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High-Resolution Adaptive Waveform Radar

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Abstract This paper presents the use of the Linear Congruence Modified Pushing Sequence (LC-MPS) waveforms application as target tracking, for Ground Control Intercept (GCI) based Fire Control Radar (FCR). The distinct features of LC-MPS are combined with Linear Frequency Modulation (LFM), and a new approach has been developed for the radar waveform design on an adaptive basis, that is suitable for fire control radar systems and Track before Detect (TBD) applications.
Keywords *Linear Frequency Coded Waveform; Ambiguity Function; LC Codes; Pushing Sequences*

1. Introduction

Modern radars can be equipped with a finite set of preprogrammed waveforms that could be used in mission critical applications. Mostly radar systems are operated either in search/surveillance mode or in tracking mode. In search mode, approximate values of range and Doppler (velocity) of the intercepted targets would serve the purpose and so low-resolution waveforms are generally used. On the other hand, in recognition of targets or in the tracking applications, accuracy in parameter measurements is a matter of concern, and one would always prefer to go in for the use of high-resolution waveforms. A system, which is equipped with the facility of selecting alternative waveforms, is termed as '*Adaptive Waveform Radar*' (AWR). In this context, the research work due to Rihaczek and Bernfeld reveal that the most appropriate waveform for search operations has to have the property of sharp ridge type ambiguity function. Unfortunately in such a case, the radar will not be able to resolve closely moving targets along the ridge causing considerable loss of resolution in Doppler along the ridge, which is not an acceptable phenomenon in most of the tracking applications [1-8].

It is in this connection, this paper proposes that the radar could use a low-resolution Doppler tolerant scheme based waveform or high-resolution LC-MPS scheme based waveform depending on the situation whether the radar is either used for searching or for tracking/recognition mode. In next section it is started with a brief description of the LC codes and Modified Pushing Sequence using LC codes switch are used to work in a track mode.

2. Linear Congruence (LC) Codes

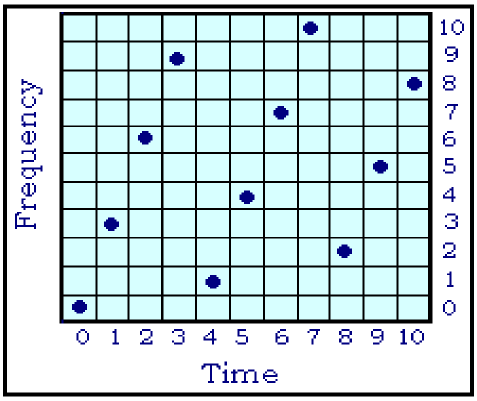
Titlebaum [9] introduced time-frequency hop codes based on the '*Theory of Linear Congruences*' and thus these codes are referred to as *LC Codes*. In this case, frequency hopping occurs over 'N' subpulses where N is a prime number. These codes are shown to exhibit good cross-correlation property [9-10], but there is no mention about their sidelobe pushing property. Bhatt et al., [11] examined and reported that LC codes possess sidelobe pushing property also. The frequency hopping sequence of LC codes can be represented in the form of a coding rule [12] as

$$(i, d_i) = (i, ai \ (\text{mod } N)); \text{ for all } i = 0, 1, 2\ldots N\text{-}1, 1 \leq a \leq N–1 \qquad (1)$$

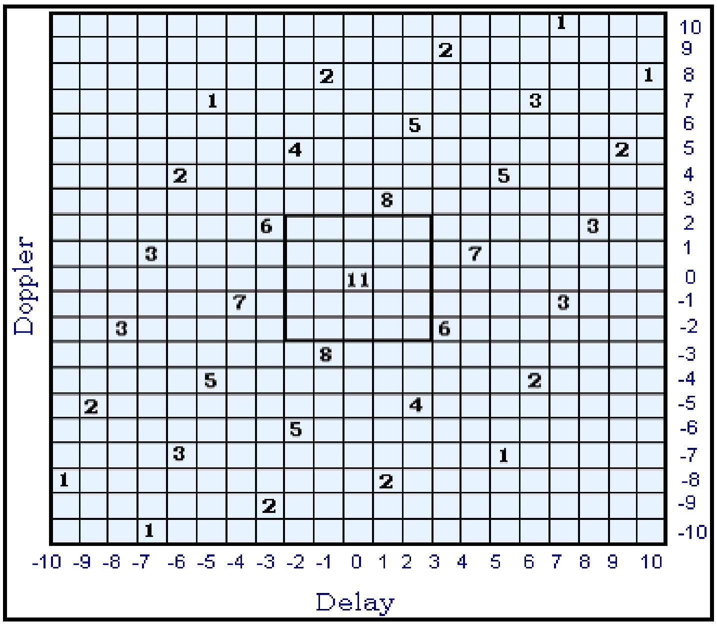
Where (i, d_i) means that the frequency d_i is transmitted at the time instant i. Since LC codes exhibit not only ideal cross-correlation property but also sidelobe pushing property, they are suitable for designing frequency coded waveforms to be used in multi-user and multi-target environments. Details of these LC codes and their characteristics are discussed in this section with appropriate examples.

Equation (1) shows that there are (N-1) choices to select the value of 'a' and thus this method generates (N–1) sequences for a given length N. To illustrate the sidelobe pushing property of LC codes, values of 'a' and 'N' are selected arbitrarily, like N = 11 and a = 3 (i.e. a > 1). Geometric array of LC code for the values of a = 3, N = 11 is shown in Figure 1 (a). The corresponding sequence is $\{d_{11}\}$ = 0, 3, 6, 9, 1, 4, 7, 10, 2, 5, 8. With reference to the placement of dots shown in Figure 1(a), it is clear that $\{d_{11}\}$ is a pushing sequence with pushing power r = 2. The sidelobe matrix of $\{d_{11}\}$ presented in Figure 1(b) shows that all the sidelobes situated away from the mainlobe at a minimum distance of 2, which is referred as pushing power [11].

In order to deal with the problems of dense target environments, Rihaczek suggested [1, 8] that the given target space must be fitted in the sidelobe-free area of the delay-doppler plane. Traditionally in the design of LC codes, the value of N is selected as per the design requirements. Once N is fixed, there are (N-1) choices to select the value of 'a'. Out of (N-1) values, only limited values of 'a' related to given 'N' can produce desired clear area corresponding to a desired pushing power r. The modification of LC codes is discussed in next section.



(a)



(b)

***Figure 1: (a)** Geometric representation; **(b)** Sidelobe-Matrix of LC code; for a = 3, N= 11 and {d_{11}} = 0, 3, 6, 9, 1, 4, 7, 10, 2, 5, 8*

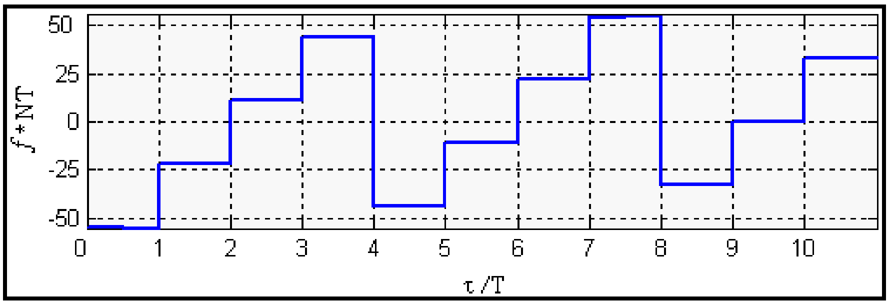
3. Modified Pushing Sequences Using LC Codes

Now, this section describes the design procedure of modification LC codes that are known as LC-MPS [11]. The desired LC codes are obtained using formula (i, d_i) = (i, ai (mod N)), where the value of N is any prime number and i = 0, 1, 2,…, (N-1). The design of LC codes lead to the possibility of (N-1) choices to select the value of 'a' for a given sequence of length N. In order to design a desired code which gives clear area around the mainlobe corresponding to pushing power 'r', the value of 'a' must be equal to (r + 1). The corresponding value of sequence length N is the smallest prime number greater than $(r + 1)^2$ as described in [11]. The concept of 'MPS using LC codes' could be better understood with the help of an example.

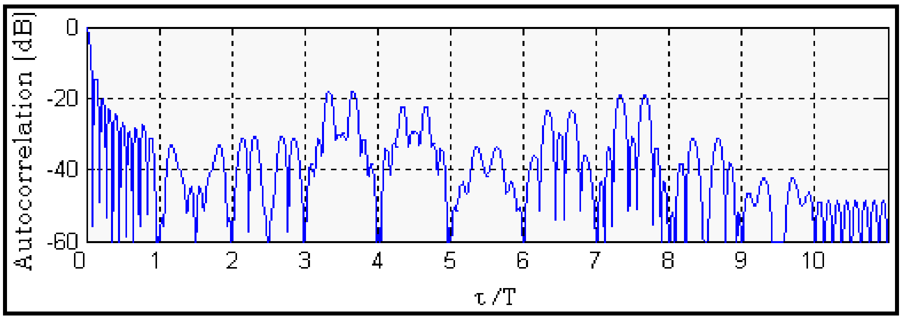
To design the LC code for pushing power r = 2, the value of 'a' should be 3, and that of 'N' is 11. Using formula (i, d_i) = (i, ai (mod N)) as stated above, the LC sequence order would turn out to be {d_{11}} = 0, 3, 6, 9, 1, 4, 7, 10, 2, 5, 8. Figures 2(a), 2(b) and 2(c) respectively show the frequency evolution, autocorrelation function and partial Ambiguity Function (AF) of LC codes with pushing power r = 2, N = 11. In order to draw the attention of the reader and to facilitate a better view of the width of the mainlobe and sidelobes level near mainlobe before applying modifications, Figure 2(c) is zoomed on to two bits on the either sides of the mainlobe.

In the process of designing MPS using LC codes, the first step to be followed is to increase the frequency spread between the consecutive subpulses. When the frequency spacing Δf = 5/T (i.e. $T\Delta f$ = 5), LFM free unmodulated waveform (i.e. TB = 0) will be associated with four grating lobes along with mainlobe in autocorrelation function (ACF). To eliminate these grating lobes, each subpulse must be modulated with LFM of specific bandwidth. The grating lobes elimination capability of LC codes with LFM could be verified in Figure 3, when the values of TB and $T\Delta f$ are chosen as 12.5 and 5 respectively. Before adding LFM to each pulse, four grating lobes could be clearly seen in Figure 3(a). These grating lobes are eliminated after superposing LFM of a specific bandwidth [13, 14] which is illustrated in Figure 3(b).

After illustrating the nullification process, the frequency evolution, autocorrelation function and partial ambiguity function of the final form of LC-MPS frequency coded waveform for r = 2, N = 11 are shown in Figures 4(a), 4(b) and 4(c) respectively. Improvement in sidelobe suppression near mainlobe and reduction in width of the mainlobe after adding LFM to each subpulse are evident from Figure 4(c), which is zoomed for convenience on two bits near mainlobe. The ambiguity function shown in Figure 4(c) clearly exhibits the high resolution property of LC-MPS waveforms.



(a)



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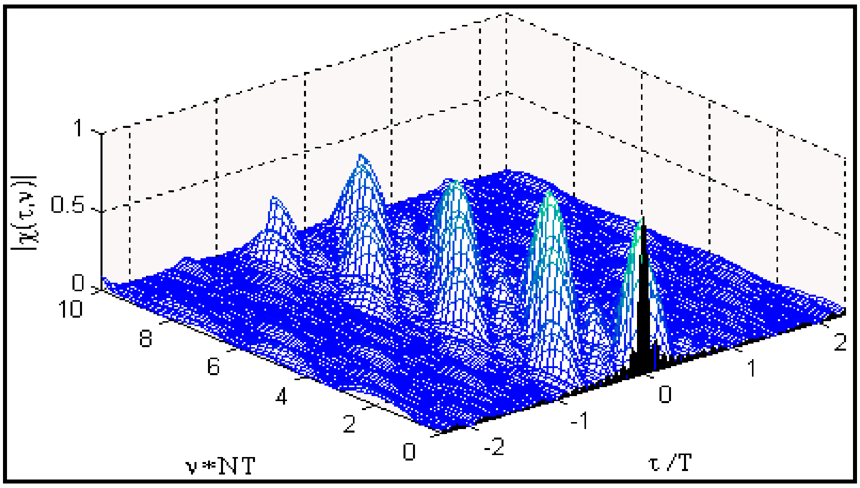
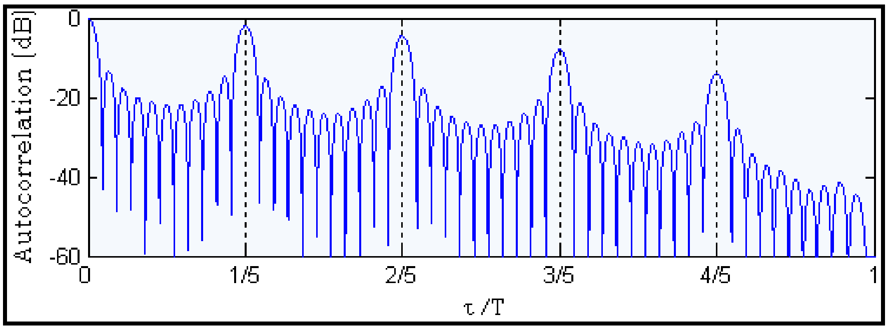
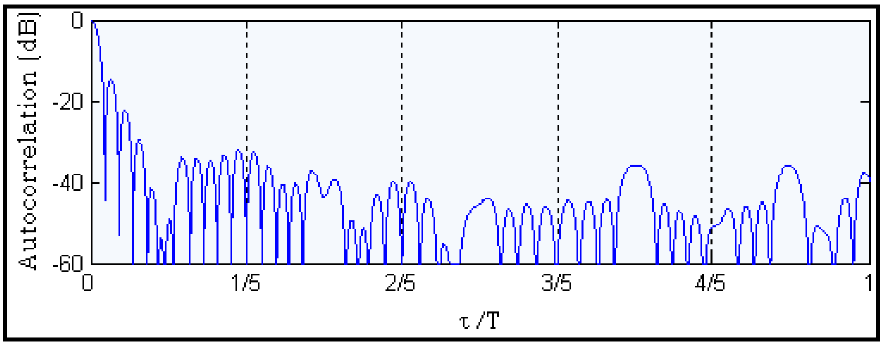


(c)

***Figure 2**: **(a)** Frequency evolution; **(b)** Autocorrelation function; **(c)** Partial AF, of LC codes for r = 2, N = 11*

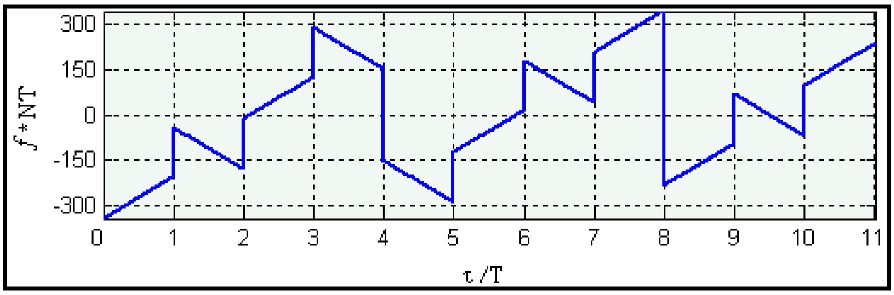


(a)

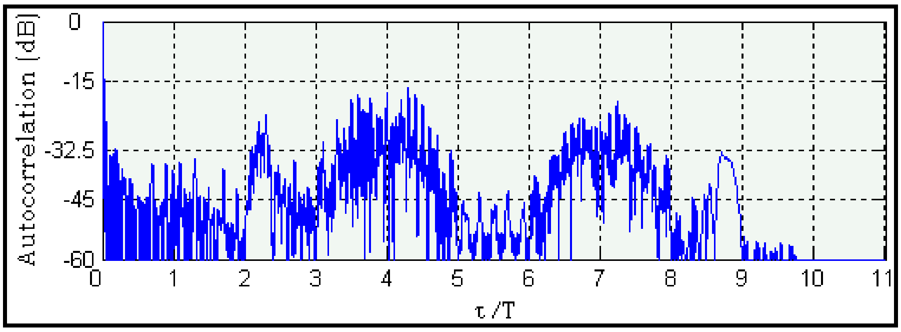


(b)

Figure 3: *ACF of LC code for r = 2, N = 11:* ***(a)*** *Δf T = 5, TB = 0;* ***(b)*** *Δf T = 5, TB = 12.5*



(a)



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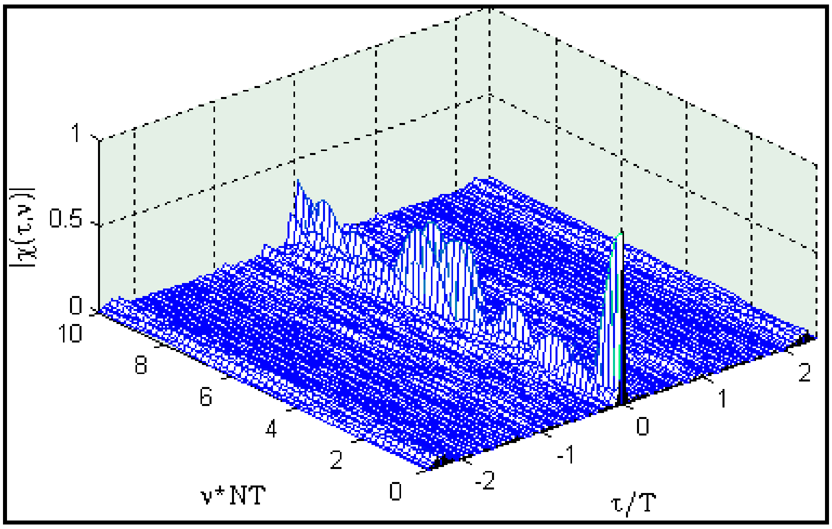


(c)

Figure 4: ***(a)*** *Frequency evolution;* ***(b)*** *Autocorrelation function;* ***(c)*** *Partial AF, of LC-MPS for r = 2, N = 11, BT = 12.5, T∆f =5*

4. Adaptive Waveform Radar Scheme

This paper reveals the design approach and illustrations of the related LFM and LC-MPS waveform features, which can be used in an adaptive manner, for searching as well as tracking radar applications. As per this scheme, a low-resolution Doppler tolerant Linear Frequency Modulated (LFM) waveform [15-16] could be used by radar in order to obtain approximate values of *range* and *Doppler* of the intercepting target. The complexity involved in the signal processing and computation would be very low in this search mode and so *fast detection* of target with an appreciable probability of detection can be ensured.

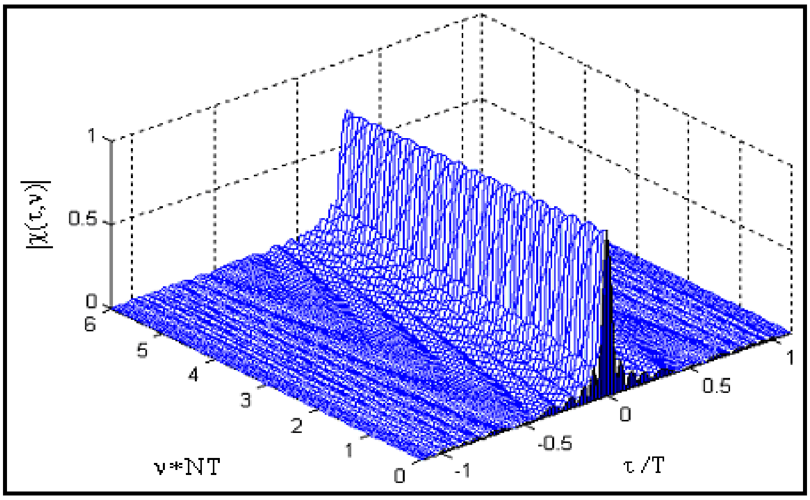


Figure 5: *Ambiguity Function of LFM waveform*

It can be observed from the ambiguity function of LFM waveform, which is shown in Figure 5 that the LFM waveform has a long narrow ridge with excellent Doppler tolerance but low Doppler resolution. The multiple targets present along the ridge of the chirp ambiguity function will not be resolved. Therefore, Doppler tolerant waveforms are most effective in the detection of targets initially in search mode.

Once, the target is detected, the radar is to lock on to the target for tracking purposes. In such a case, LC-MPS scheme based waveform could be used in order to obtain highly accurate and reliable values of range and velocity of the selected target for offensive operations such as guidance and control. The radar electronics should be programmed in such a manner that a viable strategy of switching between search and track modes is carried out either by an operator or by preloaded intelligent software associated with the system [6, 17-18].

Modern surveillance radars like AN/TPS-59 and AN/FPS-117 are long-range surveillance systems that employ LFM waveform for target detection [19]. The waveforms used by them do not provide Doppler resolution along the ridge. On the other hand, non-linear FM (NLFM) waveforms exhibit the property of Doppler sensitivity and thus they ensure better accuracy in the estimation of range and Doppler frequency.

A Multi Mission Radar (MMR) is an example which uses a NLFM sine wave based waveform for the purpose of tracking [13].

However, the use of NLFM does not guarantee appreciable suppression of sidelobes near mainlobe. Over and above, complexity and cost involved in the signal processing hardware is high [20-21]. In order to reduce the complexity of the system and to achieve better performance, one would prefer to use LC-MPS rather than NLFM in the waveform design. Thus, the adaptive waveform scheme proposed here is nothing but a finite “waveform-set” which consists of both LFM waveform and LC-MPS waveform. These waveforms could be processed by a low cost and less complex signal processing hardware.

The performance characteristics of an X-band AWR using both LFM for low-resolution and LC-MPS for high-resolution measurements are shown in Table 1. Figure 6 shows the partial ambiguity function of LC-MPS waveform, which is zoomed near mainlobe in delay-doppler plane, shows that the LC-MPS clearly exhibits the high-resolution measurement capabilities of the system. Figures 7 and 8(a)-(b) show the range resolution capabilities of LFM and LC-MPS respectively.

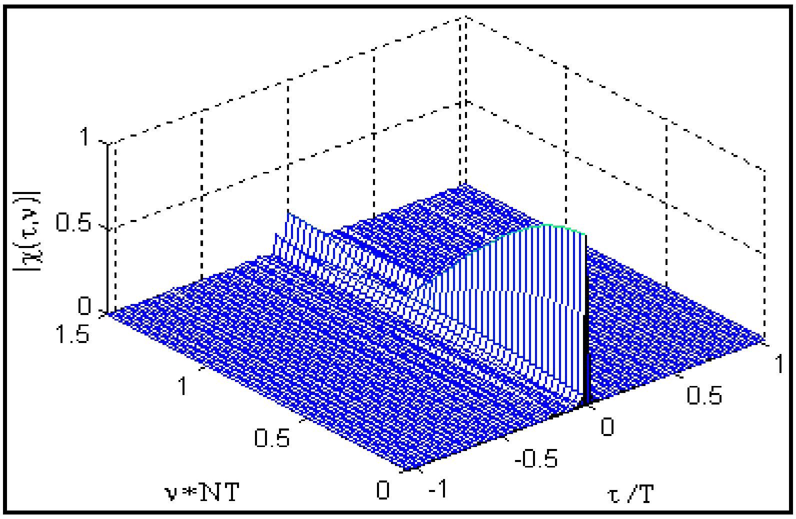


***Figure 6**: Partial Ambiguity Function (Zoomed on One Bit) of LC-MPS Waveform, as per Table 1 (for Single Pulse)*

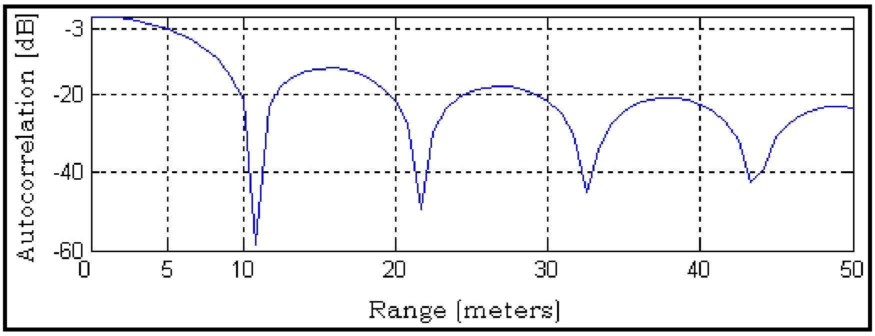
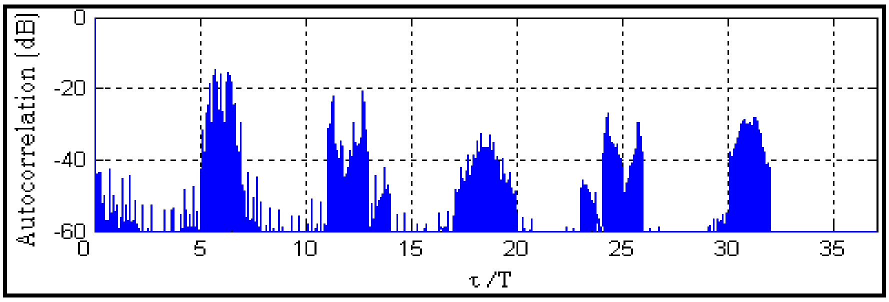
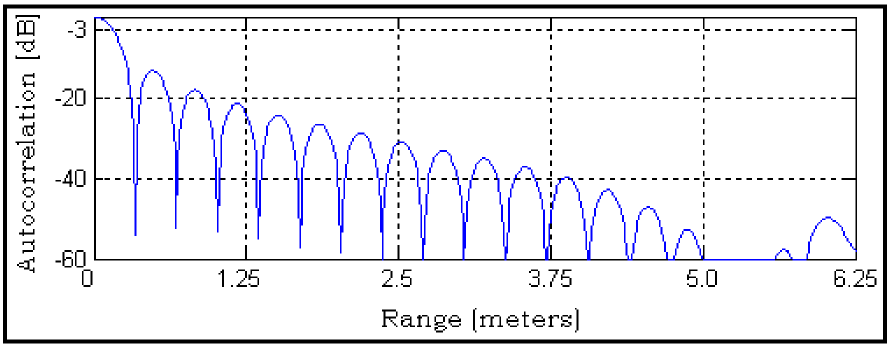


Figure 7: *Autocorrelation Function of Low-Resolution (LFM) Waveform as per Table 1 (Zoomed on Mainlobe)*



(a)



(b)

***Figure 8**: **(a)** Autocorrelation Function; **(b)** Partial Autocorrelation Function of High-Resolution (LC-MPS) Waveform as per Table 6.1; (zoomed on τ/T = 0.1)*

5. Applications of LC-MPS Based Adaptive Waveform Radar

Advances in digital signal processing technologies allow a wider variety of waveforms to be implemented and processed simultaneously. The concept of adaptive waveform radar, which is suggested in the present work, can be used to perform multiple tasks, which can optimize the use of the modern HRR systems. Such design can be implemented where both low-resolution and high-resolution measurements are required. The requirements of such systems are - Fire Control Radar (FCR) Systems [8, 13], Track before Detect (TBD) Applications [22], etc., where both low-resolution as well as high-resolution (for search as well as tracking) operations are desired. One application of adaptive waveform radar concept is fire control radar system, which is explained below.

The purpose of fire control radar system is to search the target in free space as per the information given by the early warning radar. While searching, it makes use of wide beam width and a large resolution cell, so that all those targets available well within the cell resolution limits can be detected. For this purpose LFM is used. The advantages of LFM based search radar are [19, 23].

(i) LFM is easier to implement, and can be processed using one multiplication with a matched reference signal.
(ii) LFM has no frequency sidelobes, and it utilizes the spectrum efficiently.
(iii) Entire volume of ambiguity function is concentrated into a sharp ridge.
(iv) The time sidelobe performance of LFM waveform is excellent for large Doppler shifts, which is clear from Figure 5.

Once target of interest is detected, this data can be used as an input to the tracking system, which uses high-resolution waveforms. The high-resolution waveform radar is capable of measuring the range (delay) and velocity (Doppler) of the target with the accuracy of 32 centimeters and 2 m/sec respectively. This accurate range and velocity can be used to calculate the future position of the target, and the same is passed on to the fire equipment such as anti-aircraft guns or missile launchers, which form the integral part of the radar system. The advantages of high-resolution (LC-MPS) based track radar are [21, 24].

(i) It avoids glint, which occurs due to multiple scatters within the range resolution cell.
(ii) Tracking accuracy is better in range as well as in angle compared to that of low-resolution systems.
(iii) High range resolution improves tracking in presence of chaff and clutters [25].
(iv) Improves low-angle tracking performance.
(v) Monopulse tracking system with high range resolution capability can produce a 3D-like image of a target [25].

Effective use of the proposed technique would indeed optimize the detection, recognition and tracking performance of futuristic high-resolution radar systems.

6. Discussions and Conclusions

This paper proposes a novel approach to design waveforms for a cost effective and less complex radar system, which would work reliably in a dense, and multi target environments in an adaptive manner.

The various radar parameters are computed for both LFM and LC-MPS waveforms by considering a suitable example of an X-band radar system. The range resolution accuracies in low-resolution (LFM) and in high-resolution (LC-MPS) modes are 5 m. and 32 cm. respectively. These values can be calculated by using formula $\Delta R = c/2B$, and are achieved approximately at –3 dB levels, which are evident in Figures 7 and 8(b). Figure 8(b) is zoomed on one-tenth portion of the mainlobe ($\tau/T = 0.1$) and Figure 6 is zoomed on mainlobe area. Figure 8(a) shows the ACF of LC-MPS where the clear area (sidelobe suppressed region) in range is clearly noticeable up to $\tau/T = 5$, which offers a clear area of nearly ±315 meters with respect to mainlobe.

Figure 6 shows the partial ambiguity function of LC-MPS for single pulse case. It can be seen that the amplitude of the mainlobe drops to the level of –3 dB when $v^*NT \approx 0.4$ or $v \approx 0.4/NT$ (where $NT = T_p$), which is approximately equal to 26 KHz when only single pulse is processed (as T_p = 15.4 μsec). On the other hand, in case of above considered example (in Table 1) where 10 pulses are processed together to generate one cycle of Doppler shift, the Doppler resolution is improved to 100 Hz. However, to overcome the Doppler matched filter loss for the higher values of Doppler shifted version of the signal, a bank of Doppler matched filters must be used.

The central idea behind this approach is that the radar would work in search mode using LFM waveform and in track mode using LC-MPS based waveform, which may enhance the *detection, tracking, and recognition capabilities of the near-future radar systems.*

Table 1: *Parameters for LFM and LC-MPS X-Band AWR*

Parameters	LFM	LC-MPS
Radar Operating Band (GHz)	8.4 To 8.862	8.4 To 8.862
Radar Instantaneous bandwidth B (MHz)	30	30
Pulse Coding	LFM	LC-MPS
Sequence Length N	LFM	37
Δf (MHz)	30	12
Overlap ratio ($B/\Delta f$)	1	2.5
Pulse Length T_p (μs)	15.4	15.4
Pulse Repetition Interval (ms)	1.0	1.0
Radar Resolution ΔR (meters)	5	0.32
Doppler Resolution (when 10 pulses are processed together)	Doppler tolerant	100 Hz (velocity resolution ≈ 2 m/sec)
Compression Ratio	462	7123

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