mismatched filter terms, then $M_N(z)= [B_{N2}(z^{-1}).[B_{N1}(z^{-1})].[F_{N1}(z).F_{N2}(z)]$.

6. Performance Evaluation calculations for compound Barker code:

Peak Side Lobe Ratio (PSLR) is equal to the ratio of the energy in the chirp corresponding to the highest side lobe normalized by the energy in the chirp at the peak response.

PSLR= $|Yn\ peak\ sidelobe|^2 / |Y0|^2$

Where Y_0 =peak voltage response of the filter

Yn =voltage of n^{th} range side lobe

7. Simulation Results:

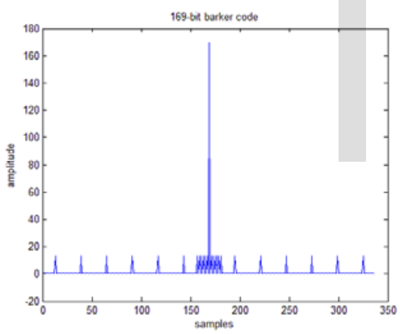

Fig 4.ACF of Compound Barker code 169

Figure 4 shows the autocorrelation function of the Compound Barker code of length 169(13x13).

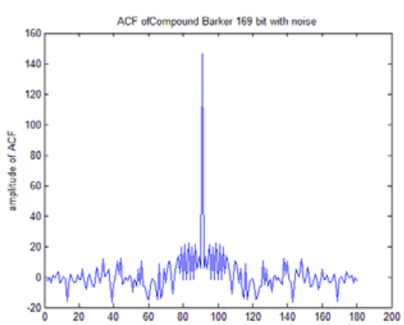

Fig.5 ACF of compound Barker code with noise

Figure 5 shows the autocorrelation function of Compound Barker code of length169 with Gaussian noise is added.

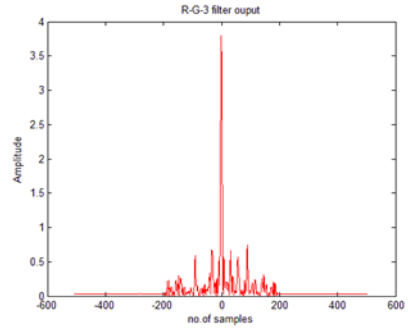

Fig 6 R-G-3 stage wiener filter for Compound Barker code of length 169.

In figure6. the mismatched filter out put(R-G-m) for Compound Barker code of length 169.Where m is the number of stages for the wiener filter ,here m=3.

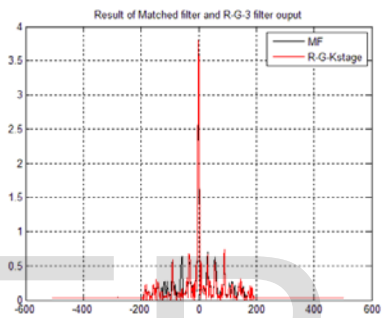

Fig.7 R-G-3 stage wiener filter for Compound Barker code of length 169 and matched filter output.

figure 7 shows the comparison results of matched filter output for Compound Barker code of length 169with Gaussian noise and the(R-G –m) filter for the same Compound Barker code of length 169.Where m is the number of stages in the (R-G –m) filter and here the m value is 3.

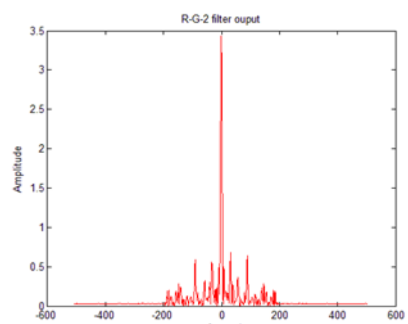

Fig 8. R-G-2 stage wiener filter for Compound Barker code of length 169.

figure 8 shows the mismatched filter out put(R-G-m) for Compound Barker code of length 169.Where m is the number of stages for the wiener filter ,here m=2.

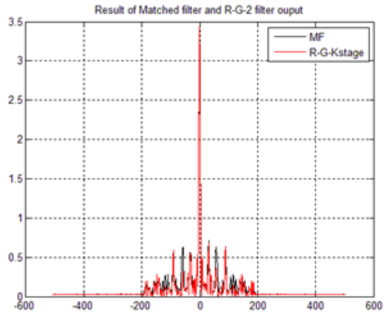

Fig 9. R-G-2 stage wiener filter for Compound Barker code of length 169.

figure 9 shows the comparison results of matched filter output for Compound Barker code of length 169 with Gaussian noise and the (R-G –m) filter for compound Barker code of length 169.Where m is the number of stages in the (R-G-m) filter. Here the m value is 2.

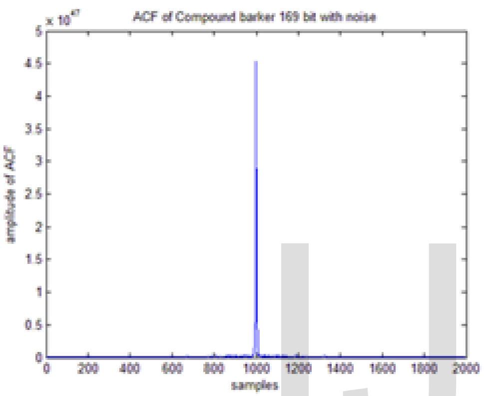

Figure. 10 ACF of compound Barker code of length 169

In figure 10 shows three stages cascading mismatched filter output of Compound Barker code of length 169.

Table 1

Compound Barker code Inner outer		Code Length	(R-G-2) filter PSLR	(R-G-3) filter PSLR	Cascaded filter PSLR
5	5	25	17.42	18.59	98.1
7	5	35	46.6	46.6	93.6
11	5	55	35.09	33.85	95.8
13	5	65	46.05	26.04	90.02
5	7	35	24.78	22.78	91.07
5	11	55	54.79	24.64	88.02
5	13	65	45.05	34.84	90.02
13	13	169	42.8	40.2	106.01

Table 1 shows different Compound Barker codes generated by using Barker code lengths of 5,7,11 and 13.The PSLR values are calculated for mismatched filter(R-G-m) and for three stages cascading mismatched filter. These PSLR values are compared. By examining the results the three stage cascading mismatched filter obtains better side lobe level reduction ratio than the(R-G-m) mismatched filter technique with lesser hard ware complexity

Conclusions:

The R-G-m filter is observed to be suppresses the sidelobes more than that of windowing technique. This filter is applicable to any binary coding signals and the filter coefficients can be calculated by the wiener filtering method. But the number of stages is chosen based on the required value of main lobe-to-peak-side lobe level andthe LSNR. And also it requires more multipliers and adders depending upon the number of stages increased .The hard ware structure also very complicated for higher stages. But the technique cascading mismatched filtering method achieves greater sidelobe levels than remaining techniques and it uses less circuitry and less number of adders and multipliers than the R-G filter. But the hard ware structure complicated for higher stages than the (R-G) filter method

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