Doppler Effect Analysis Of NLFM Signals

Adithya Valli Nettem, Elizabath Rani Daniel, Kavitha Chandu

Abstract: Waveform design plays a critical role in the current radar technology. Different radar signals can be achieved using tools like ambiguity function and autocorrelation function. Linear Frequency Modulation (LFM) waveform is the most used radar waveform. The main difficulty in LFM is its first high side-lobe level despite of its simple design and Doppler tolerance characteristics. A weighting function is desired to reduce the side-lobe with a penalty of mismatch loss. In an effort, to achieve low auto-correlation side-lobe levels, Non-Linear Frequency Modulation (NLFM) signal has been explored. NLFM has a spectral weighting function inherently in their modulation function which exhibits profoundly reduced side-lobes from its analogues LFM. In this paper, five different NLFM signals are investigated and their performance is assessed based on the study of Doppler Effect, Doppler tolerance and PSLR values. The matlab simulation results were used to decide the most suitable waveform for side lobe reduction.

Keywords: Ambiguity function, Doppler Effect, LFM, Mainlobe Width, NLFM, PSLR.

1 INTRODUCTION

Radar systems employ pulse compression as it can resolve the contradiction between range resolution and average transmitted power effectively [1]. The transmitted pulse is modulated to attain significant time-bandwidth product (BT). Different modulation techniques available are frequency and phase modulation [2–4]. Pulse compression by using LFM suffers from side lobes, which can be decreased by using different side lobe suppression techniques. The shaping is obtained by varying the pulse amplitude along the time axis. In LFM, frequency varies in direct proportion to time very much similar to amplitude change with frequency. Shaping the spectrum by amplitude weighting an LFM pulse has a serious problem [5-6]. The spectral energy could be reduced at the edges giving a window shaped spectrum by reducing the signal amplitude at the pulse edges with constant pulse amplitude so as to spend less time in each spectral interval near the band edges or both [7]. This approach in which variable sweep rates are used is called Non Linear Frequency Modulation. Linear FM has uniform spectrum as transmitter gives equal time to each frequency, modification to this uniform spectrum by deviating the rate of change of frequencies is termed as Non-linear frequency modulation (NLFM) [8]. LFM is favoured as it can shape the power spectral density (PSD) such that the autocorrelation function showcases profoundly reduced side-lobes from its analogues LFM. Consequently, no additional filtering is required and maximum SNR performance is preserved [9]. In high-resolution radar (HRR) major research directions refer at designing improved waveforms with rectangular envelope, but with suitably modified FM laws so that the matched filter response contains lower side-lobe than in the standard LFM case [10].

2 AMBIGUITY FUNCTION

The ambiguity function represents the output of the matched filter and it correlates the disturbance caused by the range or Doppler shift of a target when compared to a reference target. Generally the output of matched filter is approximated by autocorrelation function of the transmitted signal when the signal to noise ratio is large (i.e. the noise is ignored) but, in many radar applications the received echo signal has a Doppler frequency shift i.e. the received echo signal does not have the same frequency as transmitted signal, in this case, the output of matched filter is considered as the cross-correlation between the Doppler- shifted received signal and the transmitted signal. Mathematically ambiguity function is given by following equation

$$\boldsymbol{\chi(T_R, f_d) = \int_{\infty}^{\infty} u(t)u^*(t+T_R)e^{j2\pi f_d t}dt} \quad (1)$$

where T_R is the true time delay and f_d is the Doppler frequency and the squared magnitude of above Eq(3) $|\chi(T_R, f_d)^2|$, is called the ambiguity function. The best possible Ambiguity function would be with narrow central spike and little noise. This summarizes that the ratio of the main lobe to side-lobe peak level should be high. The invariance property of AF defines that the energy removed or reduced at one place must appear at another place. Thus, main-lobe contains most of the energy and side-lobes have less energy. Estimating the range and the radial velocity of the moving target is the difficult task in radar signal processing, where the range is proportional to round-trip travel time i.e. the delay time of the radar signal while the radial velocity is proportional to the Doppler frequency shift. The radar signal estimated is maximized if the receiver filter is matched to the transmitted waveform [12]. In LFM the volume of the ambiguity function has a shape of a slowly decaying diagonal ridge because of which it is insensitive to Doppler shifts. Among all the available pulse compression waveforms no waveform is absolute for target resolution. Having said that, optimal ambiguity surface should be of a sharp central spike surrounded by a clear area with no volume [12].

3 NLFM SIGNALS

Side lobe reduction using NLFM signals is based on choosing appropriate spectrum shape [13]. To acquire a compressed pulse in the time domain with naturally low sidelobes, require a signal spectrum that decreases towards the band edges, with a compact discontinuities in the frequency domain [14] .To generate such spectrum shape, it is necessary to determine the phase function f(τ) that produces this type of spectrum. In radar systems theory numerous research work has been done to design optimum (level of sidelobe suppression) NLFM signals, all the work done generally can

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- *NLFM signals have wide applicability inside the pulse-compression radar systems. They protest to afford a good range resolution, better SNR, less expensive, good interference mitigation and a spectral weighting function inherently in their modulation function which presents the case that a pure matched filter gives low side-lobe [11].*

be categorized into two directions. One is based on design of NLFM signal using LFM signals introducing predistortion on short intervals into temporal domain or spectral domain and the other is the design by using predefined power spectral density function using different methods as stationary phase principle, iterative methods and explicit functions cluster method [15-21]. In this paper, a NLFM signal is generated using simple two-stage and tri-stage PWLFM functions which are described below.

In the present paper, 5 different NLFM waveforms are studied:

1) Two-Stage LFM (NLFM1): Two-Stage LFM signal formed by concatenating two piece wise LFM functions with a sweep rate of α0 in the first stage and α1 in the second stage as shown in Eq(2). The total pulse width of the chirp signal τ is divided into two time slots with respective pulse widths T1 and T2. If B1 and B2 are the corresponding bandwidths of the first and second stage LFM functions, then the corresponding sweep rates can be defined as

$$\alpha_0 = \frac{B_1}{T_1} \qquad \alpha_1 = \frac{B_2}{T_2}$$

$$f(\tau) = \begin{cases} \alpha_0\tau & 0 \le \tau \le T_1 \\ B_1 + \alpha_1(\tau - T_1) & T_1 \le \tau \le (T_1 + T_2) \end{cases}$$

(2)

1. 2) Three-Stage LFM (NLFM2): Three-Stage NLFM signal is formed by concatenating the instantaneous frequency functions of three piece wise LFM function with each different sweep rates.

The instantaneous frequency of this NLFM can be written as following Eq (3)

$$f(\tau) = \begin{cases} \alpha_0\tau & 0 \le \tau \le T_1 \\ B_1 + \alpha_1(\tau - T_1) & T_1 \le \tau \le (T_1 + T_2) \\ B_1 + B_2 + \alpha_2(\tau - (T_1 + T_2)) & (T_1 + T_2) \le \tau \le (T_3 + (T_1 + T_2)) \end{cases}$$

(3)

and corresponding sweep rates can be defined as follows

$$\alpha_0 = \frac{B_1}{T_1} \qquad \alpha_1 = \frac{B_2}{T_2} \qquad \alpha_3 = \frac{B_3}{T_3}$$

3) Modified Two-Stage LFM1 (NLFM3): Modified Two-Stage LFM1 signal is formed by concatenating the instantaneous frequency functions of two piece wise functions with first stage having a NLFM sweep rate of αo by means of exponential function and followed by LFM sweep rate of α1 in the second stage as shown in Eq(4).

$$f(\tau) = \begin{cases} \alpha_0 \exp(\tau)\tau^2 & 0 \le \tau \le T_1 \\ B_1 + \alpha_1(\tau - T_1) & T_1 \le \tau \le (T_1 + T_2) \end{cases} \quad (4)$$

4) Modified Two-Stage LFM2 (NLFM4): Modified Two-Stage LFM2 signal is formed by concatenating the instantaneous frequency functions of two piece wise functions with first stage having a LFM sweep rate of α1 and followed by a NLFM sweep rate of αo by means of exponential function as shown in Eq(5).

$$f(\tau) = \begin{cases} \alpha_0\tau & 0 \le \tau \le T_1 \\ B_1 + \alpha_1 \exp(\tau)(\tau - T_1)^2 & T_1 \le \tau \le (T_1 + T_2) \end{cases} \quad (5)$$

5) Curved Shaped NLFM (NLFM5): Curved Shaped NLFM signal is formed by concatenating the instantaneous frequency variations of two piece wise functions with two stages having a NLFM sweep rate of αo and α1 by means of exponential functions in both the stages as shown in Eq(6)

$$f(\tau) = \begin{cases} \alpha_0 \exp(\tau)\tau^2 & 0 \le \tau \le T_1 \\ B_1 + \alpha_1 \exp(\tau)(\tau - T_1)^2 & T_1 \le \tau \le (T_1 + T_2) \end{cases}$$

(6)

4 SIMULATIONS & RESULTS

Simulations were done with B=20MHz and T=10μs for all the above described 5 NLFM signals and the performance is measured using parameters PSLR and Mainlobe width. Fig 1 shows the frequency variation of the all the NLFM signals. Fig 2 shows the effect of sidelobe control factor (SLCF) on PSLR values i.e. based on the different combinations of B1, T1 and B2, T2. From the figure it is evident that with the increase in the SLCF, PSLR values are increasing. Among all the signals NLFM3 and NLFM5 exhibit better PSLR values. Maximum PSLR values obtained with NLFM3 and NLFM5 is -28db. NLFM5 is most powerful in suppressing sidelobes with the increase in SLCF when compared to other NLFM signals. Fig 3 shows how the mainlobe width varies based on the variation of SLCF. As the SLCF increases, width of mainlobe increases. NLFM1 and NLFM2 signal has a mainlobe width of 0.00022μs and when SLCF increases the mainlobe width increases to 0.00032μs. NLFM3 has a mainlobe width of 0.00027μs and when SLCF increases the mainlobe width increases to 0.00045μs. NLFM3 signal is most affected with the variation of SLCF. NLFM4 has a mainlobe width of 0.00021μs and when SLCF increases the mainlobe width increases to 0.00029μs. NLFM5 has a mainlobe width of 0.00028μs and when SLCF increases the mainlobe width increases to 0.00035μs.

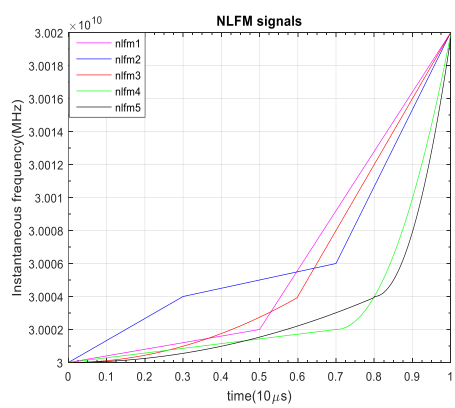

***Fig.1** Frequency Variation of NLFM signals*

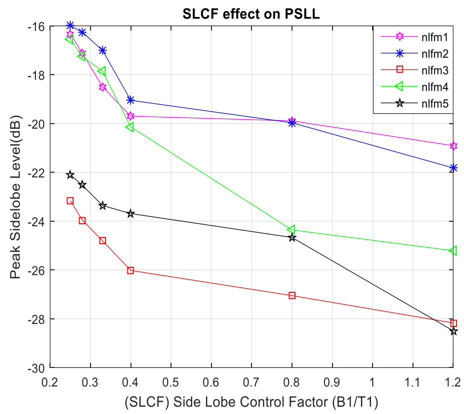

Fig.2 *PSLR of NLFM signals with the variation of SLCF.*

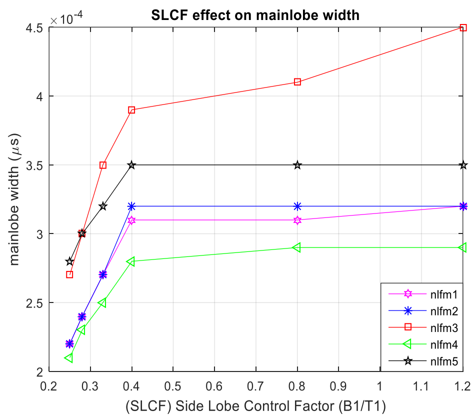

Fig.3 *Mainlobe width of NLFM signals with the variation of SLCF.*

To evaluate the Doppler effect of the NLFM signals, there are several parameters that will be analyzed, such as peak sidelobe level (PSLL), Doppler tolerance and Doppler resolution. All these parameters are affected by the speed of the target or object. This simulation is performed to compare the performance of above described NLFM signals against Doppler Effect with different frequencies of radar fc 5GHz-30GHz and speed of the target from 100 km/hour until 5000 km/hour as shown in the below Table1.

Table 1: *Doppler shifts for different carrier frequencies and velocities.*

fc(GHz)	Vr(km/hr)	fd(Hz)
5	100-5000	900Hz-47kHz
10	100-5000	1.851kHz-92.592kHz
20	100-5000	3.703kHz-185.185kHz
30	100-5000	1.851kHz-277.777kHz

Fig 4 shows the Doppler Effect on PSLR values with the variation of speed of the target. From the figure it is clear that the NLFM1, NLFM2 and NLFM4 are most affected by the Doppler frequency. In stationary condition PSLR value of NLFM1 is -22.97dB, when the target has a speed of 5000km/hr the PSLR values is drastically reduced to -7.46dB. In stationary condition PSLR value of NLFM2 is -21.52dB, when the target has a speed of 5000km/hr the PSLR values is drastically reduced to -5.67dB. In stationary condition PSLR value of NLFM4 is -21.74dB, when the target has a speed of 5000km/hr the PSLR values is drastically reduced to -3.39dB. NLFM3 and NLFM5 show less variation with the increase in the speed of the target. In stationary condition PSLR value of NLFM5 is -23.75dB, when the target has a speed of 5000km/hr the PSLR values is reduced to -16.72dB. In stationary condition PSLR value of NLFM3 is -28.55dB, when the target has a speed of 5000km/hr the PSLR values is reduced to -23.67dB but still has the highest PSLR value compared to other NLFM signals.

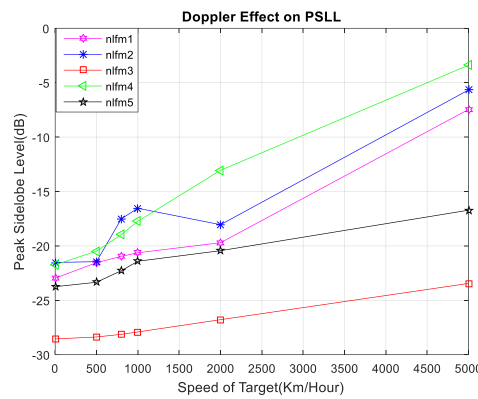

Fig.4 *Doppler Effect to PSLR values of NLFM signals.*

Fig 5-9 shows the ambiguity function plots of all the NLFM signals described above for two different ranges of fd=900Hz-47kHz and fd=1.851kHz-277.777kHz when fc=5GHZ and 30GHz. When the Doppler shift f_d is in range 900Hz to 47kHz all the 5 NLFM signals simulated show the same range doppler characteristics as LFM for small doppler shifts and also good doppler resolutions with reference to the PSLR values. When the Doppler shift fd is in range 1.851kHz-277.777kHz, NLFM1-NLFM3 signals so almost same doppler properties as in LFM but NLFM4 and NLFM5 the response dropped rapidly as compared to LFM, which indicates that these signals are not tolerant to high Doppler frequency shifts but posses good doppler resolutions with reference to PSLR values.

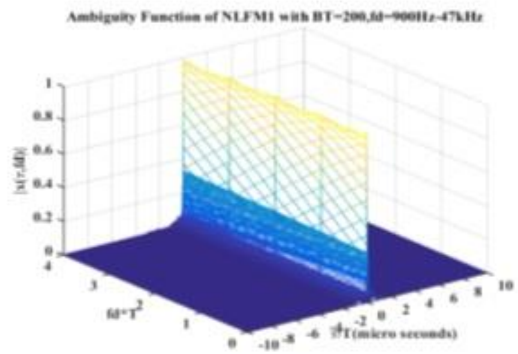

***Fig.5 (a)** Ambiguity functions of NFLM1.*

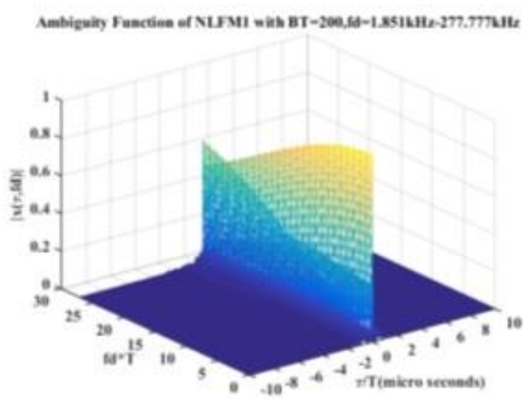

***Fig.5 (b)** Ambiguity functions of NFLM1.*

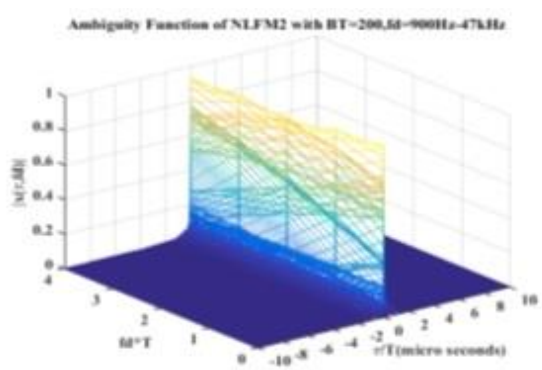

***Fig.6 (a)** Ambiguity functions of NFLM2.*

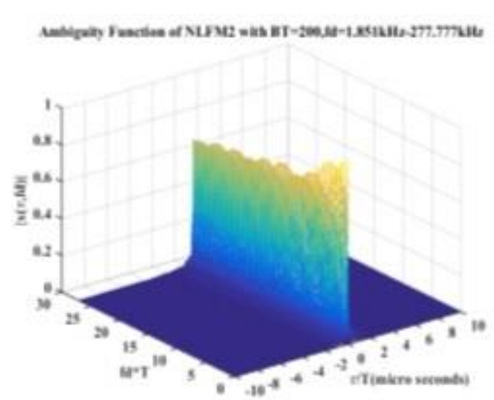

***Fig.6 (b)** Ambiguity functions of NFLM2.*

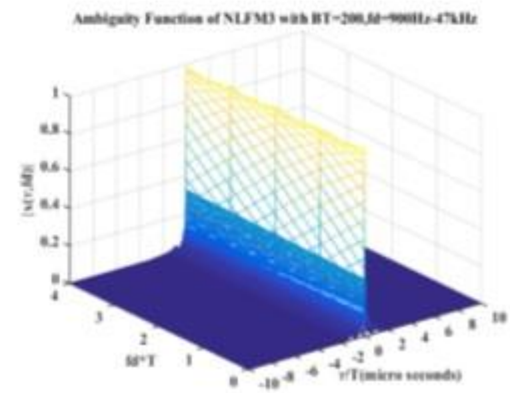

***Fig.7 (a)** Ambiguity functions of NFLM3.*

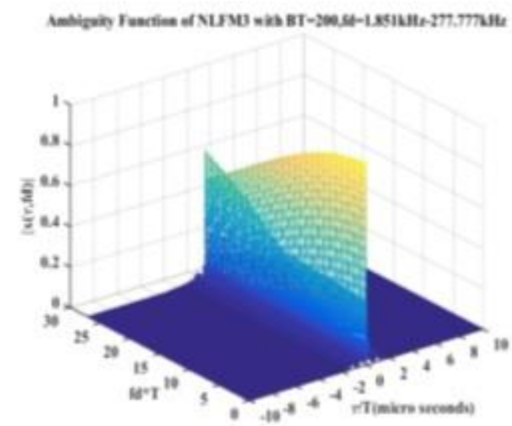

***Fig.7 (b)** Ambiguity functions of NFLM3.*

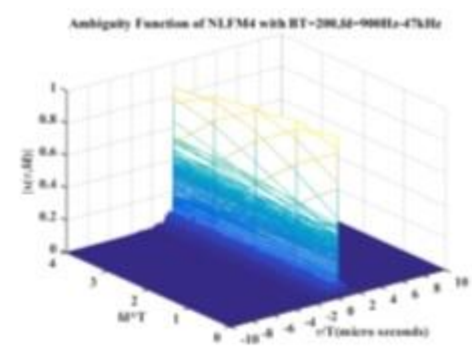

***Fig.8 (a)** Ambiguity functions of NFLM4.*

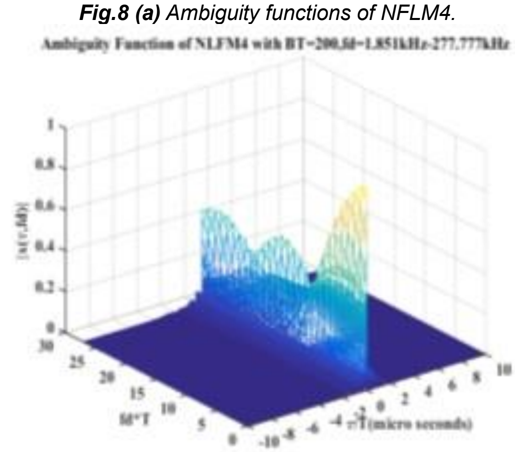

***Fig.8 (b)** Ambiguity functions of NFLM4.*

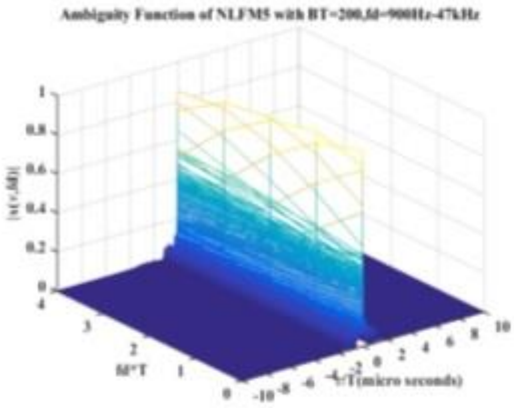

Fig.9 (a) *Ambiguity functions of NFLM5.*

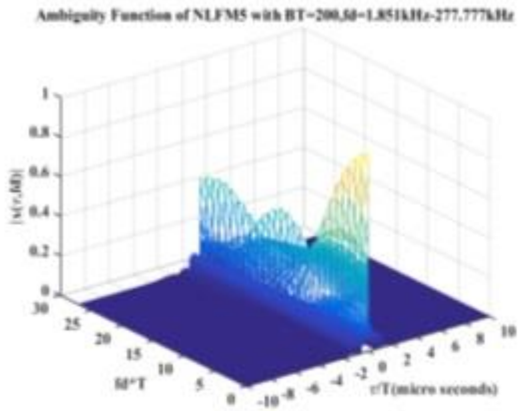

Fig.9 (b) *Ambiguity functions of NFLM5.*

5 CONCLUSION

In this paper we have presented a 5 different NLFM signals design using LFM and modified LFM functions. From the simulations we illustrate that the NLFM3 and NLFM5 exhibits maximum PSLR values compared to standard LFM signal and also NLFM3 signal shows the similar range doppler characteristics as of LFM signal and also has a good range resolution with reference to the PSLR values. Amongst all the NLMF signals it can be a good choice for sidelobe reduction and better target detection.

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