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Optimal Selectionof Binary Codes for Pulse Compression in Surveillance Radar

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ABSTRACT

The papers aim to make a comparative study of binary phase codes in Radar pulse compression. Pulse compression allows radar to use long waveforms in order to obtain high energy and simultaneously achieve the resolution of a short pulse by internal modulation of the longpulse. This technique increases signal bandwidth through frequency or phase coding. This paper does a comparative analysis of binary codes based on the simulation results of their autocorrelation function and identifies 13 bit Barker code as the most optimal binary code for surveillance radar.

Keywords: Pulse compression, Range resolution, Peak side lobe level (PSL), Barker Code, Golay Code

1. INTRODUCTION

RADAR is an acronym of Radio Detection and Ranging. There was a rapid growth in radar technology and systems during World War II. The major areas of radar applications includes military, remote sensing, air traffic control, law enforcement and highway safety, aircraft safety and navigation, ship safety and space[1][4]. Simple pulsed radar is limited in range sensitivity by the average radiation power and, in range resolution by the pulse length. The pulse compression theory has been introduced in order to get a high range resolution as well as a good detection probability[2].Pulse compression allows the use oflong waveforms to obtain high energy and simultaneously achieve the resolution of a short pulse by internal modulation of the long pulse. The resolution is the ability of radar to distinguish targets that are closely spaced together in either range or bearing. The receiver matched filter output is the autocorrelation of the signal. If matched filter is not able to give satisfactory PSL, a mismatch filter can be used so as to reduce the side lobes further at a cost of introducing SNR mismatch loss. Low autocorrelation side lobes are required to prevent the masking of weak targets that occurs in the range side lobe of strong target the internal modulation may be binary phase coding, polyphase coding, frequency modulation, and frequency stepping. There are many advantages of using pulse compression techniques in the radar field. They include reduction of peak power, relevant reduction of high voltages in radar transmitter, protection against detection by radar detectors, significant improvement of range resolution, relevant reduction in clutter troubles and protection against jamming coming from spread spectrum action[1][4].

2. PULSE COMPRESSION

High energy (Power * Time) Transmit signal is required to improve detection threshold.

$$E= P_t * T \qquad (1)$$

So to detect the received echo and for long-range detection application, energy should be high .This achieved by either increasing the transmitted power or increasing interval time. High-power transmitters present problems because it requires high-voltage power supplies (kV) beside reliability problems and safety issues, big size, heavier, more expensive. Radar provides the good range resolution aswell as long detection of thetarget.By definition, Range Resolution is the ability to detect targets close proximity to each other as distinct objects only by measurement of their ranges (distances from radar) which usually expressed in terms of the minimum distance by which two targets of equal strength at the same azimuth and elevation angles must be spaced to be separately distinguishable.The most common radar signal or waveform is a series of short duration, somewhatrectangular-shaped pulses modulating a sinewave carrier. Increasing the interval time$\boldsymbol{\tau}$ contradicts with range resolution[3].

$$\Delta R = \frac{c\tau}{2} = \frac{c}{2*B} \; as \; \tau = 1/B \qquad (2)$$

Short pulses are better for range resolution, but contradict with energy, long range detection, carrier frequency and SNR. Long pulses are better for signal reception, but contradict with range resolution and minimum range.At the transmitter, the signal has relatively small amplitude for ease to generate and is large in time to ensure enough energy in the signal as shown in Figure 1. At the receiver, the signal has very high amplitude to be detected and is small in time.

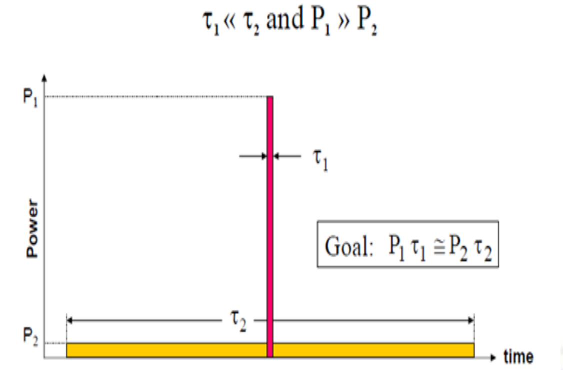

Fig 1Concept of Pulse Compression

Frequency or phase modulation can be used to increase the spectral width of a long pulse to obtain the resolution of a short pulse. This is called "pulse compression".

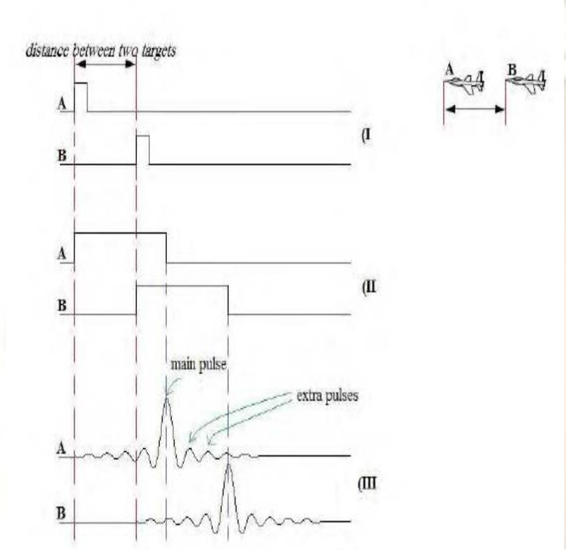

Fig 2: Increase in Resolution due to Pulse compression

This technique can increase signal bandwidth through frequency or phase coding. Although, amplitude modulation is not forbidden but usually is not used. The received echo is processed in the receiver matched filter to produce a short pulse with duration 1/B, where B is bandwidth of compressed pulse. This technique is of interest when the radar is not able to generate enough required power. So, a concise summary for pulse compression is gathering two opposite benefits "High Range Resolution" and "high detection probability" concurrently. A long pulse is modulated or coded to increase its bandwidth .On reception the modulated long –pulse echo signal is passed through the matched filter which performs the cross-correlation between transmit reference and received echo. However, the limitation is that it has range doppler cross coupling, resulting in measurement errors unless one of the coordinates (range or doppler) is determined. Range side lobes are high, compared with nonlinear FM and phase-coded waveforms.

3. Binary Phase coding

This waveform is one in which intra-pulse modulation is obtained by subdividing the pulse into sub pulses of equal duration, each having a particular phase. The phase of each sub pulse is set in accordance with a given code or code sequence..They are preferred in jamming conditions, as the coding of the transmitted signal gives an additional degree of protection against ECM.In this form of pulse compression, a long pulse of duration T is divided into N sub pulses each of width τ. The code or sequence is used to describe the phases of the individual sub pulses of a phase coded waveform[1][4]. Each has certain desirable properties and the choice often depends on the application.

An increase in bandwidth is achieved by changing the phase of each sub-pulse. The phase of each sub-pulse is chosen to be either 0 or π radians. The output of the matched filter will be a spike of width τ with an amplitude N times greater than that of long pulse. The pulse compression ratio is $N = T/\tau \approx BT$, where $B \approx 1/\tau$ = bandwidth. The output waveform extends a distance T to either side of the peak response, or central spike. The portions of the output waveform other than the spike arecalled time side-lobes.

3.1 Auto/Cross Correlation in Pulse Compression:

The performance of range resolution radar depends on the autocorrelation pattern of the coded waveform which is the matched filter compressed output. The binary sequences having ±1 as elements find more importance in pulse compression as they have good aperiodic autocorrelation function and ideal energy efficiency. The Energy efficiency is defined as the ratio of energy in the actual energy in the sequence to the energy if every element in the sequence had the maximum amplitude. The Binary sequences can be easily generated, processed and stored in digital circuitry. But the limitation comes when longer length sequences with lower Peak Side Lobe Ratio (PSLR) are needed. The Peak Side Lobe Ratio is defined from the autocorrelation pattern as the ratio of the peak side lobe amplitude to the main lobe peak amplitude and is expressed in decibels. The aperiodic autocorrelation r(k) of a sequence of length N which is nothing but the output of the matchedfilter or the matched filter compressed output is given as

$$r(k) = \sum_{i=0}^{N-1-k} y_i y_{i+k}, k = 0,1,2....N-1 \quad (3)$$

For best performance, the autocorrelation pattern of the optimum coded waveform must have a large peak value for zero shift (main lobe) and zero value for non-zero shifts.

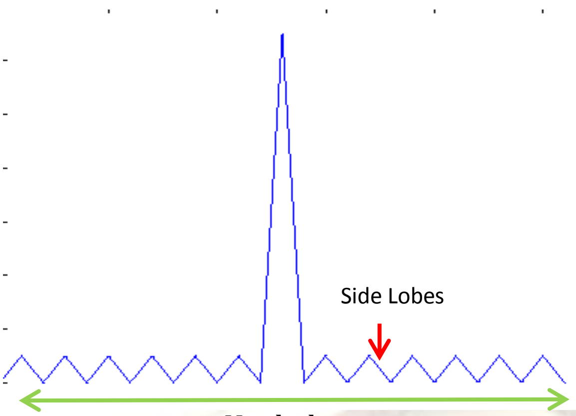

Fig 3 Auto-correlation of the binary phase code.

3.2 Types of Binarycodes

3.2.1 Linear Recursive Sequences, or Shift-Register Codes

One method for obtaining a set of random-like phase codes is to employ a shift register with feedback and modulo 2 addition that generates a pseudorandom sequence of zeros and ones of length 2n- 1, where n is the number of stages in the shift register. An n-stage shift register consists of n consecutive two-state memory units controlled by a single clock. The two states considered here are 0 and 1. At each clock pulse, the state of each stage is shifted to the next stage in line.

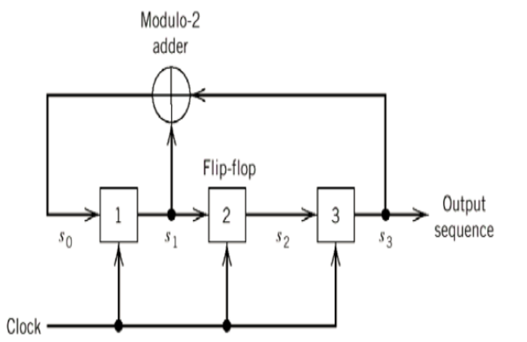

Fig4: Three Stage PN Sequence Generator

An n-stage binary device has a total of 2n different possible states.Thus an n-stage shift register can generate a binary sequence of length no greater than 2n- 1 before repeating. The actual sequence obtained depends on both the feedback Connection and the initial loading of the shift register. When the output sequence of an n-stage shift register is of period 2n- 1, it is called a maximal length sequence, or m-sequence.This type of waveform is also known as a linear recursive sequence (LRS), pseudorandom sequence, pseudo noise (PN) sequence, or binary shift-register sequence. They are linear since they obey the superposition theorem. When applied to phase-coded pulse compression, the zeros correspond to zero phase of the sub pulse and the ones correspond to π radians phase.There can be more than one maximal length sequence, depending on the feedback connection. Withthe proper code, the highest (power) side lobe can be about l/2N that of the maximum compressed-pulse power. Linear recursive sequences have an advantage that they can be long, giving high compression ratios and there are many of them allowing secure enciphering of waveforms. Their disadvantage is that their auto correlation functions contain partial sums with values greater than one so that windowing must be used to reduce range leakage.

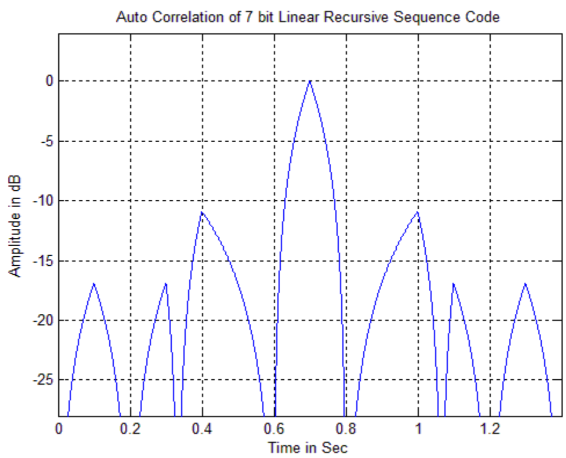

Fig 5: Simulation of 7 bitLinear Recursive Sequence

3.2.2Complementary Codes

Golay complementary codes have properties that are useful in radar and communications systems. The sum of autocorrelations of each of a Golay complementary code pair is a delta function. This property can be used for the complete removal of side lobes from radar signals, by transmitting each code, match–filtering the returns and combining them[4].

Table 1: Side/Main Lobe ratio of Binary Phase Codes[3]

Type of code	**Ratio In dB(Side lobe / Main Lobe)**
13 bit Barker code	-22.27
16 bit Complimentary	-24.08
32 bit Complimentary	-30.10
64 bit Complimentary	-36.12
128 bit Complimentary	-42.14

Theoretically, there are no side lobes on the time axis when complementary codes are employed. Complementary codes can be obtained with either binary or polyphase sequences[1].

There are two problems, however, that limit the use of complementary codes.The first is that the two codes have to be transmitted on two separate pulses, detected separately, and then subtracted. Any movement of the target or instability in the system that occurs during the time between the two pulses can result in incomplete cancellation of the side lobes. Transmitting the two codes simultaneously at two different frequencies does not solve the problem since the target response can vary with frequency. The second problem is that the side lobes are not zero after cancellation when there is a doppler frequency shift so that the ambiguity diagram will contain other regions with high side lobes. Thus this method of obtaining zero side lobes has serious practical difficulties and is not as attractive as it might seem at first glance.In a practical application, the two sequences must be separated in time, frequency, or polarization, which results in de-correlationof radar returns so that complete side lobe cancellation may not occur. Hence they have not been widely used in pulse compression radars.

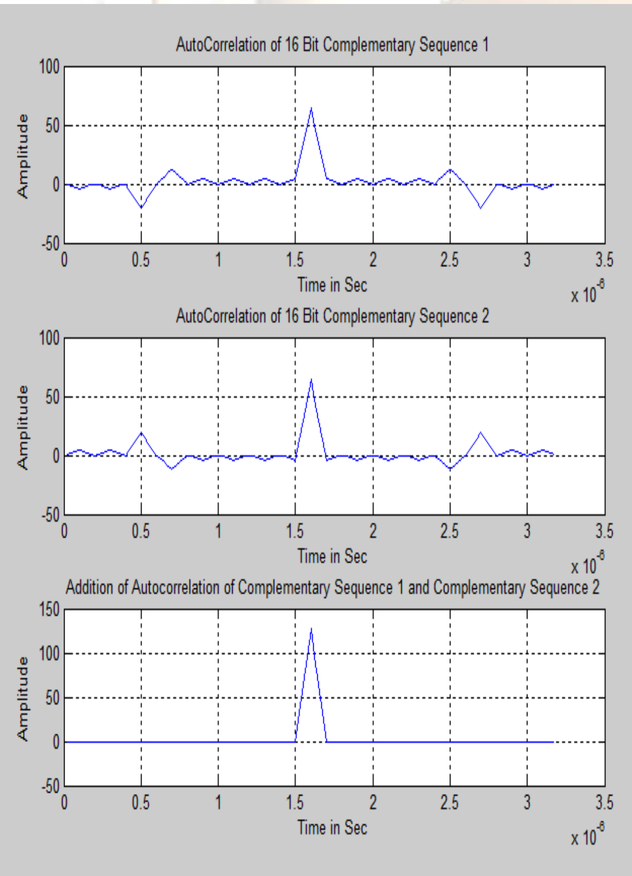

Fig 6: Simulation of 16 bit complimentary code

3.2.3 Barker codes

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. The binary phase-coded sequence of 0, π values that result in equal side-lobes after passes through the matched filter is called a Barker code. The barker codes are listed in Table 2. Autocorrelation simulation results are shown in fig8. These simulation results match with the calculated PSL shown in table 2. It can also be observed that with increase in bit length, the PSL improves.

. Table 2 Side / Main Lobe ratio in Barker codes[1]

Code Length	**Code Elements**	**Side lobe level, dB**
2	+ −, + +	−6.0
3	+ + −	−9.5
4	+ + − +, + + + −	−12.0
5	+ + + − +	−14.0
7	+ + + − − + −	−16.9
11	+ + + − − − + − − + −	−20.8
13	+ + + + + − − + + − + − +	−22.3

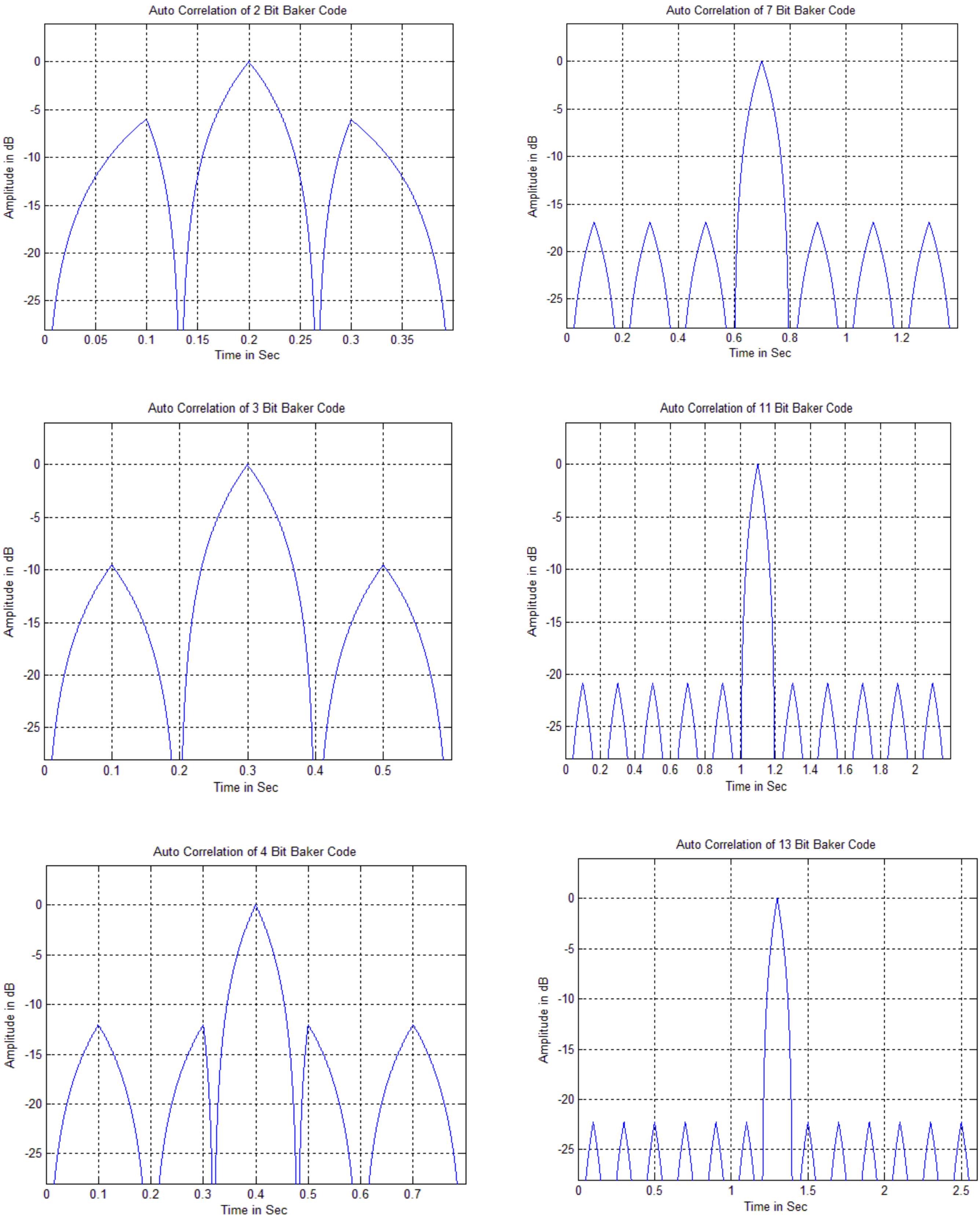

Fig. 7Auto-correlation Simulation Results of 2-bit, 3-bit, 4-bit, 7-bit, 11-bit, 13-bit barker code

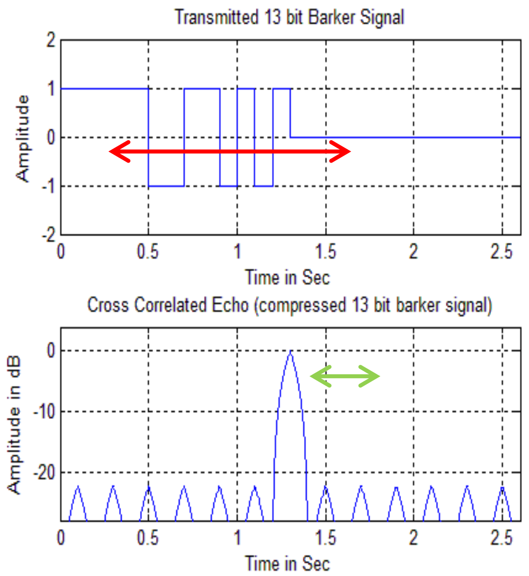

Fig 8 Simulation Result of Pulse Compression

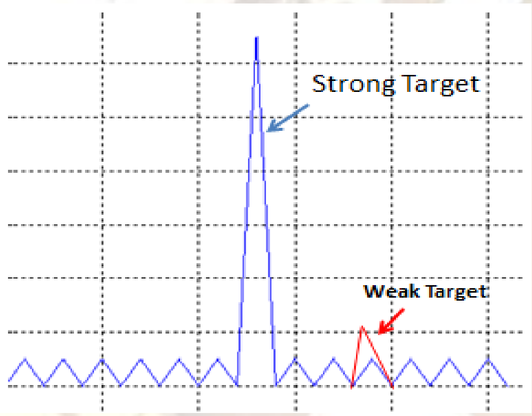

Fig 9 Need for high PSL & uniform side lobes

4. Simulation of Binary Codes in Pulse Doppler Radar application:

Fig 10 shows the block diagram of a Modulation and Demodulation scheme in Pulse Doppler Radar. The transmit carrier is modulated using the binary codes and transmitted using antenna after signal conditioning (amplification). For demodulation, both TX as well as RX signals are sampled and are passed through IQ Demodulator. The demodulated I,Q signals still consists of high frequency carrier. In order to remove the high frequency carrier signals, the demodulated I,Q signals are passed through a 4th Order Chebyshev Type 1 Low Pass Filter. After filter, the Matched Filter block performs the cross-correlation between TX_conj and RX where TX_conj = I_tx – jQ_tx and RX = I_rx + jQ_rx. Fig 11-13 shows the simulation results of the performance of the binary codes when passed through the Modulation-Demodulation scheme of Pulse Doppler Radar. For simulation purpose, the received echo is added with Additive White Gaussian Noise of -27dB. Thus, these results show the performance of the binary codes in the presence of noise.

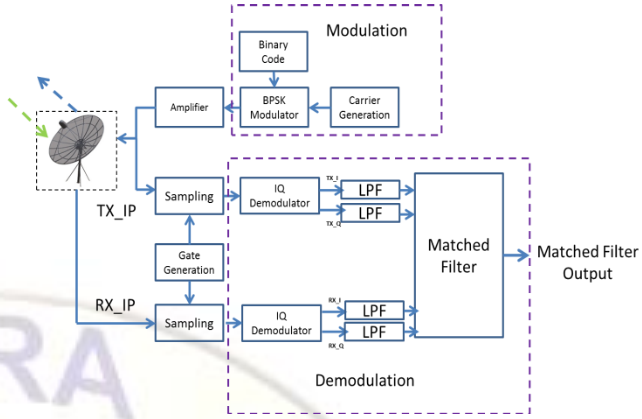

Fig10. Modulation- Demodulation in Pulse Doppler Radar

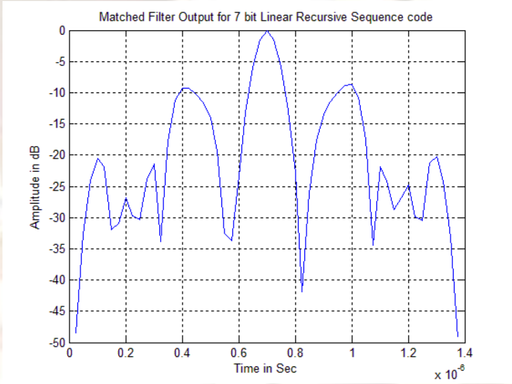

Fig 11. Matched Filter Output for 7 Bit Linear Recursive Sequence

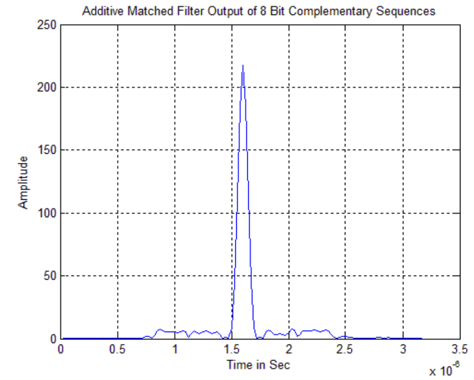

Fig 12. Matched Filter Output for 8 Bit Complementary Sequence

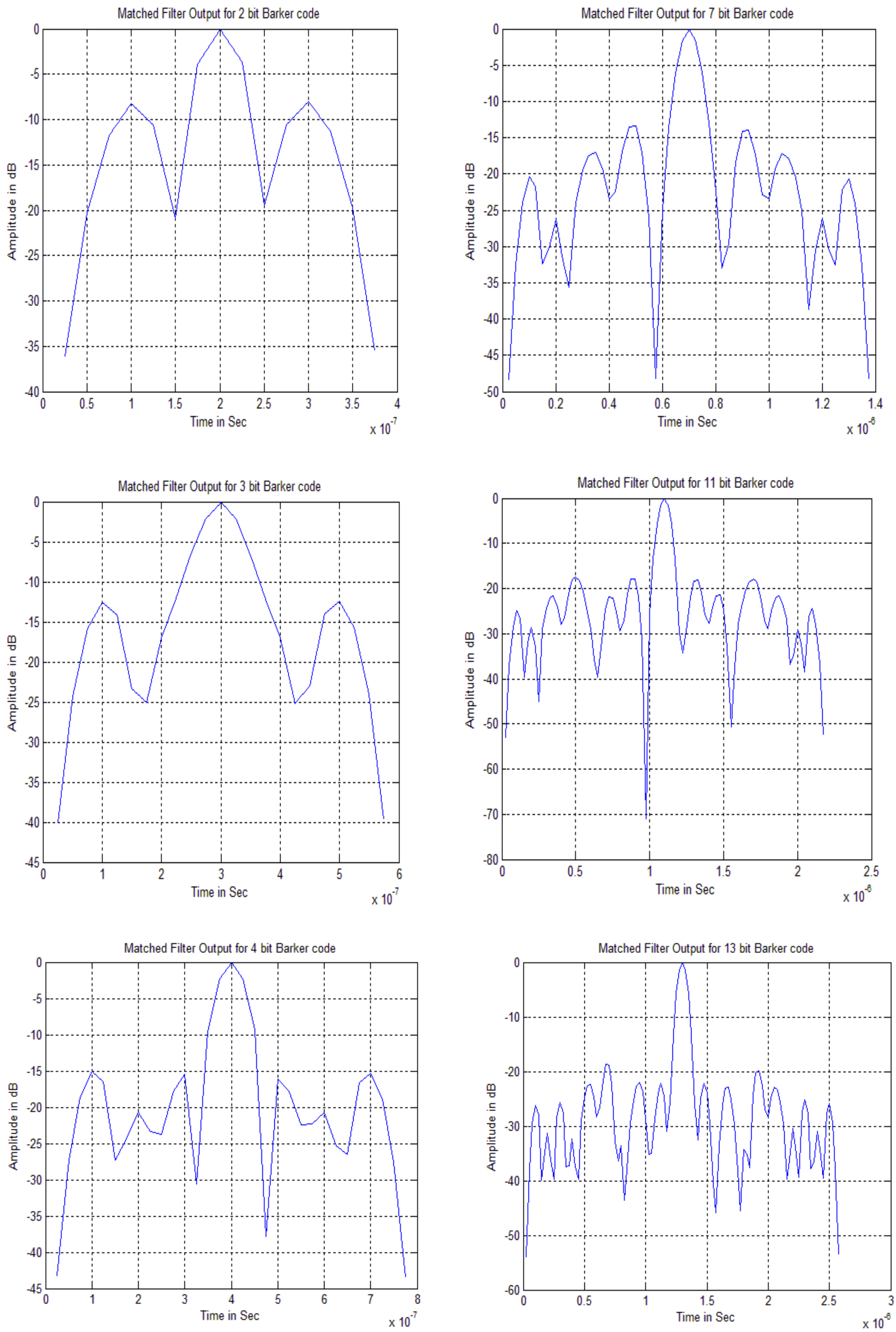

Fig 13. Matched Filter Output of 2-bit,3-bit,4-bit,7-bit, 11-bit, 13-bit Barker Code

5. Comparative Analysis and Optimal Selection of Binary Phase Codes

There are two criteria for the selection of optimal phase codes:

a) Auto-correlation function of the phase codes should have uniform side-lobes.

b) They should have high peak to side lobe ratio (PSL).

Fig 10. Shows a scenario where a strong target & weak target are in the nearby vicinity. If the selected binary phase code does not have high PSL & uniform side lobes then the weak target will be masked under side lobes of strong target and thereby goes undetected.

Based on the simulation results in Table 1, we can conclude that although higher length of linear sequence code will yield higher PSL unlike barker codes they do not possess uniform side lobes. Although Complementary Codes provide a very high PSLR, it requires two separate sequences and thereby two different echoes must be received before any target information can be obtained. Based on empirical data of surveillance radar, the radar cross section (RCS) for heavy vehicle is 20 & crawling man is 0.05. Thus, range side lobes of strong target should be below $10\log(\frac{0.05}{20}) = -26dB$ to detect weak target. This is an extreme case wherein it is assumed that a crawling man and a heavy vehicle are co-located (within same antenna beam). Practically, 22dB PSL may be sufficient which is obtained using 13 bit barker code. Results from section 4 also show that when passed through Modulator- Demodulator of Pulse Doppler Radar under presence of noise, 13 Bit barker code provides the required PSLR with fairly uniform sidelobes.

5. Conclusion:

The need for pulse compression is established in section 1 and section 2. Different types of binary phase codes used for pulse compression are introduced and simulated results of autocorrelation function of each of the binary phase codes are presented and compared. In section 4, a real life scenario is simulated by passing the binary codes modulated carrier signal through Modulator – Demodulator Scheme of Pulse Doppler Radar. The received echo is degraded using Additive White Gaussian Noise of -27dB. Based on the comparative analysis in section 3, section 4 and PSLR requirements in Surveillance Radar, it was concluded that 13 bit barker code is the most optimal binary phase code for surveillance radar .

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