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Optimization of two-stage NLFM signal using Heuristic approach

Chandu Kavitha[1]*, Nettem Adithya Valli[2], Madhavaprasad Dasari[1]

1 Department of Electronics and Physics, GITAM Institute of Science, GITAM Deemed to be University, Visakhapatnam, 530045, A.P, India
2 Department of Electrical Electronics and Communication Engineering, GITAM Institute of Technology, GITAM deemed to be University, Visakhapatnam, 530045, A.P, India

****Corresponding author**.

kchandu@gitam.edu

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Abstract

Background/Objectives: The design of appropriate Non-Linear Frequency Modulation (NLFM) signals continues to be the focus of research in radar pulse compression theory for sidelobe reduction. This study focuses on a heuristic design and optimization algorithm to optimize the side lobe values of the NLFM signal designed using two-piece wise linear frequency modulation (LFM) functions. **Methods**: 1) Heuristic search identifies the optimum B1, T1, and B2, T2, which yield the lowest sidelobe value of the designed function. 2) Compute all the side lobe values of the designed NLFM signal using an algorithm developed in Python scripting language. To plot a complete contour map for all the calculated side lobe values, which helps identify the associated variations in the range of side lobe values. Finally, optimize the side lobe values keeping the main lobe width and time-bandwidth (BT) product unchanged by designing a dynamic optimization algorithm. **Findings**: The algorithm developed considered all side lobe levels after the main lobe for optimization. The focus is mainly on the peak sidelobe ratio (PSLR) value without affecting the other parameters. The results demonstrate that the achieved side lobes exhibit their desired levels. **Novelty**: The method is useful in all types of hardware associated with weather radar applications to military solutions. The technique can be extended to other multistage signals consisting of piecewise linear Segments.

Keywords: Contour; LFM; NLFM; optimization; PSLR

1 Introduction

In modern radar systems, radar waveform design based on complex signal and pulse compression is vital for better detectability and range resolution. Its autocorrelation properties judge the performance of any signal designed. The autocorrelation of the designed function should have a low peak sidelobe ratio (PSLR) values and narrow main lobe width. Many studies focused on Non-Linear Frequency Modulation (NLFM) waveforms as they suppress sidelobe

values better, but the waveform design is complicated. The most common methods used for the NLFM design are stationary phase, iteration method, and explicit functions cluster methods.

NLFM designed using two/tri stage is proposed in 2009. NLFM developed using two-stage frequency modulated (FM) waveforms has the advantage of no mismatch loss. Implementation is simple. It can achieve a -19 dB of sidelobe reduction without any weighing technique[1]. C. E. Cook and J. Paolillo[2] in 1964 proved that a predistorted linear FM pulse compression signal is a realizable means for exerting control over the spectrum function. H. D. Griffiths and L. Vinagre[3] in 1994 provided an alternative way of explaining the above technique. They presented a pulse compression technique that is suitable for a satellite born rain radar with ultralow range sidelobes. The waveform was designed with linear FM over the majority of the pulse and with small portions of higher FM rate signal at the beginning and end of the pulse.

Later, several attempts were made to improve the performance of NLFM waveforms[4–6]. Many studies reported that the use of tan function[7], S-shaped[8], and Curve-shaped NLFM[9] waveforms result in low side lobe values. The best peak sidelobe level achieved by the above techniques is approximately -18.6 dB. However, whether the optimization of two-stage linear frequency modulation (LFM) yields NLFM with better PSLR values can be examined. G. Jin et al.,[10] used Augmented Lagrangian Genetic Algorithm (ALGA) for optimization of NLFM waveform and achieved lower sidelobes and narrow main lobe width. They also proposed a modified NLFM generation method based on the principle of stationary phase (POSP)[11]. The developed signal generator will be employed in LuTan-1 (LT-1) mission which is an innovative spaceborne bistatic SAR mission.

In the present study, the NLFM waveform designed using two-piece wise LFM signals[12–14] is optimized to obtain a low sidelobe level under a limitation of the time-bandwidth product. A heuristic design provides desirable solutions, as the classic methods are slow, taking random points giving near-optimal solutions.

The NLFM signal's autocorrelation function varies with different values of B1, T1, B2, and T2. Before optimization, a heuristic search is performed by changing the parameters B1, T1, B2, and T2 to the finest level (0.1 resolution) to find an autocorrelation function, which yields a low PSLR value.

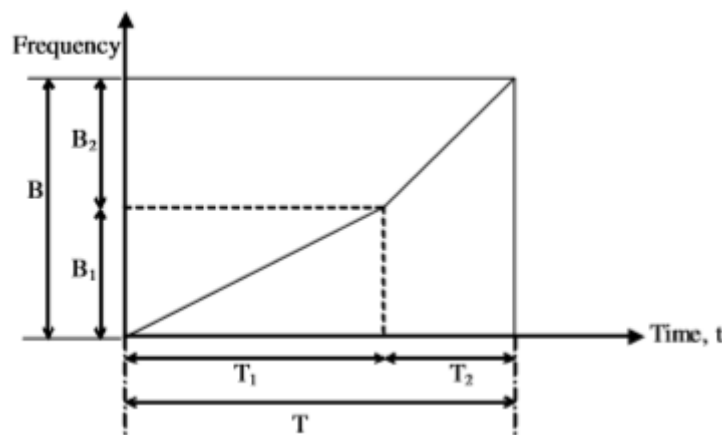## 2 Non-Linear Frequency Modulation (NLFM) waveform design

Fig 1. Frequency variation of two-stage NLFM function

Non-linear signal (Figure 1) designed using simple two-stage piecewise LFM functions as given below:

$$f(t)_{NLFM} = \begin{cases} k_0 t & 0 \le t \le T_1 \\ B_1 + k_1 (t - T_1) & T_1 \le t \le (T_1 + T_2) \end{cases} \tag{1}$$

NLFM signal is formed by concatenating two-piece wise LFM functions with a sweep rate of k_0 in the first and k_1 in the second stage. The entire pulse width of the chirp signal 't' is separated into two-time slots with individual pulse widths T_1 and T_2. If B_1 and B_2 are the equivalent bandwidths of the first and second stage LFM functions, the resultant sweep rates are

$$k_0 = \frac{B_1}{T_1}, \ k_1 = \frac{B_2}{T_2}$$

The corresponding variation of phase is obtained by integrating equation (1)

$$\varphi(t)_{NLFM} = \begin{cases} 2\pi(k_0)\dfrac{t^2}{2} & 0 \leq t \leq T_1 \\ 2\pi(B_1 t + k_1(\dfrac{t^2}{2} - T_1 t)) & T_1 \leq t \leq T_1 + T_2 \end{cases} \tag{2}$$

The complex signal of NLFM is given by the following equation

$$s(t)_{NLFM} = exp(j\varphi(t)_{NLFM}) \qquad \frac{-\tau}{2} \leq t \leq \frac{\tau}{2} \tag{3}$$

Simulations are carried out with T $=10\mu s$, B = 20 MHz, and with different combinations of B_1, T_1, and B_2, T_2. All the possible combinations are examined by choosing different sweep rates α_0, α_1 for both piecewise linear frequency modulation (PWLFM) functions, as shown in Figures 2, 3, 4 and 5. Table 1 shows the PSLR values obtained with different configurations. The simulations show that the small variation in B_1, T_1, and B_2, T_2 is affecting the PSLR values. This function's best possible solution is achieved for B_1=2MHz, T_1=3μs, and B_2=18MHz, T_2=7μs with PSLR of -21.99 dB.
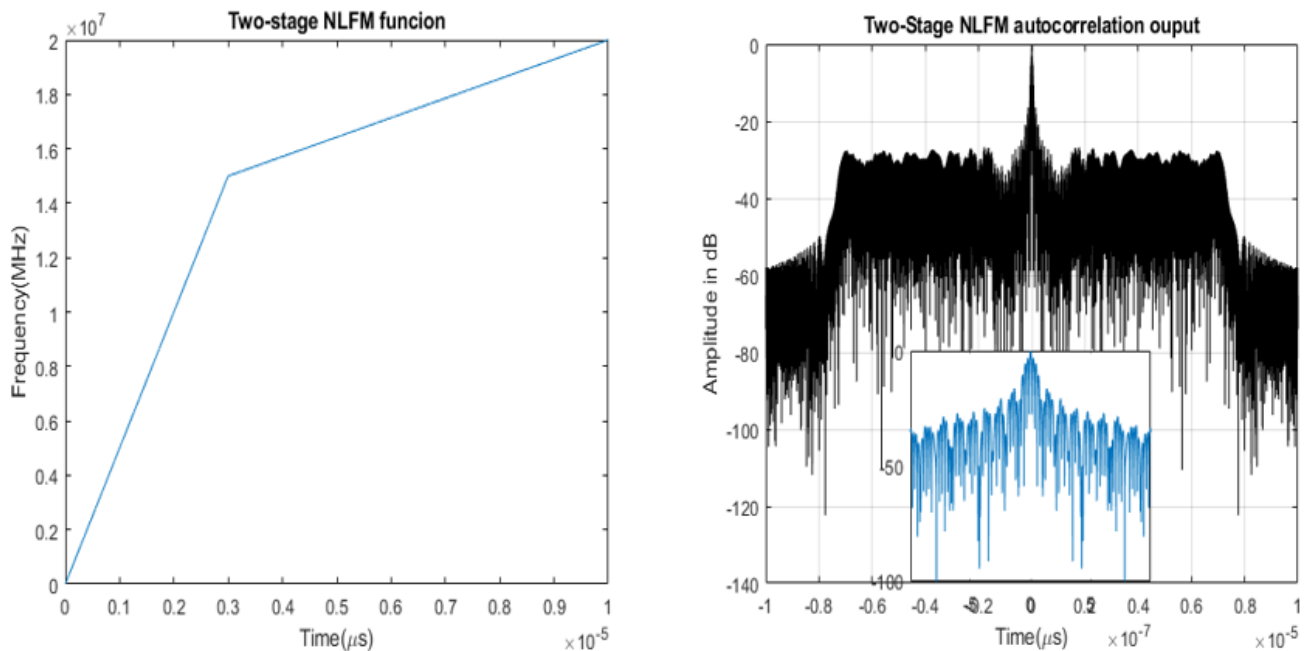
Fig 2. (a) Frequency variation of two-stage NLFM function $(f(t)_{NLFM})$
(b) Matched filter output for configuration I
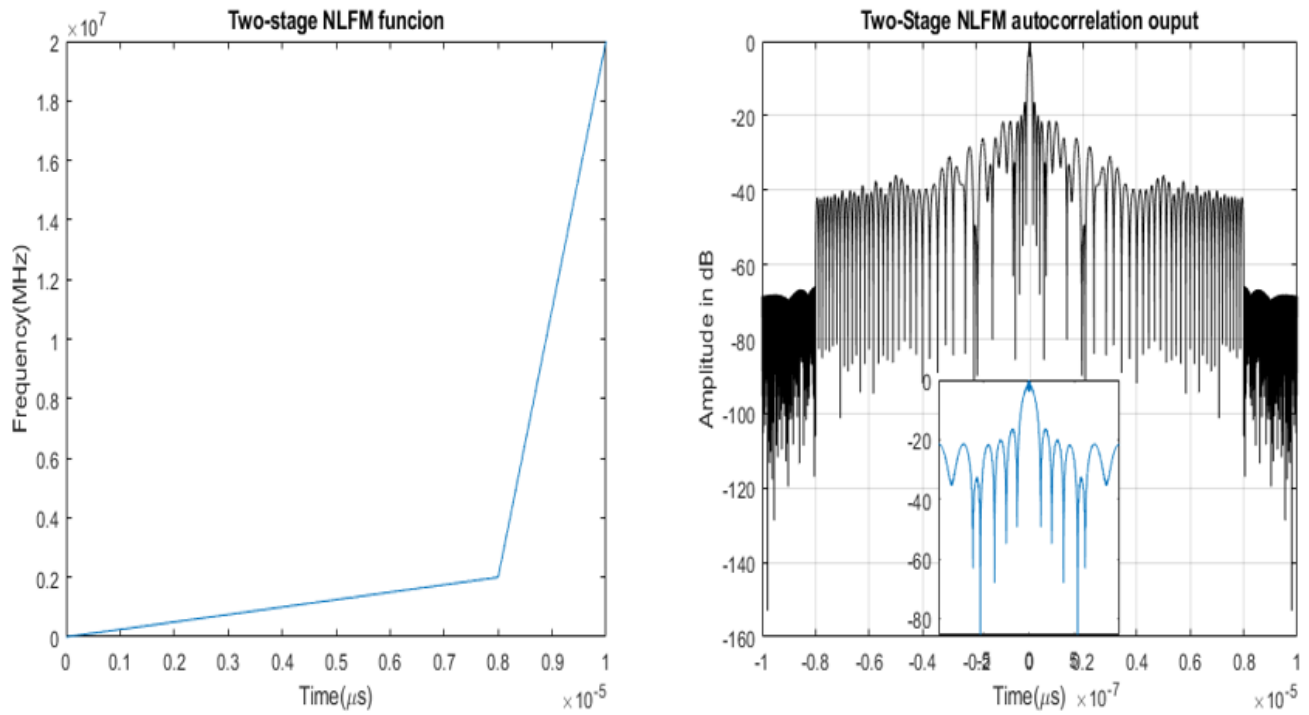
Fig 3. (a) Frequency variation of two-stage NLFM function $(f(t)_{NLFM})$
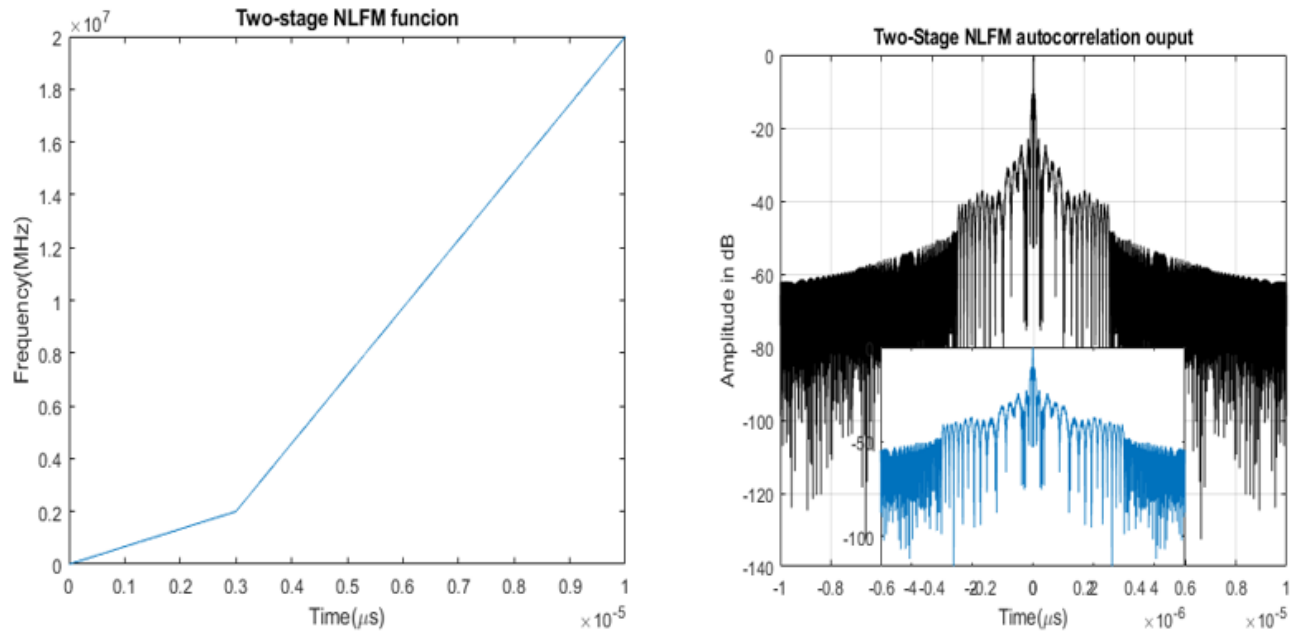(b) Matched filter output for configuration II
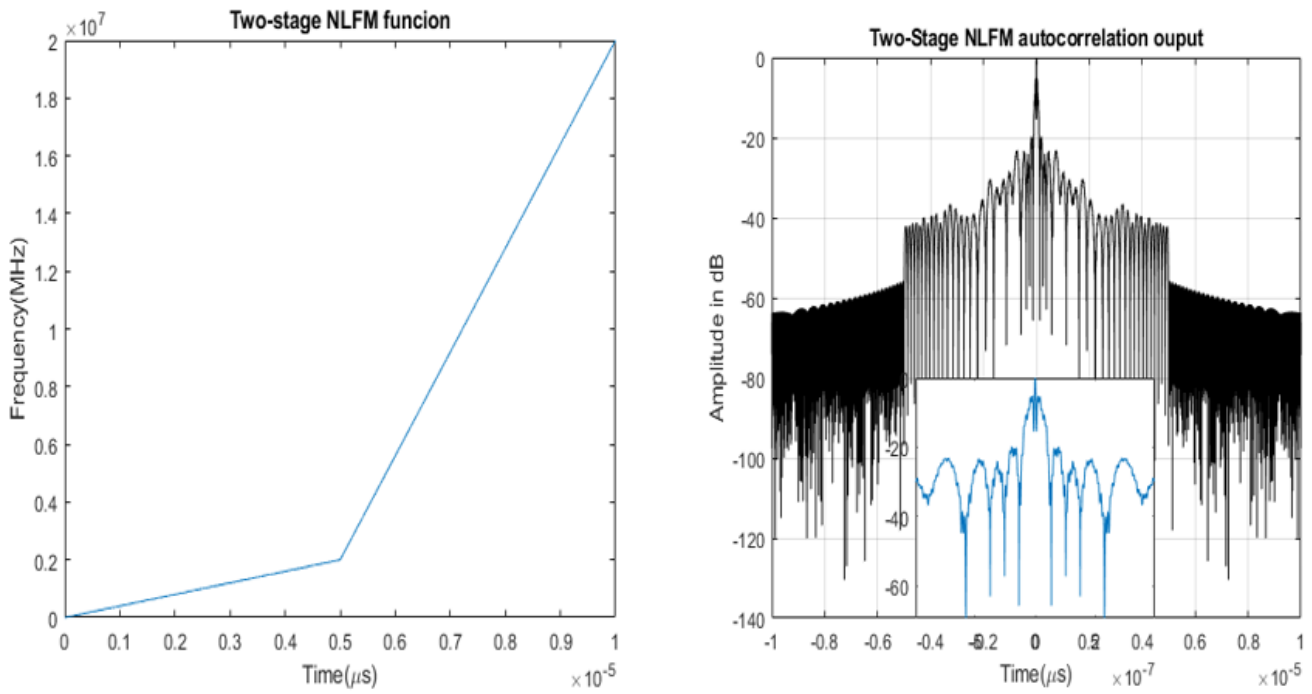
Fig 4. (a) Frequency variation of two-stage NLFM function $(f(t)_{NLFM})$
(b) Matched filter output for configuration III

Fig 5. (a) Frequency variation of two-stage NLFM function $(f(t)_{NLFM})$
(b) Matched filter output for configuration IV

Table 1. PSLR values of the two-stage NLFM function for different configurations

Configurations	BT=200
	PSLR (dB)
I	-10.62
II	-16.56
III	-20.24
IV	-21.99

3 Heuristic search

It is evident from the simulations that the sidelobe values of the designed function vary drastically with a small change in the values of B_1, T_1, and B_2, T_2. To identify the optimum B_1, T_1, and B_2, T_2 yields the lowest sidelobe value; a heuristic search is performed. A contour map or heat map (Figure 6 (a) & 6(b) respectively) plotted for all the possible values of B_1, T_1, based on the algorithm written in Python scripting language, enabled us to obtain an optimum solution in a quick time (Figure 6(c)). The plot helps to identify the associated variations in the range of sidelobe levels capable of determining breakpoint values of two piecewise LFM functions for a given BT product. The color bar at the side of the contour and heat map indicates the values of PSLR obtained. The darkness of the color helps to identify the minimum values of PSLR.

Xcorr is the autocorrelation of chirp signal s (t), and SL (Xcorr) is the first side lobe value for Xcorr. The auto-correlation function is computed for the chirp signal. Then first side lobe value (PSLR) is obtained by identifying the first null from the right-hand side of the autocorrelation plot. The peak value next to the null represents the first side lobe value. The entire procedure is repeated for the complete range of B_1 and T_1 following the algorithm.
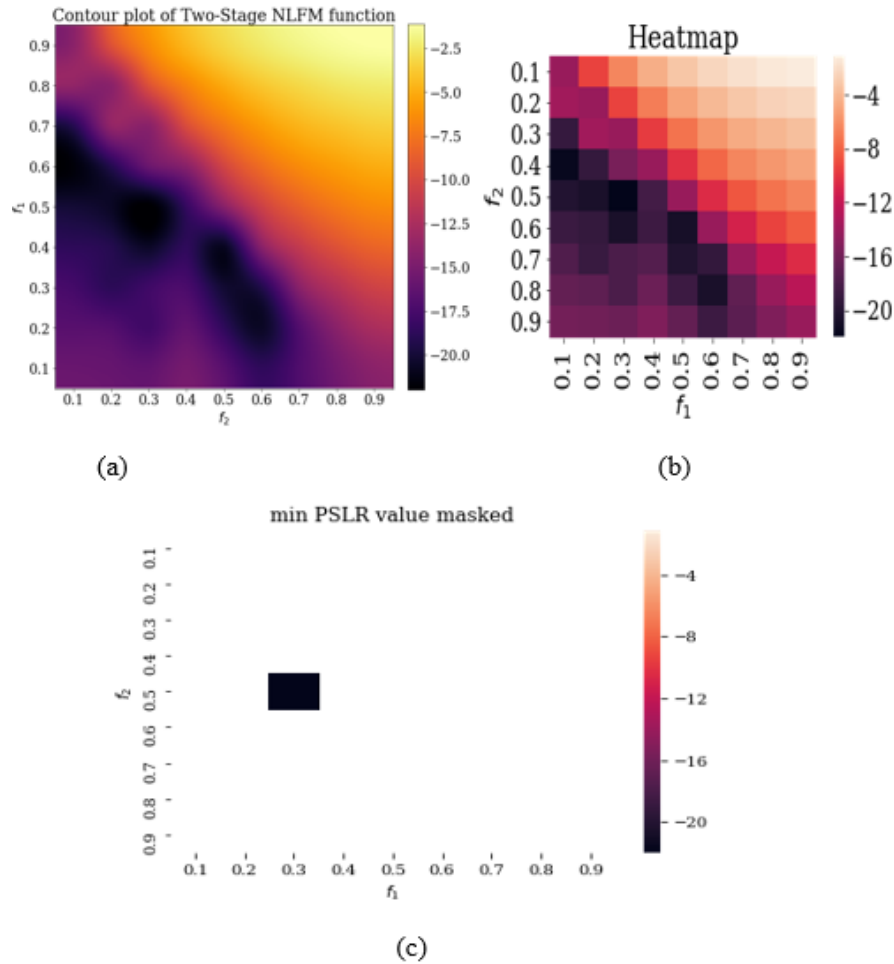
Fig 6. (a) Contour map of sidelobe values as a function of the breakpoints $f_1=B_1/B$ and $f_2=T_1/T$ (b) Heatmap (c) Masked Heatmap for min PSLR value

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Algorithm 1: Computing the contour map of a two-stage NLFM function.

Procedure NLFM 2-STAGE CONTOUR
    for B1 in B1 ranges do
    for T1 in T1 ranges do
        Xcorr (B1, T1) — autocorr[s (t, B1, T1)]
        PSLR (B1, T1) — SL (Xcorr (B1, T1))
        end for
    end for
The data for PSLR (B1, T1) is stored in a file or plotted as a contour for visual reference.
    end procedure
    Procedure SL (Xcorr (B1, T1))
    Find the first zero in the right half of Xcorr (B1, T1)
        $SL_{loc} \leftarrow$ B1 location of the subsequent maxima (M1).
        $SL_{val} \leftarrow$ SLval Peak value of M1.
    Return SLloc and SLval
    end procedure

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4 Optimization

The autocorrelation function with the lowest PSLR, i.e., -21.99 dB obtained from the above algorithm, is considered for optimization. The process involves an iteration to run cyclically until the stop criteria reach. The desired PSLR is set, which is specific to radar application. The following are the steps involved during the optimization process

1) Optimum values of B_1, T_1, and B_2, T_2 at the maximum PSLR value -21.99dB are identified from the contour plot analysis, and an NLFM function is designed using these values.

2) The right half of the autocorrelation plot (Figure 7) obtained for the above said values are taken. The first null is identified, and the peak sidelobe values (PSLR) are determined (SL (Xcorr)).
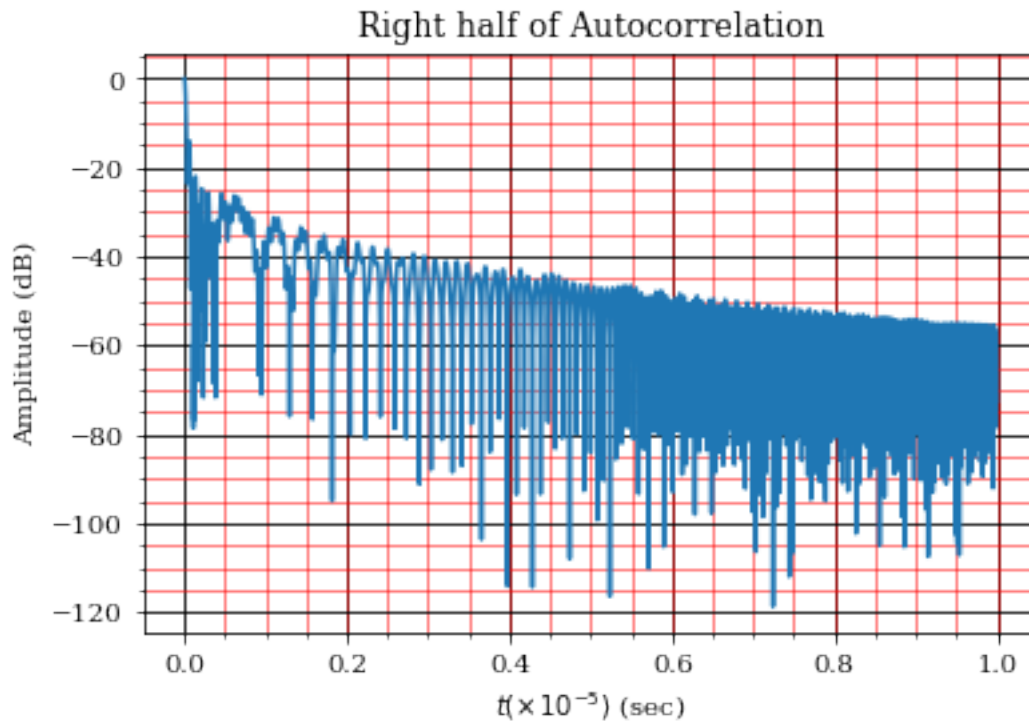

Fig 7. Right half of autocorrelation plot

3) $D_0[\,]$ is an array constructed for all the sidelobe values for the right half of the autocorrelation plot by identifying all the nulls. The first sidelobe value is identified from the array and stored in $D_0[i]$ as $PSLR_0$.

4) The desired PSLR value is $PSLR_D$, set based on the application.

5) The random number "d" is generated in such a way that the first sidelobe value $PSLR_0$ is equal to the desired value $PSLR_D$ (First it set to -30 dB and later to -60dB.)

for i in range (length (D_0)):

if $D_0[i]$==-21.99:

x=i

y=$D_0[i]$

for j in range(x, length(D_0)):

$D_0[j]$=(d)*$D_0[j]$/y

6) Random number "d" is uniformly divided throughout the array and new array $D_0[]$ is constructed and plotted. The corresponding autocorrelation function plots are shown in Figure 8 .
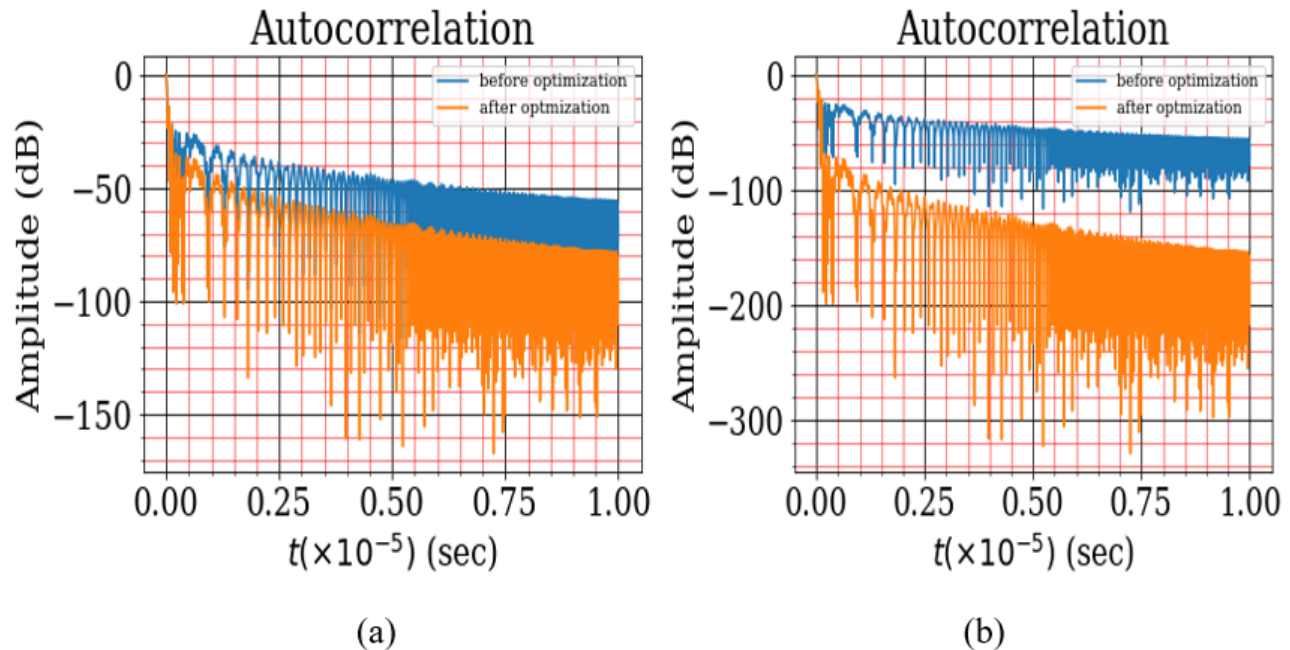
Fig 8. (a)Optimization when PSLR$_D$ = -30dB (b) Optimization when PSLR$_D$ =-60dB

5 Conclusion

A generalized heuristic design and optimization algorithm developed achieved low side lobe values of the designed NLFM signal. Heuristic search helped to identify the lowest PSLR yielded by the function. Simulations were run for the finest resolutions to obtain more accurate PSLR values. The lowest PSLR value for the designed NLFM function is -21.99dB for 0.1 resolution. A dynamic optimization algorithm developed is applied further to reduce PSLR values to the desired optimum level. The technique reduced the side lobe values to the optimum values of - 30dB and -60dB for two different radar applications, which can be applied to any value specifically required for radar applications.

Thus, this study demonstrated a technique using a highly flexible optimization algorithm for designing pulse compression waveforms. This method is simple and more flexible. This technique allows for a globally optimized theoretical waveform design without any modulation techniques. Additionally, it is capable of optimizing waveforms based on the autocorrelation function of a given system. In this algorithm, the focus is on PSLR value without affecting the other parameters. The algorithm developed considered all side lobe levels after the main lobe for optimization. The method can be used in all types of hardware associated with weather radar applications to military solutions. This technique can be extended to other multistage signals consisting of piecewise linear segments.

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