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Phase Coded Waveforms for Pulse Compression Radar Systems

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ABSTRACT: Discrete-time signals or sequences with good aperiodic and periodic autocorrelation properties have several applications in radars, measurements and communications. Among the options open for research in radar signal processing, design of coded waveforms is one of higher priorities in this domain. The application of coded signalsfor non-coherent systems such as non-coherent radar (using magnetrons) and radar like systems invites researchers to investigate the waveforms that can improve the detection and resolution capability of non-coherent pulse compression radar systems. This paper proposes the aperiodic and periodic binary and ternary waveforms, which can be used for coherent and non- coherent pulse compression (NCPC) applications. For non-coherent processing, the on-off waveforms and their references are also presented.

Keywords: Autocorrelation, pulse compression, non-coherent pulse compression, matched filter, ternary sequences.

Abbreviations: PSL, peak sidelobe, CPC, coherent pulse compression, AACF, aperiodic autocorrelation function; NCPC, Non-coherent Pulse Compression; OOK, on-off keying; MPSL, minimum peak sidelobe; PACF, periodic autocorrelation function; CW, continuous wave; ZCZ, zero-correlation zone; SNR, signal to noise ratio.

I. INTRODUCTION

In general pulse compression is a well-known technique to improve the signal-to-noise ratio (SNR) of received signal out of a weak long pulse. Radarsemploy pulse compression technique to accomplish the detection capability of high energy long duration pulse and range-resolution corresponding to short pulse simultaneously. In this context, the key role is played by modulation of transmitted pulse that increase the bandwidth, which intern improves the range resolution of the radar by implementing matched filter in the receiver [1-2]. Widely used modulation techniques are either phase or frequency [3-4]. Generally, phase modulation is preferred due to ease of implementation. Further, the performance of radar could be significantly improved, if the selection of waveform is optimum as per the operational environment. Two basic pulse compression techniques, which are used in radar systems are coherent [3] and non-coherent pulse compression [5-9]. This paper presents the various aperiodic and periodic waveforms, which can be used in coherent and non-coherent radar systems for enhancing the detection and resolution capabilities. In section II, properties of aperiodic and periodic waveforms are discussed. Section III explains about the basic concept of coherent and non-coherent pulse compression techniques. Periodic signals for coherent and non-coherent pulse compression are explained in section IV. Discussions and conclusions are given in section V.

II. PROPERTIES OF APERIODIC AND PERIODIC SEQUENCES

Let us consider a sequence of length N is $s_i(n)$ and the periodic repetition of sequence $s_i(n)$ represented by $\hat{s}_i(n)$. As the matched filter is used in radar receiver which is a correlator.

Therefore, the autocorrelation or cross-correlation of aperiodic and periodic sequences at the output of the matched filter can be given by

$$R_{ii}(\tau) = \sum_{n=0}^{N-1} s_i(n)\, s_i^*(n+\tau) \quad (1)$$

$$R_{ii}(\tau) = \sum_{n=0}^{N-1} s_i(n)\, \hat{s}_i^*(n+\tau) \quad (2)$$

$$R_{ij}(\tau) = \sum_{n=0}^{N-1} s_i(n)\, \hat{s}_j^*(n+\tau) \quad (3)$$

$$R_{ii}(\tau) = \begin{cases} E, & \text{for } \tau = 0 \\ 0, & \text{for } \tau \neq 0 \end{cases} \quad (4)$$

In the region $0 \le \tau \le N$,

Where $\hat{s}_i(n+\tau) = s_i((n+\tau) \bmod N)$, and $\tau = mt_b$ is total delay time and t_b is single bit duration. Equation (1) represents the *aperiodic* autocorrelation function of sequence $s_i(n)$, whereas equations (2) and (3) represent the autocorrelation and cross-correlation of *periodic sequences*. In autocorrelation, the transmitted signal and reference signal both are same but for cross-correlation, the transmitted signal and reference signals are different. Additionally, in radar systems, matched filter is used in receiver to enhance the signal-to-noise ratio which is proportional to $2E/N_0$. In this expression, E denotes the energy contained by received signal. Therefore, special attention is required for radar signal design that to detect the target at long range, the transmitted signal must have sufficient energy [1].

The energy, which is associated with the sequence is given by

$$E = \sum_{n=0}^{N-1} s_i^2(n) \quad (5)$$

While selecting waveforms for radar, it is important to discuss about the energy efficiency of the transmitted pulse. Formula for calculating η is:

$$\eta = \sum_{n=0}^{N-1} \frac{s^2(n)}{|s^2(n)|_{max}} \quad (6)$$

Hence, this paper is mainly focused on the sequences which have perfect periodic autocorrelation property and higher energy efficiency. Coherent and non-coherent pulse compression is discussed in section III.

III. COHERENT AND NON-COHERENT PULSE COMPRESSION

The basic concept of Coherent Pulse Compression (CPC) radar is shown in Fig. 1. In this processing technique, either phase or frequency modulated pulse is transmitted and while receiving the replica of transmitted signal is correlated with the received signal that is reflected by the target. Fig. 2, is showing the output of the matched filter which aperiodic autocorrelation of the Barker code N = 13. At delay τ = 0, the output is maximum which is called peak lobe. Other than the peak-lobe at the output is called the sidelobes. For the detection of small targets near large target, the sidelobe must be low. Therefore, low peak sidelobe (PSL) play an important role in the selection of waveform for radar applications.

Non-coherent pulse compression (NCPC) is a new variant of pulse compression which was suggested by N. Levanon [5-8]. His publications on NCPC are based on On-Off Keying (OOK). OOK signals can use saturation amplifier, pulsed oscillator (e.g., magnetron) and laser. The major advantage of NCPC over CPC is random phase of each sub-pulse is acceptable, which makes signal processing simple. Fig. 3 shows the simple block diagram of NCPC radar system [9].One simple way of designing aperiodic waveform for the NCPC radar system is Manchester coding technique. In this design the transmitted signal is derived from any biphase code which have good autocorrelation property. Such biphase codes are Barker codes, minimum peak sidelobe (MPSL) sequences etc.

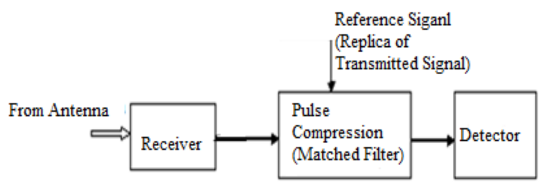
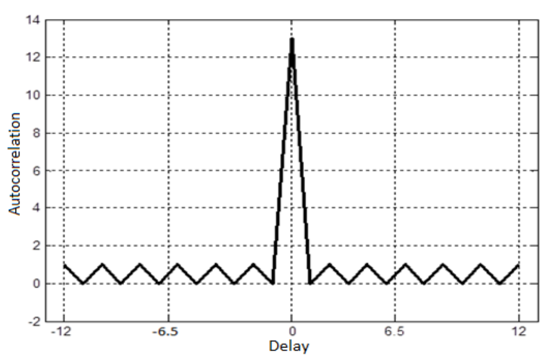


Fig. 1. Block diagram of Coherent Pulse Compression radar receiver.



Transmitted Signal = [1 1 1 1 1 -1 -1 1 1 -1 1 -1 1]
Reference Signal = [1 1 1 1 1 -1 -1 1 1 -1 1 -1 1]

Fig. 2. Aperiodic autocorrelation function of Barker code N =13.

In this process, Barker sequence or MPSL sequences is represented by Manchester-coded (1 → 10, and 0 → 01) sequence. For example, Barker sequence of length 13 is converted as:

N = [1 1 1 1 1 -1 -1 1 1 -1 1 -1 1] and its Manchester coded signal that is transmitted signal 'a' is given by (7).

a = [1 0 1 0 1 0 1 0 1 0 0 1 0 1 1 0 1 0 0 1 1 0 0 1 1 0] (7)

The major difficulty in the design of NCPC waveforms is its reference signal. Levanon suggested that for aperiodic waveforms, the reference signal can be simply designed by replacing '0' of the transmitted signal with '-1' in the reference signal. Hence, the reference signal 'b' for (7) is given by (8).

b = [1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 1 -1]. (8)

Fig. 3 shows the simple block diagram of NCPC radar receiver in which a simple envelope detection (square law detector) can be like conventional radar systems. The compressed output of the filter is given by (9)

$$\sum_{k=0}^{N-1}|a_k|^2 b_k \quad (9)$$

Where a_k and b_k are the elements of '*a*' and '*b*' respectively given in equations (7) & (8). The output after pulse compression is depicted in Fig. 4.

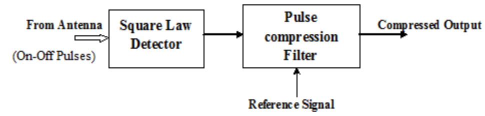


Fig. 3. Block diagram of Non-coherent Pulse Compression (NCPC) radar receiver.

From Figs. 2 and 4, it can be observed that the aperiodic correlation sidelobes of Barker codes and Manchester coded Barker code exhibit peak sidelobe of ±1. It accomplishes that the sequences which have good autocorrelation property can also be used for NCPC radar systems. Two major drawback of Manchester coding are (i) The target may go undetected if it coincides with the negative peaks near the mainlobe, which can be understood from figure 4. (ii) The duty cycle of transmitted code is 50% and energy efficiency of Manchester coded waveform is also 50%.

On principle, it is not possible to design the sequences with ideal *aperiodic autocorrelation function* (AACF) [10]. On the other hand, it is easier to generate the sequences which disappear all off-peak sidelobes in its Periodic Autocorrelation Function (PACF) and such sequences can be extensively used in continuous wave (CW) radars. Their properties and applications to radar systems are considered in [11-16].

A. Periodic Waveforms

The sequences that exhibit lowest off-peak sidelobes equal to $|R_{ii}(\tau \neq 0)| = 1$ are M-sequences and Legendre sequences. Fig. 5 shows the periodic autocorrelation function of M-sequence of length N=31. This is the output of coherent processing where transmitted signal and reference signals are same and amplitude of the transmitted pulse is constant. The output of the matched filter in this case is termed as autocorrelation function.

M sequence N = 31 = [1 -1 -1 -1 -1 1 -1 -1 1 -1 1 1 -1 -1 1 1 1 1 1 -1 -1 -1 1 1 -1 1 1 1 -1 1 -1] is two valued binary codes {±1} and produces *periodic auto-correlation* of peak value 31 and all off-peak sidelobes of value 1. Levanon [8] and Jahangir [17] demonstrated the application of these M-sequences for NCPC radar. When such sequences are used for NCPC radar like systems, during transmission unipolar version {0, 1} of M-sequence is '-1' is replaced with '0' and reference signal is same two valued binary code. Fig. 6(b) shows that the peak value of the main lobe if 16 and all sidelobes between main peaks are zero. This is due to 16 bits of 1's and 15 bits 0's are in transmitted signal. These unipolar M-sequence exhibit perfect periodic cross-correlation property between transmitted signal and reference signal, at the cost of high energy loss. It is reasonable that when radar uses transmitter sources as magnetron or direct-detection laser, they use on-off keying (OOK), where ‘1’ represents ON and ‘0’ represents OFF condition of the transmitter.

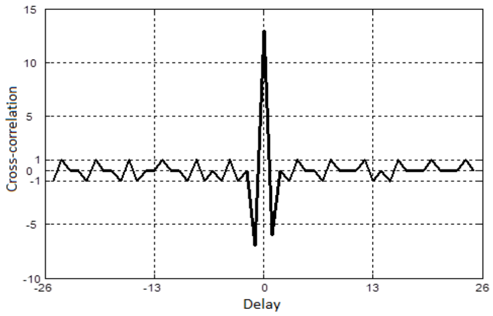


Fig. 4. Cross-correlation of transmitted and reference signals, Barker Manchester code N=26.

Signal = *a*= [1 0 1 0 1 0 1 0 1 0 0 1 0 1 1 0 1 0 0 1 1 0 0 1 1 0]
Reference = *b* = [1 -1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 1 -1]

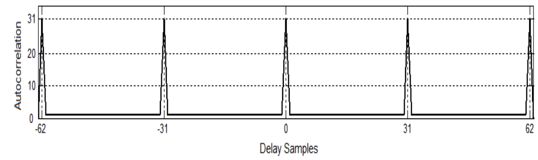
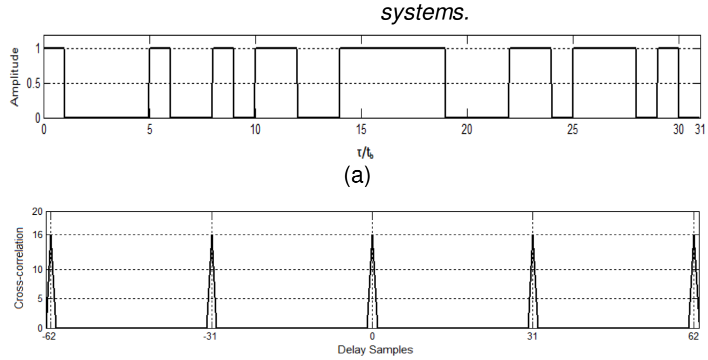


Fig. 5. Periodic autocorrelation function of M-sequence of length N=31.

From the above discussion, it realizes that when M-sequences are used for coherent processing the energy efficiency is 100% but sidelobes level is 1. On the other hand, when these signals are used for non-coherent pulse compression, they exhibit perfect periodic cross-correlation that is zero sidelobes, but energy efficiency is nearly 50%. These sequences are also referred as *zero correlation zone (ZCZ) sequences or punctured sequences* [18-19]. This motivates us to identify the sequences, which demonstrate the perfect periodic correlation properties in addition to higher energy efficiency. *In next section this paper presents ternary sequences that satisfy both the requirements and can be applied to both coherent and noncoherent radar systems.*



(a)

(b)

Signal: = [1 0 0 0 0 1 0 0 1 0 1 1 0 0 1 1 1 1 1 0 0 0 1 1 0 1 1 1 0 1 0]
Reference = [1 -1 -1 -1 -1 1 -1 -1 1 -1 1 1 -1 -1 1 1 1 1 1 -1 -1 -1 1 1 -1 1 1 1 -1 1 -1]
Fig. 6. M-sequence N = 31, (a) Amplitude of transmitted pulse (b) Cross-correlation function.

IV. PERIODIC WAVEFORMS FOR COHERENT AND NON-COHERENT PROCESSING

When dealing with periodic sequences, aim is to achieve high range resolution that needs longer sequence length and higher duty cycle (i.e. more number of 1’s than ‘0’s in a sequence). This sought for sequences, which have much longer lengths than Barker codes and must have higher energy efficiency. The periodic waveforms with higher average duty cycle also avoid the pulse–train conflict between average power and unambiguous range [8]. Therefore, this paper examines the ternary sequences which have perfect periodic autocorrelation property with good energy efficiency and can be used for both coherent and non-coherent radar applications. Fig. 7 shows the coherent processing of ternary sequence N=31. The autocorrelation function shows that the peak value is 25, because there are 25 1’s in sequence. On the other hand, when it is processed non-coherently that is on-off periodic waveforms, all -1 also becomes +1 and zeros remains same. The amplitude and cross-correlation properties of such sequences are shown in fig. 8 where the unipolar transmitted signal and its reference signal are given. The important point which is to noted here is that in both the cases (coherent and non-coherent) sidelobes are zero and peak lobe value is 25. This property of perfect periodic ternary code is also demonstrated by taking an example of ternary code of length N = 21. Fig. 9 (a) shows the autocorrelation function of coherent processing whereas Fg. 9(b) shows the cross-correlation function after non-coherent processing. Table 1 presents some ternary sequences, *which can be used for coherent and non-coherent pulse compression radar systems simultaneously*. Such type of more signals can be derived from ternary sequences, which exhibit perfect periodic autocorrelation property such as Ipatov codes [20]. In case of coherent processing the transmitted and reference signals are same whereas for non-coherent processing transmitted signal and reference signals are different. The reference signal in NCPC case to be calculated in such a way that all off-peak sidelobes become zero. The value of ‘β’ can be calculated from equation (3), when it is kept equal to zero and $\tau \neq 0$.

$$\beta = -\frac{((N-1)-M)}{M} \quad (10)$$

where ‘M’ is number of zeros in the perfect periodic ternary signal of odd length ‘N’. As the number of zeros are less in these sequences, the energy efficiency of such sequences is high compared to OOK sequences derived from M-sequences or Legendre sequences.

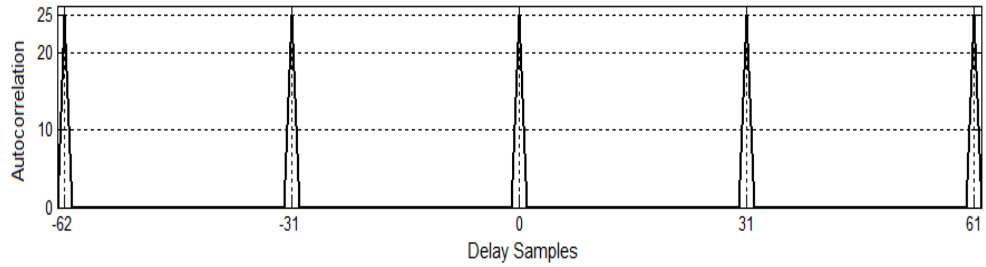
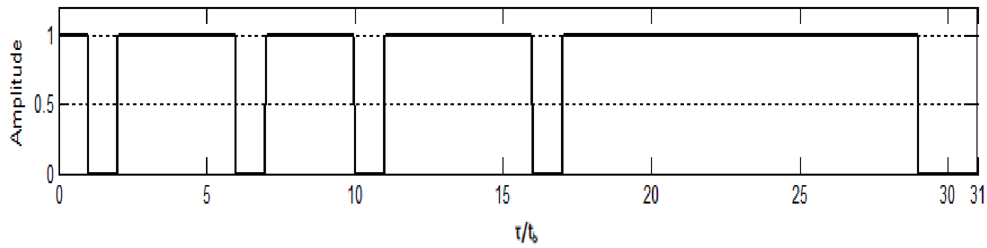
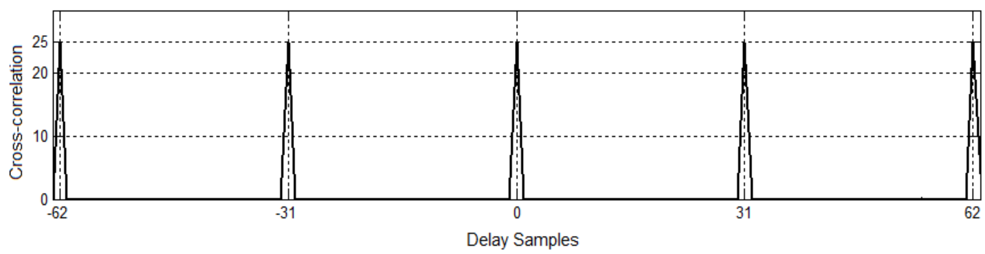


Fig. 7. Coherent processing of Ternary sequence N=31 = [1 0 1 1 1 -1 0 -1 -1 -1 0 1 -1 1 1 -1 0 1 -1 1 -1 1 1 1 -1 -1 1 1 1 0 0] autocorrelation function.



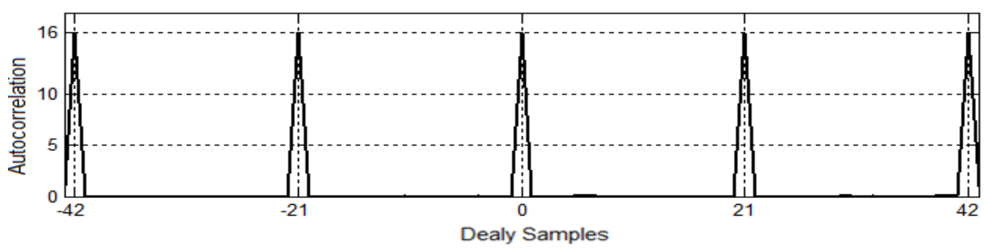
(a)



(b)

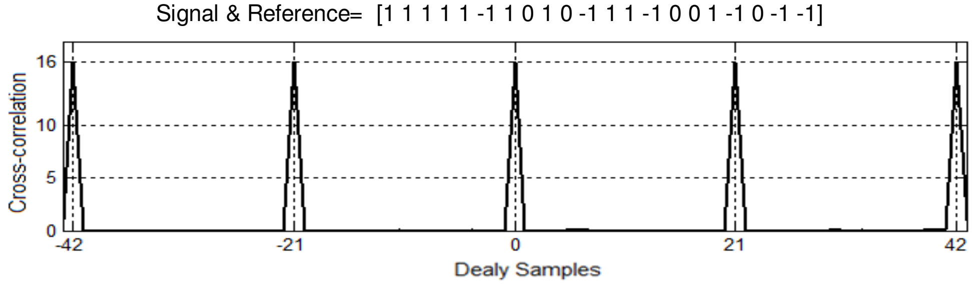
Fig. 8. Non-Coherent Processing of Ternary sequence N=31 (a) Amplitude (b) cross-correlation.

Signal = [1 0 1 1 1 1 0 1 1 1 0 1 1 1 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 0 0]
Reference = [1 -4 1 1 1 1 -4 1 1 1 -4 1 1 1 1 1 -4 1 1 1 1 1 1 1 1 1 1 1 1 -4 -4]



(a) Coherent processing of Ternary Signal N= 21.

Signal & Reference= [1 1 1 1 1 -1 1 0 1 0 -1 1 1 -1 0 0 1 -1 0 -1 -1]



(b) Non-coherent processing of Ternary Signal N = 21.

Fig. 9. Coherent and non-coherent processing of Ternary sequence N=21.
Signal = [1 1 1 1 1 1 1 0 1 0 1 1 1 1 0 0 1 1 0 11]
Reference = [1 11 1 1 1 1 -3 1 -3 1 1 1 1 -3 -3 1 1 -3 1 1]

Table 1: Perfect Periodic Ternary Sequences for Coherent and Non-coherent Processing.

N	(η in %)	Coherent Processing	On-Off signal for Non-coherent Processing
13	69	**Sig:** [1 0 1 0 0 1 -1 1 0 -1 -1 1 1]	**Sig:** [1 0 1 0 0 1 1 1 0 1 1 1 1]
		Ref: [1 0 1 0 0 1 -1 1 0 -1 -1 1 1]	**Ref:** [1 β 1 β β 1 1 1 β 1 1 1 1, β= -2]
21	76	**Sig:**[1 1 1 1 1 -1 1 0 1 0 -1 1 1 -1 0 0 1 -1 0 -1 -1]	**Sig:** [1 1 1 1 1 1 1 0 1 0 1 1 1 1 0 0 1 1 0 1 1]
		Ref:[1 1 1 1 1 -1 1 0 1 0 -1 1 1 -1 0 0 1 -1 0 -1 -1]	**Ref:** [1 1 1 1 1 1 1 β 1 β 1 1 1 1 β β 1 1 β 1 1, β = -3]
31	81	**Sig:**[1 0 1 1 1 -1 0 -1 -1 -1 0 1 -1 1 1 -1 0 1 -1 1 -1 1 1 1 -1 -1 1 1 1 0 0]	**Sig:** [1 0 1 1 1 1 0 1 1 1 0 1 1 1 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 0 0]
		Ref:[1 0 1 1 1 -1 0 -1 -1 -1 0 1 -1 1 1 -1 0 1 -1 1 -1 1 1 1 -1 -1 1 1 1 0 0]	**Ref:** [1 β 1 1 1 1 β 1 1 1 β 1 1 1 1 1 β 1 1 1 1 1 1 1 1 1 1 1 1 β β, β = -4]
57	86	**Sig:** [1 0 1 1 1 1 -1 -1 -1 1 1 0 1 1 1 -1 -1 -1 1 11 -1 1 -1 1 1 1 1 1 -1 1 0 -1 1 -1 0 -1 -1 -1 1 -1 -1 0 1 -1 1 1 -1 -1 1 1 0 -1 1 -1 1 0 0]	**Sig:** [1 0 1 1 1 1 1 1 1 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 0 1 1 1 1 1 1 0 1 1 1 1 1 1 1 1 1 0 1 1 1 1 0 0]
		Ref: [1 0 1 1 1 1 -1 -1 -1 1 1 0 1 1 1 -1 -1 -1 1 1 -1 1 -1 1 1 1 1 1 -1 1 0 -1 1 -1 0 -1 -1 -1 1 -1 -1 0 1 -1 1 1 -1 -1 1 1 0 -1 1 -1 1 0 0]	**Ref:** [1 β 1 1 1 1 1 1 1 1 1 β 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 β 1 1 1 β 1 1 1 1 1 1 β 1 1 1 1 1 1 1 1 1 β 1 1 1 1 β β, β = -6]
73	87.7	**Sig:** [-1 1 -1 1 -1 0 1 1 1 1 -1 -1 1 1 -1 -1 -1 1 -1 -1 -1 0 1 1 -1 1 0 1 1 1 1 -1 -1 -1 1 1 -1 1 -1 -1 -1 -1 1 -1 0 1 1 -1 1 -1 -1 -1 1 0 1 1 -1 1 1 -1 1 1 -1 0 0 1 0 1 1 1 0 1 1]	**Sig:** [1 1 1 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 1 1 1 1 0 1 1 1 1 1 1 1 1 1 0 0 1 0 1 1 1 0 1 1]
		Ref: [-1 1 -1 1 -1 0 1 1 1 1 -1 -1 1 1 -1 -1 -1 1 -1 -1 -1 0 1 1 -1 1 0 1 1 1 1 -1 -1 -1 1 1 -1 1 -1 -1 -1 -1 1 -1 0 1 1 -1 1 -1 -1 -1 1 0 1 1 -1 1 1 -1 1 1 -1 0 0 1 0 1 1 1 0 1 1]	**Ref:** [1 1 1 1 1 β 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 β 1 1 1 1 β 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 β 1 1 1 1 1 1 1 β 1 1 1 1 1 1 1 1 1 β β 1 β 1 1 1 β 1 1: β = -7]

V. DISCUSSIONS AND CONCLUSIONS

This paper considers coherent and Non-coherent pulse compression and presented both aperiodic and periodic autocorrelation functions of various on-off waveforms. It is also demonstrated that the perfect periodic ternary sequences can be used simultaneously for both applications without degrading the energy efficiency. NCPC is Doppler tolerant because after square law detector phase information is not required and integration of many pulses is much simpler than coherent integration. However, due to non-coherency these systems suffer from signal-to-noise ratio (SNR) loss [8]. Though there are many advantages of NCPC over coherent processing but it is significantly more sensitive to the noise. By using perfect ternary sequences, a system can implement both CPC and NCPC but the option to switch to NCPC is preferred only when phase information coherency is lost in received signal.

VI. FUTURE SCOPE

The performance of these sequences must be checked in real time applications in various noise backgrounds.

Conflict of interest. The author declares that he has no conflict of interest.

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