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Peak Side Lobe Reduction analysis of NLFM and Improved NLFM Radar signal with Non-Uniform PRI

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Abstract*—The problem of determining a good radar signal with the objective of minimizing autocorrelation sidelobes with non-uniform PRI is addressed. Linear Frequency Modulated signal (LFM) is frequently used pulse compression waveform but the LFM signal results in first side lobe of -13dB corresponding to the main lobe. Conventional uniform Pulse Repetition Interval (PRI) systems suffer from limitations like blind speeds, jamming etc. These limitations can be overcome by using non-uniform PRI waveforms. Further the range resolution of these waveforms can be improved by reducing the Peak Side Lobe Ratio (PSLR) and this can be done by appropriately choosing the PRIs and basic pulse shapes. In this paper, an attempt is done to design a radar signal to attain low autocorrelation PSLR which exhibits low side lobes and high range resolution. In order to maintain good resolution and to get suppressed side lobes of the signal, one can use a improved Non-Linear Frequency Modulation (NLFM) polynomial signal with Non-Uniform PRI. The proposed NLFM polynomial with Non-Uniform PRI is compared with LFM, NLFM, Two Stage ,Tri-Stage sweeps NLFM and a Polynomial-I NLFM. The quality of the overall best radar signal is assessed through the parameter Peak Side Lobe Ratio(PSLR) for different values of BT and PRI. From this analysis, it is found that the NLFM with Non-Uniform PRI with BT=200 gives the very low PSLR value of 69dB . Simulation results shows the reduction in the sidelobe level from LFM to Polynomial-II NLFM with Uniform and Non-Uniform PRI

Index Terms— **LFM, NLFM, PSLR, Non-Uniform, Polynomial**

I. INTRODUCTION

Generally, radar has an issue of being sensitive to interference of noise from the surrounding objects. The concepts like matched filter and pulse-compression from the radar processing theory are used to optimize the strength of received signal by attaining maximum signal to noise ratio (SNR) and high range resolution [1].

Pulse compression aids to attain maximum range resolution and increasing SNR. In order to transmit a long pulse which has a bandwidth of short pulse, pulse compression is required. LFM signal has limitations when compressed the produced side lobe is of -13dB to the peak of main lobe.

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There will be a 25% of decrease in the transmitted power for a single dB of SNR lost.

NLFM waveform is used to achieve high range resolution and high SNR as it is the drawback in LFM waveform. LFM waveforms have a disadvantage of using weighting functions which considerably decreases the SNR. In this project, by using modified NLFM technique one can generate auto-correlated functions with peak side lobe levels (PSL) that can be modified by changing the BT values [2]. Using PSL one can determine the interference of noise or the strength of signal received at the receiver when the peak side lobes are reduced then SNR increases and if the side lobe levels increase the SNR decreases. Increase in SNR means high signal strength. Similarly with a decreased SNR signal strength is low [3].

Conventional radar systems transmit a single pulse and use the received signal to detect and estimate the distance of the target. Pulse Doppler radars further estimate the velocity of the target by periodically transmitting pulses. The progressive phase shift of the received pulse is used to measure the velocity of the target. Conventional uniform PRI systems suffer from limitations like blind speeds, jamming etc. These limitations can be overcome by using non-uniform PRI waveforms [4]. Further the range resolution of these waveforms can be improved by appropriately choosing the PRIs and basic pulse shapes (LFM, NLFM, Polynomial-I NLFM and Polynomial-II NLFM).

This paper investigates the design of non-uniform PRIs radar signal with different basic linear waveforms to simultaneously improve the range resolution and PSLR.

II. EXCISING RADAR PULSE COMPRESSION WAVEFORMS

In pulse compression, a linear frequency modulation (LFM) is used. It is one of the types in different pulse compression techniques. LFM Pulse compression method is used in order to have the properties of both long pulse and short pulse which are high signal detection capability and range resolution respectively [4]. LFM signal has limitations when compressed the produced side lobe is of -13dB to the peak of main lobe. There will be a 25% of decrease in the transmitted power for a single dB of SNR lost. NLFM waveform is used to achieve high range resolution and high SNR as it is the drawback in LFM waveform. LFM waveforms have a disadvantage of using weighting functions which considerably decreases the SNR [6][7].

A. Linear Frequency Modulation (LFM)

In practical radars, LFM waveform is most frequently used pulse compression signal. The LFM signal's phase function has a coefficient k which gives an output of linear frequency over a specific time period. The LFM chirp signal is represented as [8][9][10]

$$Si(t) = exp\left\{j2\pi\left(f_c t - \frac{\mu t^2}{2}\right)\right\}, -\frac{\tau}{2} \le t \le \tau$$
$$= 0 \quad \text{, elsewhere} \tag{1}$$

Here fc is carrier frequency, µ is chirp rate or the sweep rate. The Bandwidth of the signal is given by

$$B = \mu\tau \tag{2}$$

Linear chirp waveforms can reduce PSL to -13dB but as a result SNR decreases due to the applied weighting techniques. To solve this problem one can go for Non-Linear Frequency waveforms (NLFM) which leads to better increase in SNR and high range resolution.

B. Non-Linear Frequency Modulation (NLFM)

The NLFM waveform can be used to achieve high range resolution, strong SNR and low interference of noise[2]. NLFM has better range detection characteristics than Linear Frequency Modulated wave. The NLFM signal is represented by

$$SI(t) = exp[j\emptyset(t)] \tag{3}$$

Here $\emptyset(t)$ is frequency modulation function and we can obtain f(t) with Differential phase modulation. NLFM waveform does not require any weighting technique in order to suppress the side lobes [11].

C. Improved Non- Linear Frequency Modulation

Using LFM there is a disadvantage of loss of signal due to the weighting techniques used. To overcome that we can go for Non-Linear Frequency modulation [3]. To get suppressed side lobes of the signal, we can use Non-Linear Frequency Modulation (NLFM). A NLFM signal is designed for different time sweeps called as Improved NLFM. In Improved NLFM the total time sweep and bandwidth are divided into Two Stage and Tri-Stage sweeps NLFM. Below are the few types of NLFM with different sweep rates [12][13][14].

i. Two Stage NLFM

The Simple two-stage NLFM has two LFM stages (Fig 1). The first stage and second stage have different sweep rates. The frequency varies linearly at different time frames [2]. The simple two-stage NLFM can be represented by [15][16]

$$Sw(t) = \begin{cases} \frac{B_1}{T_1}t, 0 \le t \le T_1 \\ B_1 + \frac{B_2}{T_2}t, \quad ,T_1 \le t \le T_2 \end{cases} \tag{4}$$

Phase $\emptyset(t)$ of the two stages can be obtained by integrating the above equation,

$$\emptyset(t) = \int Sw(t)dt = \begin{cases} \frac{B_1}{T_1} \times \frac{t^2}{2}, & 0 \le t \le T_1 \\ B_1 \times t + \frac{B_2}{T_2} \times \frac{t^2}{2}, & T_1 \le t \le T_2 \end{cases} \tag{5}$$

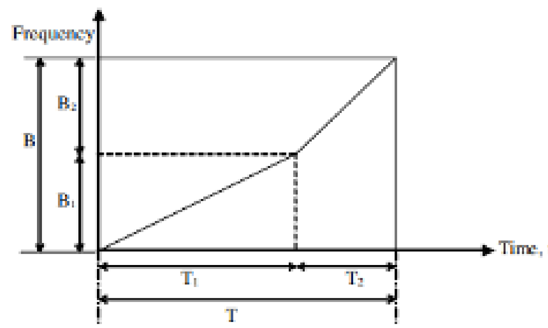

Fig. 1. Simple two-stage NLFM

ii. Tri- Stage NLFM

The Tri-stage NLFM waveform is used to suppress the side lobes. It has three stages (Fig 2). All the three stages are linearly swept with different chirp rate[17][18][19]. Of the three stages, two LFM stages have increased modulation rate at leading and trailing edges. The Tri-stage NLFM signal can be represented by[20][21],

$$Sw(t) = \begin{cases} \frac{B_1}{T_1}, & 0 \le t \le T_1 \\ B_1 + \frac{B_2}{T_2}t, & T_1 \le t \le T_2 \\ B_1 + B_2 + \frac{B_3}{T_3}t, & T_2 \le t \le T_3 \end{cases} \tag{6}$$

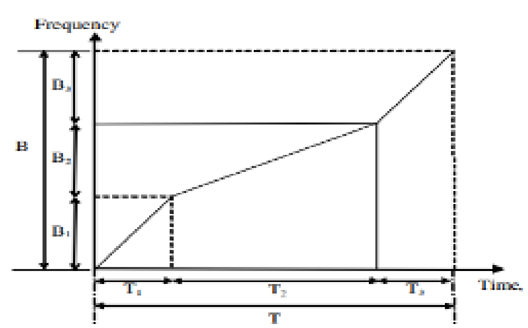

Fig. 2. Tri-stage NLFM

III. Proposed Polynomial NLFM Signal with Non-Uniform PRI

Two types of polynomial NLFM waveforms I and II are considered with Uniform and Non-Uniform PRI[1].

$$Sp(t) = exp[j\emptyset(t)] \quad (7)$$

Where $\emptyset(t) = \int f(t)$

Polynomial-I NLFM

$$fp1(t) = at^6 - bt^4 + ct^2 \quad (8)$$

Polynomial-II NLFM

$$fp2(t) = at^2 - b\sqrt{1 - Ct^2} \quad (9)$$

Where a , b , c are constants and t is the instantaneous time.

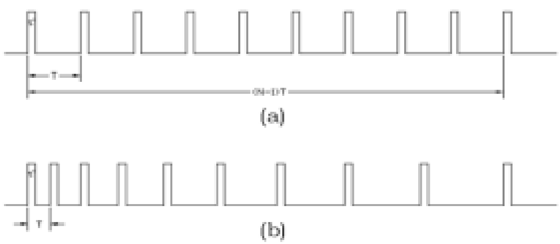

Fig.3. (a) Uniform PRI Pulse train (b) Non-Uniform Pulse Train

The expression for the normalized Uniform pulse train is

$$S(t) = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} Sp(t - iT) \quad (10)$$

Where, N is Number of pulses, T is PRI, I is index of the pulse

The expression for the normalized Non-Uniform pulse train is[22][23][24]

$$S(t) = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} Sp(t - iT_k) \quad (11)$$

Where K indicates index of the different Non-Uniform PRI

IV. Simulation Results

A LFM radar waveform is generated with duration of pulse is T=0.1µsec, Bandwidth B=20MHz with BT=200 as shown in Fig. 4

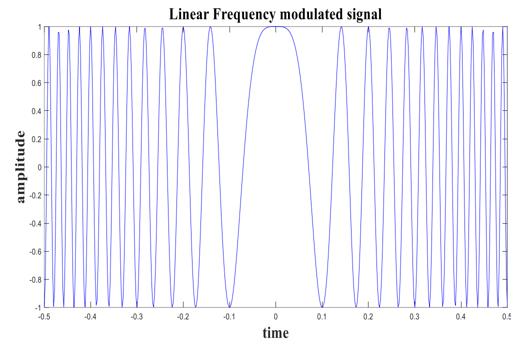

Fig. 4. LFM Chirp Signal

The resultant output after passing the above LFM signal through matched filter is shown in Fig 5

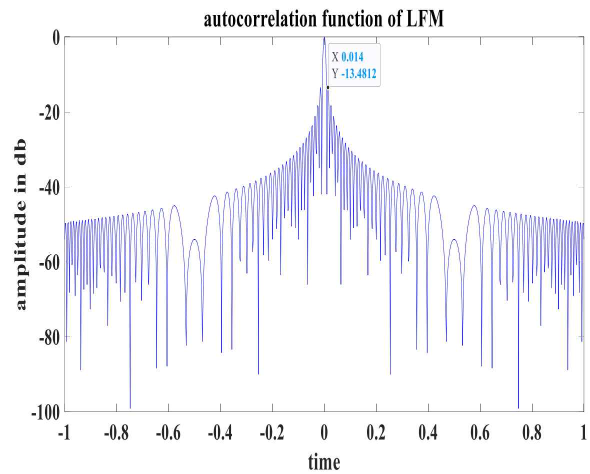

Fig. 5. Auto Correlation of LFM signal

It can be observed from simulation results of Fig 5. that the PSLR = -13.48dB is obtained for LFM signal which is very high. To reduce PSLR more a NLFM signal is designed for different BT values.

As from the Fig. 5 obtained first side lobe level of -13.48 dB which is undesirable. NLFM signal is used to overcome the above problem. For different sweep rates the frequencies vary non-linearly.

A pulse width with time duration T=0.1µs and band width B =20MHz is used to simulate NLFM waveform. Fig.6. shows the simulated NLFM signal

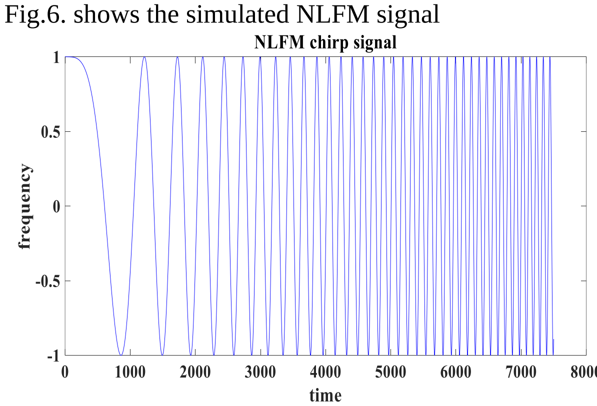

Fig. 6. NLFM Chirp Signal

The output obtained after passing the above NLFM signal through matched filter is presented in Fig 7.

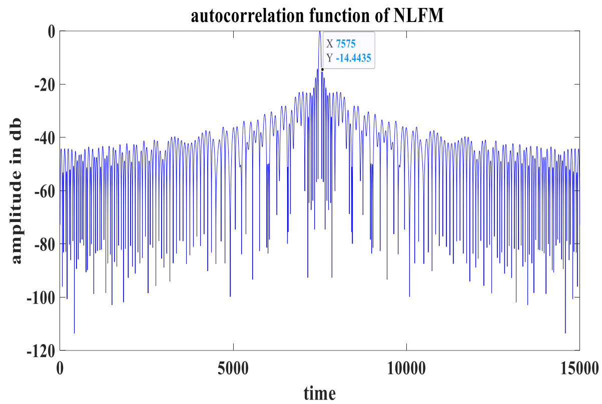

Fig. 7. Auto Correlation of NLFM signal

It can be observed from simulation results of Fig 7. that the PSLR = -14.27dB is obtained for NLFM signal which is low compared to LFM . To reduce PSLR more an Improved NLFM signal is designed for different values of BT .

Two-stage NLFM is examined to further decrease the level of first side lobes. This NLFM modulation function has two LFM stages as shown in Fig.8. It has two distinct LFM sweep rate with B1=5MHz, T1=1μsec and B2=15 MHz ,T2=9μsec for total BT of B=20MHz, T=10μsec. Modulation Function graph with different sweeps is shown in Fig 8.

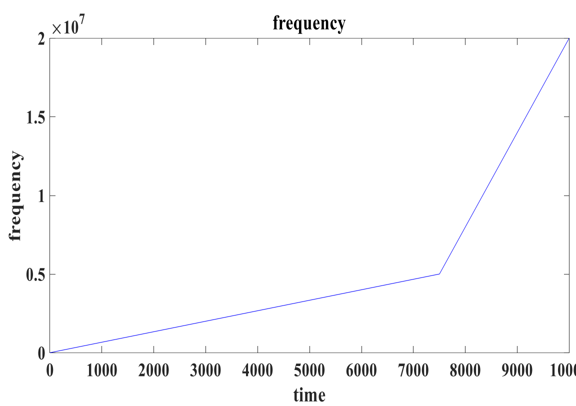

Fig. 8. Modulation Function in simple two-stage NLFM

A simple two stage NLFM signal with Pulse width T=0.1μs and Bandwidth B=20MHz is generated as depicted in Fig.9.

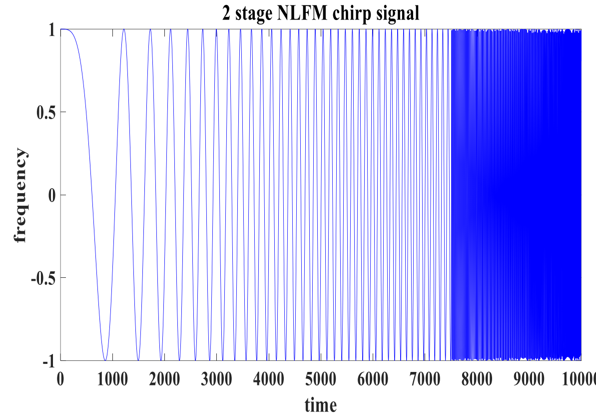

Fig. 9. Two Stage NLFM Chirp Signal

The resultant output after passing the above two-stage NLFM signal through matched filter is shown in Fig 10.

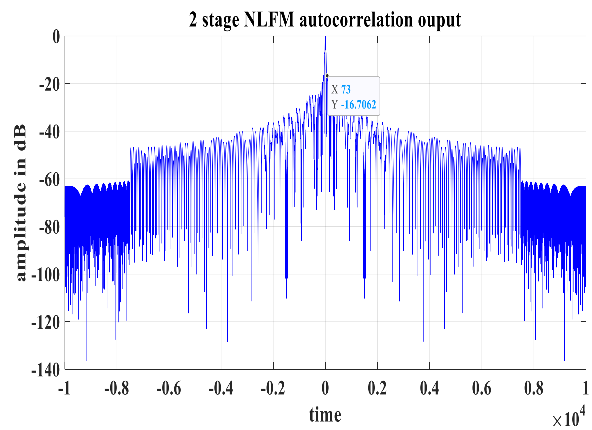

Fig. 10. Auto Correlation of two stage NLFM signal

It can be observed from simulation results of Fig 10. that the PSLR = -16.77dB is obtained for Two stage NLFM signal which is low compared to NLFM. To reduce PSLR more an Improved Tri stage NLFM signal is designed for different values of BT. A further reduction of first side lobe level can be observed in Tri Stage NLFM besides NLFM and Two-stage NLFM.

This NLFM modulation function has three LFM stages as shown in Fig 11. It has three distinct LFM sweep rate with B1=10KHz, T1=0.25msec, B2=5KHz, T2=5msec and B2=5KHz, T2=0.25 msec for total BT of B=20KHz, T=10msec. Modulation Function graph with different sweeps is shown in Fig 10. At three different time stages the linearity of increase in frequency varies and it is depicted in the Fig-11.

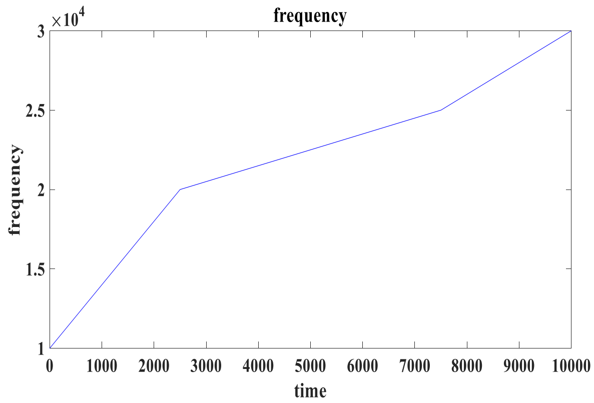

Fig. 11. Modulation Function of Tri-Stage NLFM

A Tri-stage NLFM signal of pulse width T=10ms and Bandwidth B=20KHz is simulated. The resultant output generated after passing the above tri-stage NLFM chirp signal through matched filter is shown in Fig 12.

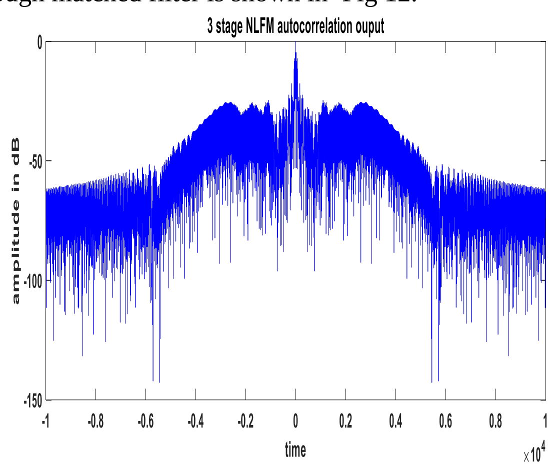

Fig. 12. Auto Correlation of Tri-Stage NLFM signal

The first side lobe level of -17.62dB is obtained after the auto correlation of tri-stage NLFM signal which is low compared to two stage NLFM. To reduce PSLR more an Improved Polynomial I & II NLFM is designed for different values of BT It can be observed that the reduced PSLR for existing methods is not enough for radar and sonar applications. A further reduction of first side lobe level can be observed in designed Polynomial-I NLFM and Polynomial-II NLFM signals besides Tri-stage NLFM. Therefore, a further decrease in first side lobe level can be observed.

A Polynomial-I NLFM signal of pulse width T=10ms and Bandwidth B=20KHz is simulated and its autocorrelation output is depicted in Fig 13. There is a drastic reduction in PSLR to -40.96dB compared to Tri-stage NLFM. More decrease in PSLR compared to polynomial -I NLFM can be observed in polynomial-II NLFM of -53.03dB.The Fig. 13 & 14 shows the autocorrelation output of polynomial-I and Polynomial-II.

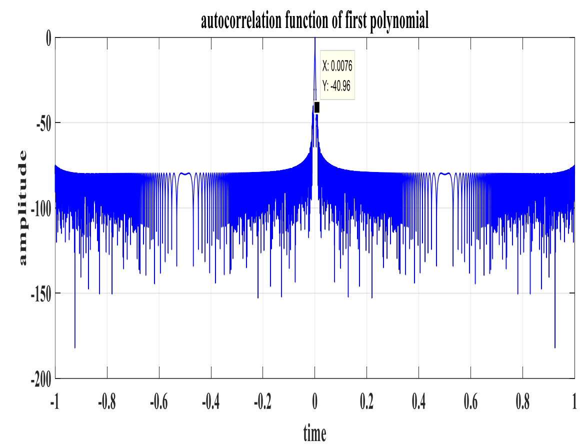

Fig. 13. Auto Correlation of Polynomial-I NLFM signal

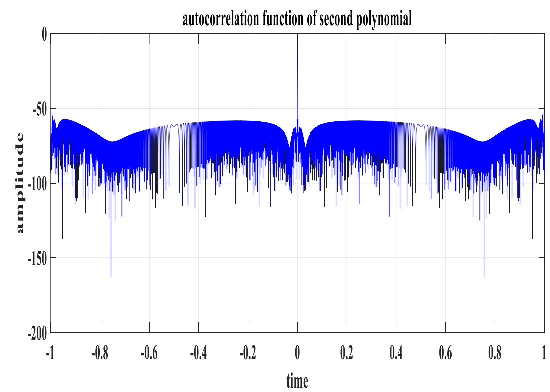

Fig. 14. Auto Correlation of Polynomial-II NLFM signal

A Non-Uniform PRI NLFM signal of pulse width T=0.4sec, PRI=5sec, N=6 and Bandwidth B=20KHz is considered and simulated. Its autocorrelation output is depicted in Fig 15. There is a drastic reduction in PSLR of 69.20dB compared to all other analyzed waveforms. The Fig. 15 shows the autocorrelation output of Non-Uniform PRI NLFM

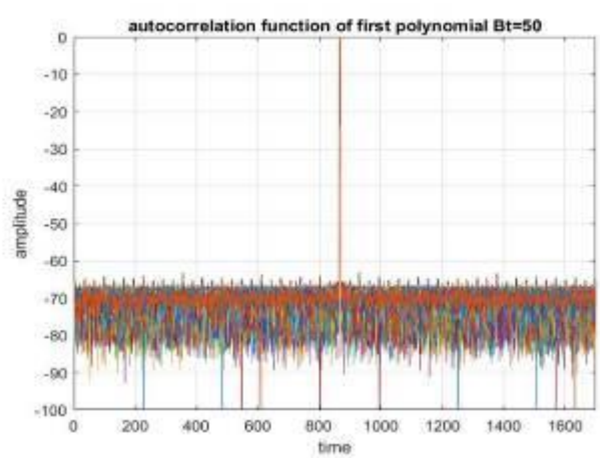

Fig. 15. Auto Correlation of Non-Uniform PRI NLFM signal

TABLE I
PSLR VALUES FOR DIFFERENT BT

Waveform	PSLR FOR BT=200	PSLR FOR BT=1000	
LFM	-13.13dB	-13.48	Existing work As given in Reference [1][2]
NLFM	-14.27dB	-14.33	
Two Stage NLFM	-16.19dB	-16.77	
Tri-Stage NLFM	-17.62dB	-18.21	
Polynomial-I NLFM	-40.96dB	-39.04	Proposed work
Polynomial-II NLFM	-53.02dB	-49.54	
NLFM with Non-Uniform PRI	-69.20dB	-69.52*	

*** It is observed that the PSLR values remains almost same for BT=200 & 1000 but width of main lobe increasing**

Table 1 shows PSLR values for all the existing signals LFM NLFM, Improved NLFM waveform signals for a BT value of 200 and 1000. It can be observed from Table 1 that the reduced PSLR for existing methods is not enough for radar and sonar applications.

The proposed method for a Non-Uniform PRI NLFM signal with a designed Polynomial-I & II signals PSLRs are shown in Table I with BT=200 and BT=1000. With a Non-Uniform PRI NLFM signal there is a drastic reduction in PSLR to -69.20dB from the -18.21dB of Tri-stage NLFM.

Comparison Analysis shows that using the proposed Non-Uniform PRI NLFM signal the PSLR value decreased to 23.38% compared to Polynomial-II NLFM and decreased to 74.5% when compared to Tri-stage NLFM.

V. CONCLUSION

In this paper, designed and generated an LFM, NLFM, Improved NLFM- Two stage, Tri stage, Polynomial-I and Polynomial-II radar signals. To overcome the problem of increased side lobe levels while using conventional LFM signal in a radar, a NLFM signal and improved NLFM signals are designed. An increased side lobe level would result in decreased Range resolution and wastage of energy. It is observed that by using Polynomial-II NLFM radar signals we can reduce the side lobe levels up to -53. 02dB.There is still a scope to decrease the side lobe levels and get clearer and more precise main lobe through a different approach of using NLFM with Non-Uniform PRI signal. Thus, using Non-Uniform NLFM PRI signal there is a drastic reduction in PSLR of about 69.20dB. In the simulation result we had seen that there is a drastic reduction in PSLR by changing PRI. Comparison Analysis shows that using the proposed Non-Uniform PRI NLFM signal the PSLR value decreased to 23.38% compared to Polynomial-II NLFM and decreased to 74.5% when compared to Tri-stage NLFM. Thus by using a Non-Uniform NLFM PRI signal the PSLR can be drastically reduced which improves resolution and SNR.

The method of non-uniform PRI sequence NLFM polynomial signal is useful for all radar and sonar applications. The technique can be extended to ascending and descending Non-Uniform PRIs and to random Non-Uniform PRIs to minimize more PSLR and for good resolution.

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