Design of less detectable RADAR waveforms using Barkar codes and polyphase codes

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***Abstract*—**Radar signal generation and processing techniques are developing with an aim of reducing interference. Signal jamming and signal detection are the areas of interest in the field of radar engineering. So there is a need for design of new waveforms which are less detectable by the hostile receiver. In this paper, the Stepped Frequency Waveforms is modulated with phase modulation techniques such as barkar codes and polyphase codes to improve the complexity and to increase the bandwidth of waveform and limiting the transmitted power using these pulse compression techniques.

***Keywords*—**Step frequency waveform, Pulse compression, Barker code, Polyphase code, Less detectable waveform.

1INTRODUCTION

Radar is an integral part of a modern weapon systems. Its ability to work in all-weather environments at long ranges is incomparable with any other existing sensors. Use of wideband microwave technology, and advanced radar signal processing techniques have greatly enhanced the detection probability and resolution characteristics of the modern radar systems. The capability of wideband/high-resolution radar in target detection, recognition and analysing the backscattering media, have increased the role of the radar for defence and many areas of civil applications. Most of the civil applications are concentrated on remote sensing, investigation of natural resources, ground mapping and high-resolution imaging of objects; whereas, the applications of military systems include intelligence, surveillance, navigation, detection, recognition, guidance of weapons, battle field surveillance, anti-aircraft fire control etc.

2 EXISTING SYSTEM

2.1 Frequency modulation pulse compression

Modulation is a technique used to increase the transmission bandwidth of the waveform. The transmitted waveform received as echo when matched filtered at the receiver side is used to extract range information about the target. Frequency modulation is a technique in which the frequency varies with time either uniformly or non-uniformly in order to obtain highly suppressed side lobes, so that pulse compression achieved is good.

Consider a rectangular pulse having single frequency with no modulation. Figure 1 shows the autocorrelation function of the rectangular waveform. It is clear from the plot that the waveform after performing matched filtering at receiver side the output occupies a particular time period. This delay area occupied

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by the waveform ambiguity plot indicates that two or more targets are distinguishable only when they are separated by a delay of a particular time period occupied in the plot.

$$S_1(t)=A_1\cos[2\Pi(f_0 + n)t] \quad (1)$$

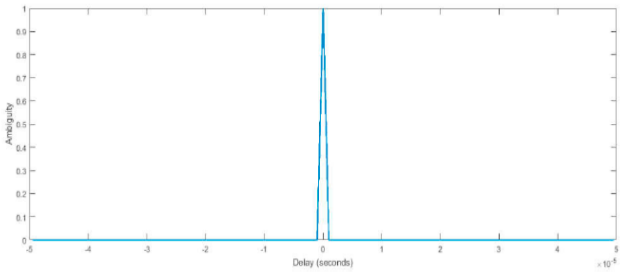

Fig 1: Autocorrelation of rectangular pulse

FW is a type of frequency modulation technique for generating a high range resolution profile. A sequence of N pulses with fixed pulse repetition Each set of N pulses is called coherent processing interval (CPI) or burst. The frequency of each pulse in the sequence is increased uniformly from one pulse to another by a fixed step size (Δf). The frequency of the first pulse is taken as carrier frequency (f0) and the subsequent pulse has a difference of step size (Δf) from the preceding pulse as shown in Figure 2 The received signal is sampled and spectral weighting is applied to reduce the side lobe levels. The quadrature component for each burst is stored and IDFT is applied to find out the range profile of the corresponding burst. Each pulse in SFW can be modulated using any modulation scheme. If the transmitted waveform for the n-th pulse.

Then the received signal from the target after a time delay of 2R/c is given as

$$S_2(t)= A_2\cos[2\Pi(f_0 + n)(t\text{-}2R/c)] \quad (2)$$

Where R is Target Range in meters, c is propagation speed in meter per second and N is number of steps or pulses Range resolution (ΔR) of SFW is determined from the overall bandwidth.

From equation 2, it can be understood that the range resolution of SFW can be increased by increasing the number of pulses in the sequence or frequency step size. The unambiguous range window (Ru) of stepped fm waveform is given by:

$$R_u = c / (2\Delta f) \quad (3)$$

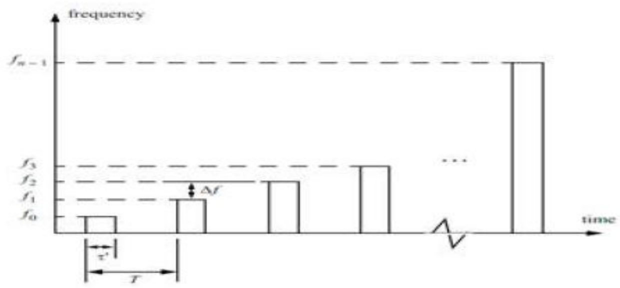

Fig 2: Stepped frequency modulated waveform

It noted that the frequency step size of the SFW plays an important role in determining the unambiguous range and range resolution. Figure 2 shows SFW with linearly increasing step size. Frequency step size is generally chosen to be approximately half the inverse of pulse width (τ):

$$\Delta f \leq 1 / \tau \quad (4)$$

A. Non- Uniform SFW:

Non-uniform SFW is designed by replacing the constant step size (Δf) parameter of SFW. For the generation of a less detectable waveform, two main parameters are to be considered; they are waveform bandwidth and modulation type. SFW have high bandwidth. In order to make stepped waveform more complex and difficult to detect the frequency step size of the waveform is set to vary accordingly either uniformly or non-uniformly based on the information provided at the transmitter end.

The non-uniform stepped waveform is modulated with LPI waveforms such as the Frank codes,P1, P2, P3, P4 codes etc.. in order to reduce the side lobes which helps in increasing the stealthiest and to implement pulse compression in SFW for generating shorter pulse with less transmitted power required for transmission of longer pulse.

2.2. Phase Modulated Pulse Compression:

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Phase modulated pulse compression is a technique in which the phase of the signal is varied with time. Phase modulation is done to increase the bandwidth of the signal. One simple way is to use binary phase shift with the code sequence. But the random sequence is not effective as the amplitude varies for each side lobe. So Barker codes were introduced which gives equal amplitude side lobes.

A. Barker codes:

Barker codes belong to binary phase coded pulse compression technique with a phase shift of 00 and 1800. These codes don't have random sequences and only particular combinations which give equal amplitude side lobes are considered. The largest combination available is 13 bits. The main advantage of this code is that no amplitude weighting is needed to suppress side lobes. The possible combinations of Barker code and the PSLR value for these combinations are listed in Table 1. These PSLR values were obtained when there is no Doppler shift and no delay introduced in the autocorrelation process.

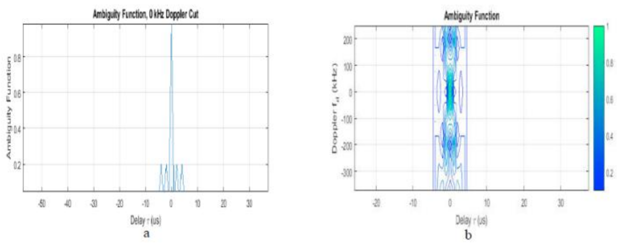


Fig 3: (a) Doppler cut of 5-bit Barker code, (b) Ambiguity function of 5-bit Barker code

The Barker bit combinations are employed for choosing the step size of nonuniform SFW. Here 5-bit combinations are taken. This result in a total of 25=32 combinations of different frequencies, but not all combinations can be selected. The main advantage of barker is combinations having equal amplitude sidelobes. The combinations used for selecting step size are 11101, 10101,11011,11100,11111 which have equal sidelobes. The main drawback of barker code is that pulse compression is achievable up to a maximum of 13 bits. The amount of pulse compression achievable is directly related to the number of sub-pulses. The Doppler cut and ambiguity function of Barker code having 5bit combinations are shown in Figure 3(a) and 3(b)

Code Length	Code Elements	PSLR(dB)
2	10,11	-6.0
3	110	-9.5
4	1101,1110	-12.0
5	11101	-14.0
7	1110010	-16.9
11	11100010010	-20.8
13	1111100110101	-22.3

Table 1: Barker codes with existing PSLR value

2.3. Phase coded non-uniform SFW:

SFW is known for high range resolution, while P1 code is known for LPI properties. So a new waveform has been developed by modulating the SFW with polyphase (P1) codes. This waveform is expected to possess both properties of the stepped waveform and polyphase codes such as high range resolution and less detectability. The varying step size is fixed to various combinations by the user.

Thus the user alone can retrieve the information about the radar transmitter waveform from the received echo signal, while the jammer or interceptor have little probability to identify and acquire the radar signals, having been entirely unaware of the frequency combinations used. The performance of the waveform is analyzed by means of ambiguity function.

2.4. Ambiguity Function:

The ambiguity function is defined as the absolute value of matched filter output envelope. The input signal to the filter is a Doppler shifted version of the return signal, to which the filter is matched. The ambiguity function is given

$$|X(\tau,f_{4})|=\left|\int_{-\infty}^{\infty} s(t) * (t+\tau).\exp(j2\pi ft)\, dt\right| \quad (5)$$

Where s(t) denotes transmitted signal, τ denotes delay and fd denotes frequency shift In any radar system, two measurements are mainly used for measuring the effectiveness of the ambiguity function: the PSLR and ISLR. The former indicates the ability of radar to detect weak targets. It is associated with the probability of false alarm in particular range bin due to the presence of a target in neighbouring range bin

PSLR(dB) = 20 * log(largest_sidelobe/mainlobe_peak) (6)

ISLR is a measure of how much energy is leaking from the main lobe of impulse response function

of the target. It is the measure of energy distributed in side lobes

ISLR(dB)=10 * log(sidelobe^2/mainlobe_peak^2) (7)

3 PROPOSED SYSTEM

3.1 Pulse Compression:

The term radar signal processing incorporates the choice of transmitting waveforms for various radars, detection, performance evaluation, and circuitry between the antenna and the displays or data processing computers. Both fields continually emphasizes communicating a maximum information in a special bandwidth and minimizing the effects of interference.

The transmitted peak power was already in megawatts, the peak power continued to increase more and more due to the need of longer range detection. Besides the technical limitation associated with it, this power increase poses a financial burden. Not only that, target resolution and accuracy became unacceptable. Siebert and others pointed out the detection range for given radar and target was dependent only on the ratio of the received signal energy to noise power spectral density and was independent of the waveform. The efforts at most radar laboratories then switched from attempts to construct higher power transmitters to attempts to use pulses that were of longer duration than the range resolution and accuracy requirements would allow.

Increasing the transmitted waveform results in increase of the average transmitted power and pulse width results in greater range resolution. Pulse compression combines the best of both techniques by transmitting a long coded pulse and processing the received echo to get a shorter pulse. The transmitted pulse is modulated by using frequency modulation or phase coding in order to get a large time-bandwidth product. Phase modulation is the widely used one.

In this, form of phase modulation is super imposed to the long pulse increasing its bandwidth. Even if they are partially overlapped, this modulation allows discriminating between two pulses. Then upon receiving an echo, the received signal is compressed through a filter and the output signal will look like the one. It consists of a peak component and some side lobes.

3.2Binary phase 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. One criterion for the selection of a good “random” phase-coded waveform is that its autocorrelation function should have equal time side-lobes. 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.

An example is shown in Figure 4. This is a Barker code of length 13. The (+) indicates 0 phase and (−) indicates π radians phase. The auto-correlation function, or output of the matched filter, is shown in Figure 5. There are six equal time side-lobes to either side of the peak, each of label 22.3 dB below the peak. The longest Barker code length is 13. The barker codes are listed in Table 2. When a larger pulse-compression ratio is desired, some form of pseudo random code is usually used. To achieve high range resolution with-out an incredibly high peak power, one needs pulse compression.

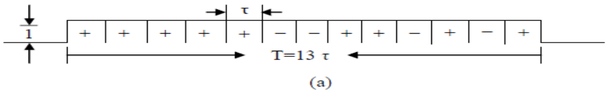


Fig 4:13-element Barker Code

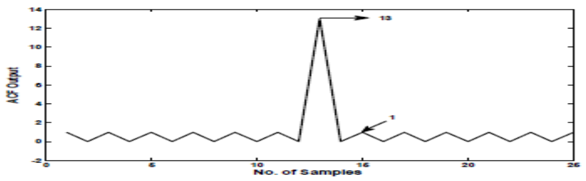


Fig 5: Autocorrelation Output

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

Table 2: Barker codes

Barker codes have been called the perfect codes because the highest side lobe is only one code element amplitude high. However, the largest pulse compression ratio that can be obtained with the barker codes is only 13. The side lobe levels obtained with the polyphase codes are not limited to any finite pulse compression ratio and exhibit better Doppler tolerance for broad range Doppler coverage than do the bi-phase codes, and they exhibit good side lobe characteristics.

3.4. Polyphase codes:

The codes that use any harmonically related phases based on a certain fundamental phase increment are called Polyphase codes and these codes are derived conceptually coherently detecting a frequency modulation pulse compression waveform with either a local oscillator at the band edge of the waveform or at band centre and by sampling the resultant in phase I and Q data at the Nyquist rate. The Nyquist rate in this case is once per cycle per second of the bandwidth of the waveform.

Frank proposed a polyphase code with good non-periodic correlation properties. Kretscher proposed different variants of Frank polyphase codes called p-codes which are more tolerant than Frank codes to receiver band limiting prior to pulse compression. Lewis has proven that the side lobes of polyphase codes can be substantially reduced after reception by following the autocorrelation with two sample sliding window subtracted for Frank and P1 codes and P3 and P4 codes.

Polyphase compression codes have been derived from step approximation to linear frequency modulation waveforms and linear frequency modulation waveforms. These codes are derived by dividing the waveform into sub codes of equal duration, and using phase value for each sub code that best matches the overall phase trajectory of the underlying waveform. In this section the polyphase codes namely P1, and P2 codes and their properties are described.

A. P1 Code:

The P1 code is obtained by the modified versions of the Frank code, with the dc frequency term in the middle of the pulse instead of at the beginning. P1 code is derived by placing the synchronous oscillators at the centre frequency of the step chirp IF waveform and sampling the baseband waveform at the Nyquist rate.

The P1 code has N^2 elements and the phase of ith element of the jth group is represented as

$$\Phi_{i,j} = -\left(\frac{\pi}{N}\right)[N-(2j-1)][(j-1)N+(i-1)] \quad (8)$$

Where the integers i and j ranges from 1 to N. For example, the P1 code with N = 4, by taking phase value modulo 2 is given by the sequence,

$$\phi_{4\times4} = \begin{bmatrix} 0 & \pi & 0 & \pi \\ \frac{5\pi}{4} & \frac{3\pi}{4} & \frac{\pi}{4} & \frac{7\pi}{4} \\ \frac{\pi}{2} & \frac{\pi}{2} & \frac{\pi}{2} & \frac{\pi}{2} \\ \frac{7\pi}{4} & \frac{\pi}{4} & \frac{3\pi}{4} & \frac{5\pi}{4} \end{bmatrix}$$

The autocorrelation function and the phase values of P1 code with length 100 are given in Figure 3.5. The PSL value is obtained as -23.99dB. P1 code has the highest phase increments from sample to sample at the two ends of the code. Thus, when waveforms phase coded with these codes are passed through band pass amplifiers in a radar receiver, P1 code is attenuated most heavily at the two ends of the waveform. This reduces the side lobes of the P1 code autocorrelation function. Hence this exhibits relatively low side lobes than Frank code. This result shows that P1 code is very pre compression bandwidth tolerant than Frank code. Also, P1 code has an autocorrelation function magnitude which is identical to the Frank code for zero Doppler shifts.

B. P2 Code:

The P2 code has the same phase increments within each phase group as the P1 code, except that the starting phases are different. The P2 code has N2 elements and the phase of *i*th element of the *j*th group is represented as

$$\Phi_{i,j} = \left(\frac{\pi}{2N}\right)[N - 2i + 1][N - 2j + 1] \quad (9)$$

Where *i* and *j* are integers ranges from 1 to N. The value of N should be even in order to get low autocorrelation side lobes. An odd value of N results in high autocorrelation side lobes. For example, the P2 code with N = 4, by taking phase value modulo 2 is given by the sequence,

$$\phi_{4\times4} = \begin{bmatrix} \frac{9\pi}{8} & \frac{3\pi}{8} & \frac{13\pi}{8} & \frac{7\pi}{8} \\ \frac{3\pi}{8} & \frac{\pi}{8} & \frac{15\pi}{8} & \frac{13\pi}{8} \\ \frac{13\pi}{8} & \frac{15\pi}{8} & \frac{\pi}{8} & \frac{3\pi}{8} \\ \frac{7\pi}{8} & \frac{13\pi}{8} & \frac{3\pi}{8} & \frac{9\pi}{8} \end{bmatrix}$$

The autocorrelation function under zero Doppler, Doppler of 0.05 and the phase values of P2 code

The peak side lobes of the P2 code are the same as the Frank code for zero Doppler case and the mean square side lobes of the P2 code are slightly less. The value of PSL obtained as -29.79dB which is same as that of Frank code. Under Doppler of 0.05 the PSL value is computed as -8.79dB which is slightly lower than that of Frank code. The phase changes in P2 code are largest towards the end of the code. The significant advantage of the P1 and P2 codes over the Frank code is that they are more tolerant of receiver band limiting prior to pulse compression. But P1 and P2 suffers from high PSL value. PSL value is obtained by the ratio of peak side lobe amplitude to the main lobe amplitude.

4 EXPERIMENTAL RESULTS

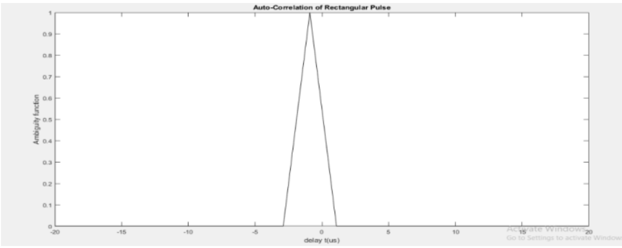


Fig 6: Output of Auto-Correlation of Rectangular Pulse

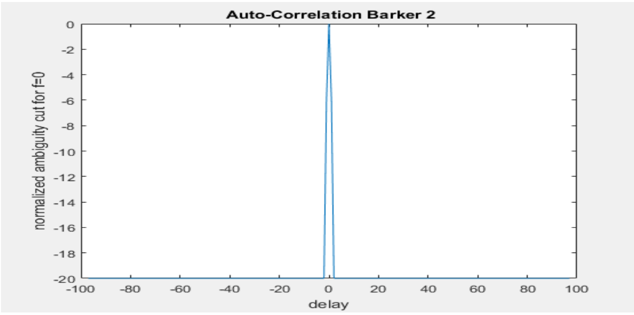


Fig 7: Auto-Correlation of 2-bit Barker code

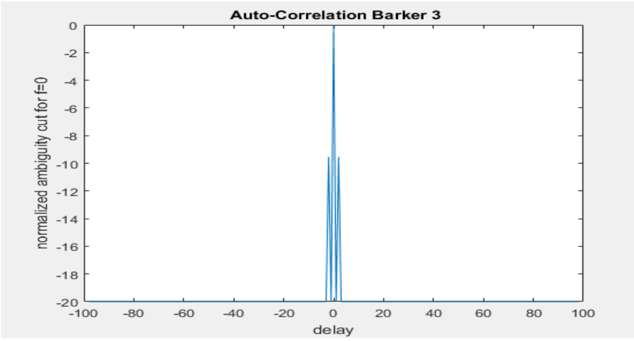


Fig 8: Auto-Correlation of 3-bit Barker code

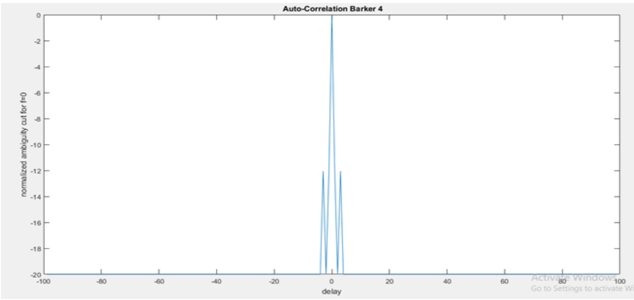


Fig 9: Auto-Correlation of 4-bit Barker code

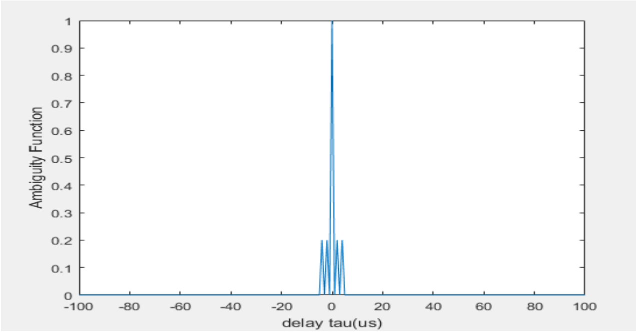


Fig 10: Auto-Correlation of 5-bit Barker code

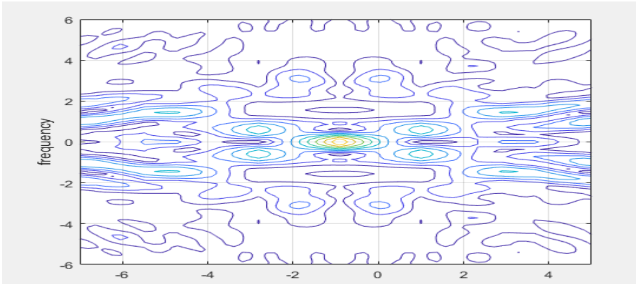


Fig 11:Ambiguity Function of 5-bit Barker code

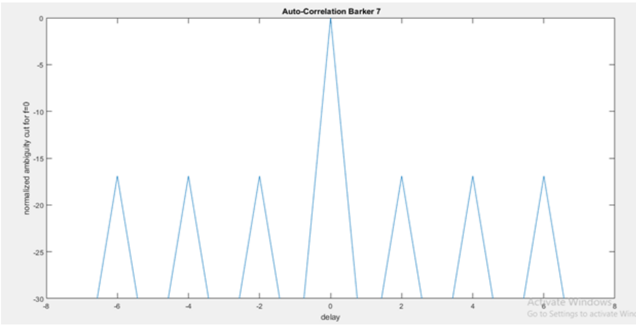


Fig 12:Auto-Correlation of 7-bot Barker code

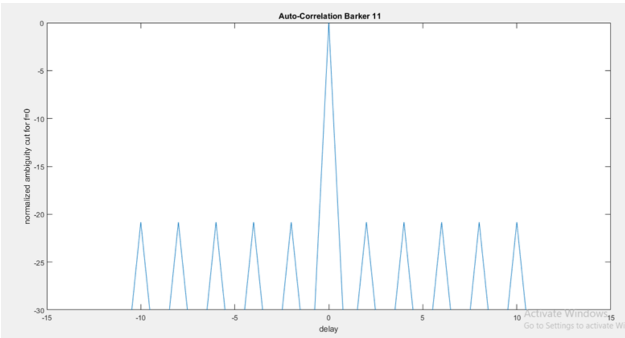


Fig 13:Auto-Correlation of 11-bit Barker code

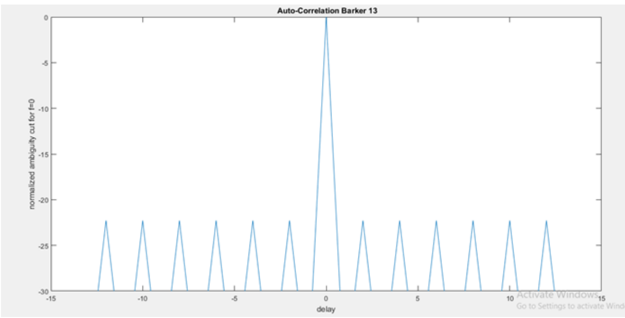


Fig 14:Auto-Correlation of 13-bit Barker code

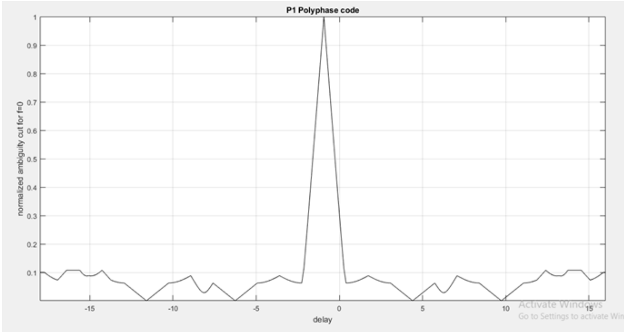


Fig 15: Doppler cut of P1code

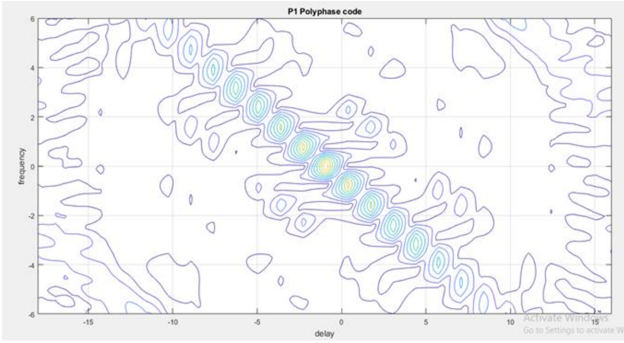


Fig 16: Ambiguity function of P1code

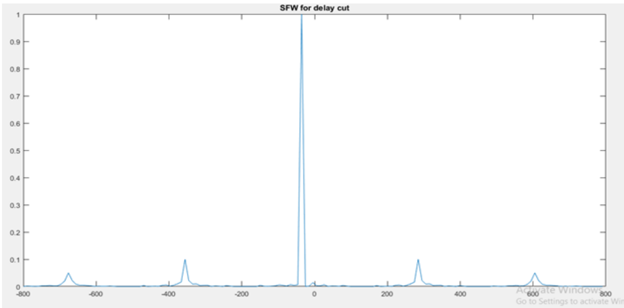


Fig 17: Delay cut of SFW

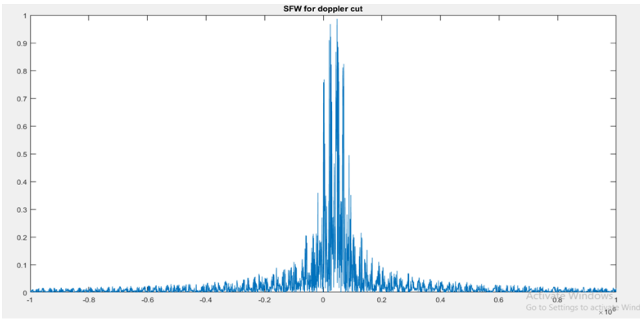


Fig 18: Doppler cut of SFW

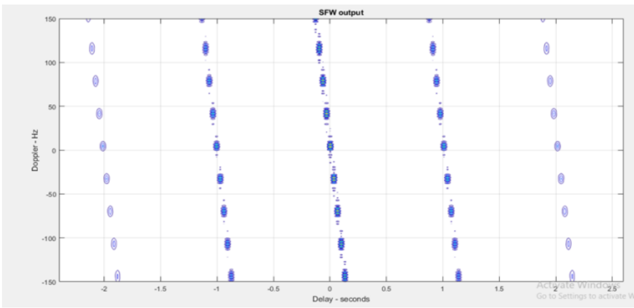
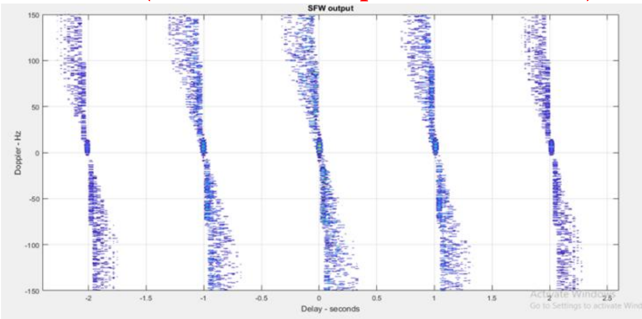


Fig 19: Ambiguity of SFW



. Fig 20: Ambiguity of SFW with varying Δf

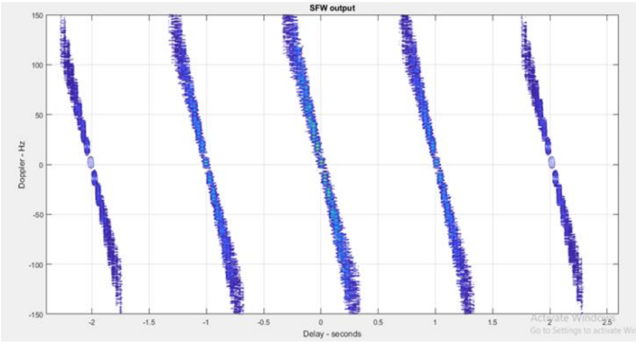


Fig 21:Ambiguity of P1 modulated SFW with varyingΔf

5 CONCLUSION

The conventional pulsed radar waveforms have been subjected to pulse compression techniques such as waveform modulation and coding. These methods result in tandem enhancements to radar sensitivity and range resolution for dynamic targets. The characteristics of the phase modulated waveform are analysed with the help of ambiguity functions Doppler plot and delay plot. The stepped waveform complexity is increased by using varying step size and is then modulated with an LPI code such as P1, thus decreasing the delectability and improving the stealthiest of radar waveforms. From the analysis of the ambiguity functions plots, it becomes apparent that the modulated waveform has good Doppler and delay characteristics along with a low probability of interception.

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