International Journal of Engineering & Technology, 7 (2.20) (2018) 219-223

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Implementation of Multi-Objective Grey Wolf Optimizer to Minimize The Sidelobes And Reduce Mainlobe Width

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Abstract

Range resolution in radar can be achieved by splitting the long pulse of high energy into the high bandwidth of short pulses using pulse compression technique. Frequency modulation (Linear frequency modulation (LFM)) signal is used to improve range resolution. To get better range resolution, frequency step is introduced between a train of LFM pulses known as stepped frequency pulse train (the SFPT). The SFPT suffers from grating lobes when the product of sub-pulse duration and frequency step becomes more than one. The grating lobes and sidelobes present in the vicinity of the mainlobe. It can cause the false alarm detection and hide the small targets. In this work, Multi-Objective Grey Wolf Algorithm (MOGWO) is used to set the parameters of SFPT to mitigate the grating lobes and minimize the sidelobes at the matched filter output. Trade-off solutions between sidelobes versus grating lobes and mainlobe width versus sidelobes are obtained using the Pareto front for different ranges of SFPT parameters.

Keywords: *Pulse compression, Sidelobes, Mainlobe width, Grating lobes, Autocorrelation function and Multi-objective optimization technique*.

1. Introduction

Radar is used to sending electromagnetic waves and receiving echo signals which will give the information about the target range and velocity. To distinguish many targets, it requires optimum resolution. High resolution can be achieved by converting strength of long duration pulses into optimum capacity narrowband pulses [1]. High range signals are used in phased array radars to get maximum resolution and optimum energy strength on the target. The conventional design of radar is not suitable for wideband waveforms. In place of wideband waveforms, stepped frequency LFM waveforms are used. This signal is stepped frequency train of liner frequency modulated signal (SLFM) or stepped frequency pulse train [SFPT] [2].
SFPT signal having N number of pulses with width t_b, corresponding to frequency step Δf is shown in figure 1 for satisfying the stipulation $B > \Delta f > 0$ parameters such as B and Δf are constant. In SFPT, the interval between the pulses are useful adjusting frequency of the signal. If the interval between the pulses is changed, grating lobes appear when $t_b \Delta f > 1$. Due to these grating lobes, the range resolution will be error-prone. Different techniques were discussed by Moran [3, 4]. Changing the width of the pulse train, reduction of lobes takes place. However, the periodicity of the signal is spoiled. Search process [5] has been used for
finding the equations amongst the parameters of SLFM signal in which the initial pair of lobes are cancelled. Most of the techniques have concentrated on the cancelation of grating lobes. Emphasis has not been given on reduction of sidelobes. Spectral weighting has been proposed for distribution of energy in the pulse train. So that sidelobes, as well as grating lobes, are reduced. [6]. In this case sensitivity of the signal decreases. A non-linear frequency modulated (NLFM) signal has been used in place of LFM signal for reduction of side lobes [7]. The difficulty in this method is that there is little tolerance of the Doppler shift. To circumvent these problems, genetic algorithm based Nondominated sorting algorithm [9] can be used in [8]. Due to $O(MN^2)$ factor, the computation time of this scheme called NSGA-II is high. Overcoming this additional problem, in this work Multi objective Grey Wolf (MOGWO) optimization technique has been found to be effective [13]. This optimization is capable of obtaining improved PSLR as well as range resolution. The optimal parameters of SFPT are determined during the optimization of MOGWO.
Section 2 of this paper deals with the analysis of SFPT signal. The formulation of the problem is presented in section 3. Multi-objective Grey Wolf optimization technique has been covered by section 4. Results of simulation are discussed in section 5 followed by section 6 deals with the conclusions.

2. Analysis of Stepped Frequency Pulse Train

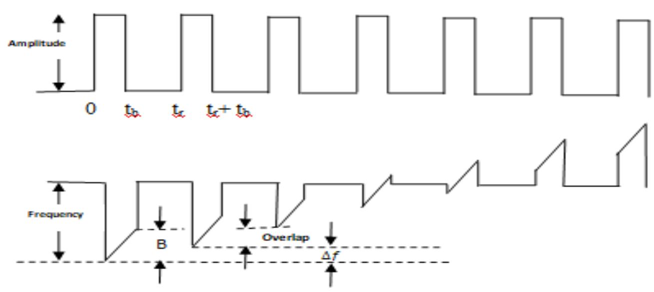

Figure 1: Waveform of SFPT

The governing equation for the pulse of t_b duration is

$$p(t) = \frac{1}{\sqrt{t_b}} rect\left(\frac{t}{t_b}\right) \quad (1)$$

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Complex envelope of LFM pulse, is given [10] as

$$p_1(t) = \frac{1}{\sqrt{t_b}} rect\left(\frac{t}{t_b}\right) \exp(j\pi k t^2) \quad (2)$$

Here k is slope frequency.

$$k = \pm \frac{B_1}{t_b}$$

The ACF of p_s(t) is Obtained [5] as

$$|R(\tau)| = \left|\left(1 - \frac{|\tau|}{t_b}\right) \sin c\left[B\tau\left(1 - \frac{|\tau|}{t_b}\right)\right]\right| \left|\frac{\sin(N\pi\tau\Delta f)}{N\sin(\pi\tau\Delta f)}\right| \quad (3)$$

$|R(\tau)|$ has two factors : ACF of LFM is the first is

$$|R_1(\tau)| = \left|\left(1 - \frac{|\tau|}{t_b}\right) \sin c\left[B\tau\left(1 - \frac{|\tau|}{t_b}\right)\right]\right| \quad (4)$$

The grating lobes is the second factor. Its ACF is

$$|R_2(\tau)| = \left|\frac{\sin(N\pi\tau\Delta f)}{N\sin(\pi\tau\Delta f)}\right| \qquad \tau \le t_b \quad (5)$$

The above equation gives the grating lobes at $\tau_g = \frac{g}{\Delta f}$ where

g =1, 2, 3,….. $\lfloor t_b \Delta f \rfloor$

3. Formulation of the Problem

The main aim of problem formulation is (a) to decrease sidelobes and grating lobes to avoid hiding of small echoes and (b) reduce the mainlobe width to improve range resolution. A balancing relation is created for grating lobes and sidelobes along with main lobe. It is proposed to reduce all the lobes [8].

Gray wolf optimization approach is used for solving the problem 1 and problem 2. Peak sidelobe ratio (PSLR) can be used to check sidelobe suppression. PSLR is defined [8 and 11] as

$$\text{PSLR (dB)} = 20 \log_{10} \frac{\max_{1<k<N} |r(k)|}{|r(0)|} \quad (6)$$

r(0) is the mainlobe level and r(k) is maximum side lobe level among all sidelobes.

The choice of t_b and B is chosen such that B > Δf. These functions are optimized as problem 1 and 2 [8].

Problem 1:

Considering minimization

f_1 = max [|R_1 (τ_g)|] where g = 1, 2 … $\lfloor t_b \Delta f \rfloor$

f_2 = PSLR in dB

N $t_b \Delta f$ > t_bB

Problem 2:

The minimum of |R_2 (τ)| results for $1/Nt_b\Delta f$ and minimum R_1(τ) results when 1/t_bB >>1. Hence the first minimum ACF is

$$\frac{\tau_{1^{st}\,null}}{t_b} = \min\left(\frac{1}{t_b B}, \frac{1}{Nt_b\Delta f}\right) \quad (7)$$

Considering minimization

(3)

f_2 = PSLR in dB

$f_3 = \frac{1}{Nt_b\Delta f}$

Subjected to the constraints $Nt_b\Delta f$ > t_b B and |R_1 (τ_g)| < ε

4. Multi-Objective Grey Wolf Optimizer (MOGWO)

The MOGWO optimizer [13] discussed here is effective in cases with multi-objectives [14, 15]. The external set of solutions covers the most effective one of a nondominated type. The functions of A and C help prospective solutions to include hyper spheres with random radii depending on the solutions. In GWO [12] search agents are permitted to determine the possible location of prey. The adaptive values of A and C ensure effective exploration as well as exploitation. For diminishing the value of A, half of the iteration steps are related to exploration of A. The balance iterations are meant for |A| < 1. Due to the selection of leading function and grid mechanism it is ensured that all iterative solutions are part of the archive. MOGWO follows roulette wheel type of selection conveying front advance. The value of C parameter helps in exploration deriving overall optimization.

As per GWO algorithm, each agent has to change the position suddenly in the initial steps as well as final steps. MOGWO has many similarities with GWO. The main difference is that GWO only saves three best solutions where as MOGWO searches around archive members.

5. Simulation Results

Simulations have been done to optimize f_1 and f_2 using MOGWO. Population size is taken as 100, and the numbers of generations are considered as 50 for problem 1. Grid Inflation and Leader Selection are 0.04 and 4. The two parameters chosen by MOGWO for obtaining low sidelobes are $t_b\Delta f$ and c.

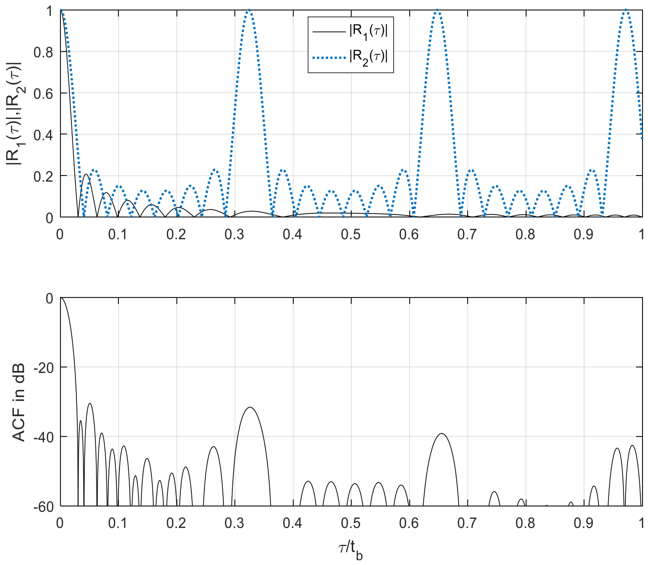

Figure 2. Stepped frequency pulse train for $t_b\Delta f$ = 3.088, c = 9.969, t_bB = 33.872 and N = 8. Top shows | $R_1(\tau)$ | (solid) and | $R_2(\tau)$ | (dash) where as bottom shows ACF in dB.

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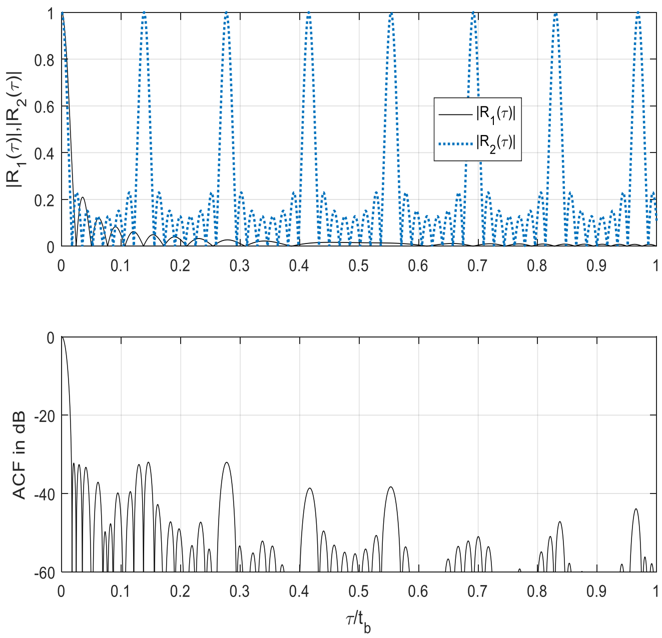

Figure 3. Stepped frequency pulse train for $t_b\Delta f$ = 7.226. c = 4.838, t_bB = 42.186 and N = 8. Top shows | $R_1(\tau)$ | (solid) and | $R_2(\tau)$ | (dash) where as bottom shows ACF in dB.

Figure 2 shows, when the nulls of $|R_1(\tau)|$ super imposed on grating lobes of $|R_2(\tau)|$, all the grating lobes are mitigated and PSLR is obtained -30.47228 dB. If grating lobe level is extended to 0.0l the PSLR is obtained -32.006 in the range $t_b\Delta f \in [2,10]$; $c \in [2,10]$ and N = 8 shown in figure 3.

For $t_b\Delta f \in [2,10]$, $c \in [2,10]$ and N = 8, the values of SFPT parameters $t_b\Delta f$ and t_bB are given by NSGA-II algorithm in (8). The maximum PSLR achieved in this region is -31.732 dB when f_1 = 0.01. As well as the PSLR -28.821 dB is achieved in the range $t_b\Delta f \in [5, 30]$; $c \in [2,10]$, $\mathcal{E} < 0.01$ and N = 8.

The Pareto fronts are used to give the trade-off solutions. The Pareto front obtained from MOGWO approach for $t_b\Delta f \in [2, 10]$, $c \in [2, 10]$ and N = 8 at the maximum threshold value $\mathcal{E} < 0.01$ is shown in figure 4. Depending up on the application requirement, the threshold level can be adjusted to obtain more number of solutions.

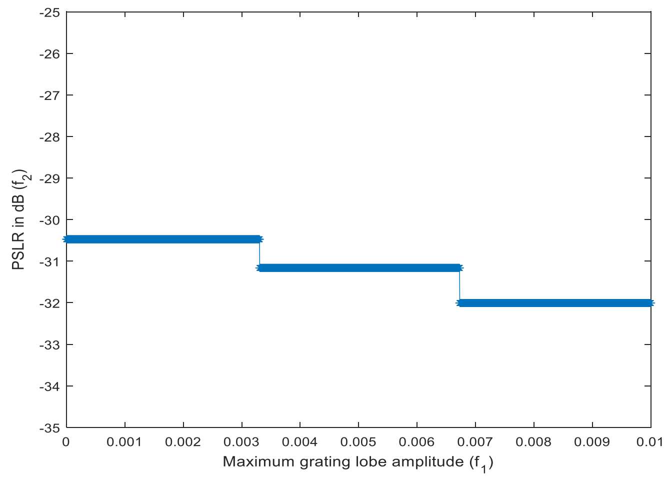

Figure 4. Pareto front obtained using MOGWO for $t_b\Delta f \in [2, 10]$, $c \in [2, 5]$, $\mathcal{E} < 0.01$ and N = 8.

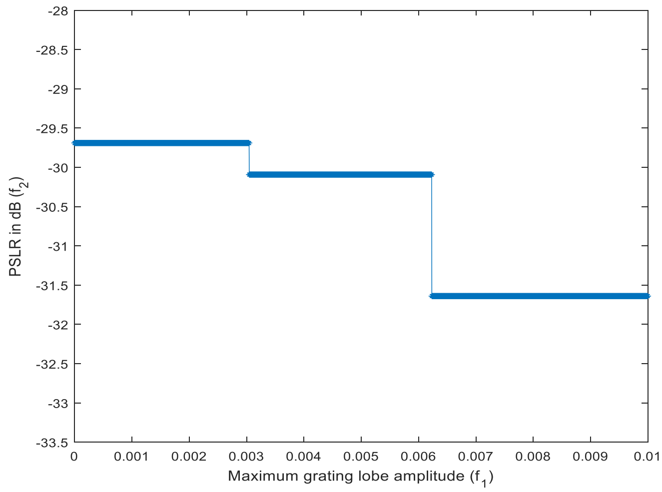

Figure 5. Pareto front obtained using MOGWO in the range $t_b\Delta f \in [2, 10]$, $c \in [2,5]$, $\mathcal{E} < 0.01$ and N = 8.

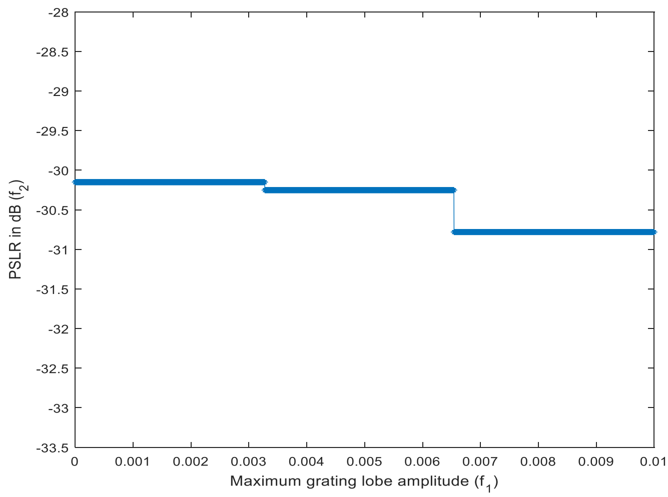

Figure 6. Pareto front obtained using MOGWO in the range $t_b\Delta f \in [2, 10]$, $c \in [2, 5]$, $\mathcal{E} < 0.01$ and N = 8.

The Pareto front obtained from MOGWO approach for $t_b\Delta f \in [2,10]$, $c \in [2, 5]$ and $t_b\Delta f \in [5,30]$, $c \in [2, 10]$, and N = 8 at the maximum value $\varepsilon < 0.01$ is shown in figures 5 and 6, the corresponding PSLR are tabulated in table 1.

For second problem, number of populations and the number of generations are 200 and 50 to obtain the optimized parameters in optimal solution for sidelobe amplitude (f_2) and mainlobe width (f_3) using MOGWO. The search agents are randomly initialized to determine the $t_b\Delta f$ and c between the limits (ranges). For $t_b\Delta f \in [2, 10]$, $c \in [2, 5]$, $\varepsilon < 0.045$ and N = 8.

The figure 7 and 8 shows the change of PSLR with the change of mainlobe width.

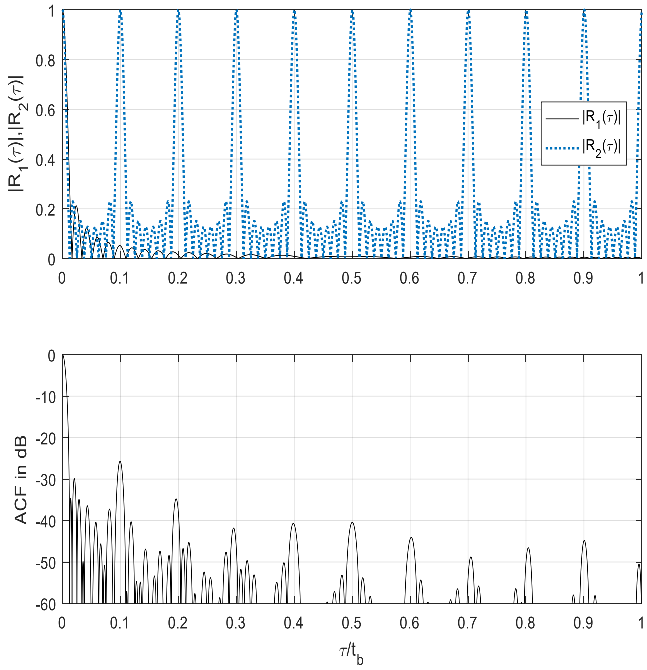

Figure 7. Stepped frequency pulse train for $t_b\Delta f$ = 9.9935, c = 5.1524 and t_bB = 61.484 and N = 8. Top shows $|R_1(\tau)|$ (solid) and $|R_2(\tau)|$ (dash) where as bottom shows ACF in dB.

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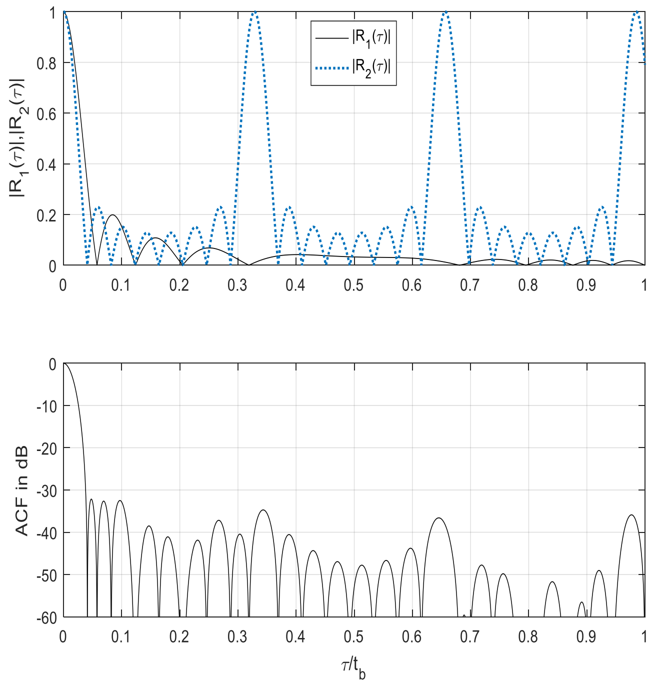

Figure 8. Stepped frequency pulse train for $t_b\Delta f$ = 3.0464, c = 5.045 and t_bB = 18.415 and N = 8. Top shows $|R_1(\tau)|$ (solid) and $|R_2(\tau)|$ (dash) where as bottom shows ACF in dB.

If the mainlobe width is changed from 0.01 to 0.041, PSLR also changes. In figure7, the PSLR is -29.4 dB and the mainlobe width is narrow. In case of figure 8, the PSLR is increased to -31.787 dB, but mainlobe width is broadened. If the application requires high PSLR to avoid false alarm, range resolution will be decreased. If the application requires high range resolution, the PSLR is decreased. So the trade-off solutions are obtained between sidelobes and mainlobe width for $t_b\Delta f \in [2. 10]$, $c \in [2, 10]$, $t_b\Delta f \in [2. 10]$, $c \in [2, 5]$ and $t_b\Delta f \in [2. 10]$, $c \in [2, 10]$, $\varepsilon < 0.045$ and N = 8 at the maximum grating lobe amplitude are set to be $\varepsilon < 0.01$ are shown .in figures 9 to 11 and the corresponding PSLR values are tabulated in table 2. The maximum PSLR is achieved in (8) using NSGA-II in the range $t_b\Delta f \in [2, 10]$, $c \in [2, 5]$, $\varepsilon < 0.045$ and N = 8 is -31.758 dB.

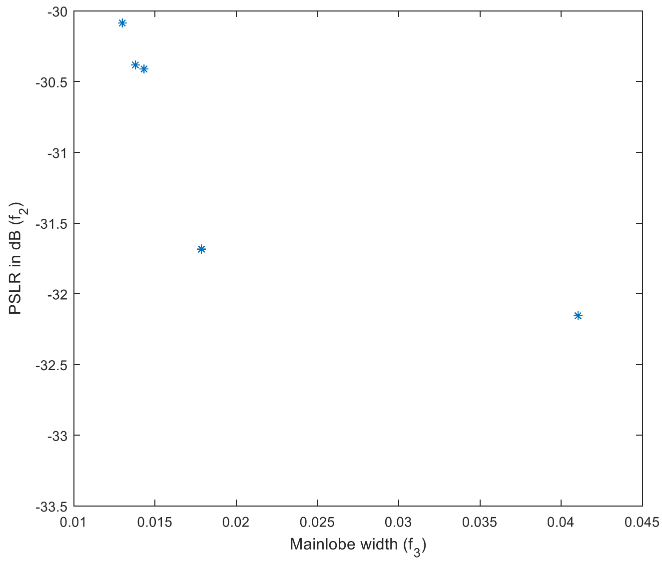

Figure 9. Pareto front obtained using MOGWO for $t_b\Delta f \in [2, 10]$, $c \in [2, 10]$, $\varepsilon < 0.045$ and N = 8.

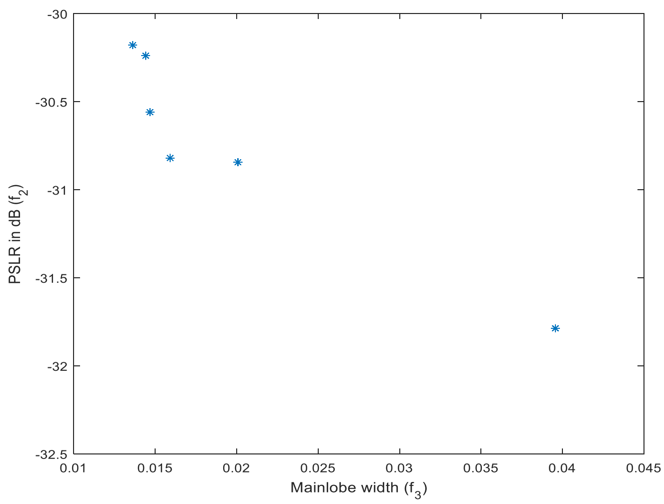

Figure 10. Pareto front obtained using MOGWO for $t_b\Delta f \in [2, 10]$, $c \in [2, 5]$, $\varepsilon < 0.01$ and N = 8.

If Peak side lobe level decreases, main lobe width is increased which decrease range resolution. If mainlobe width is decreased sidelobes amplitude is increased causes a false alarm. MOGWO approach gives the efficient trade-off solution between PSLR and mainlobe width according to the application of radar. From all the Pareto fronts of MOGWO, it is observed that the number of non-dominated solutions are less for problem 2 when compared to problem 1.

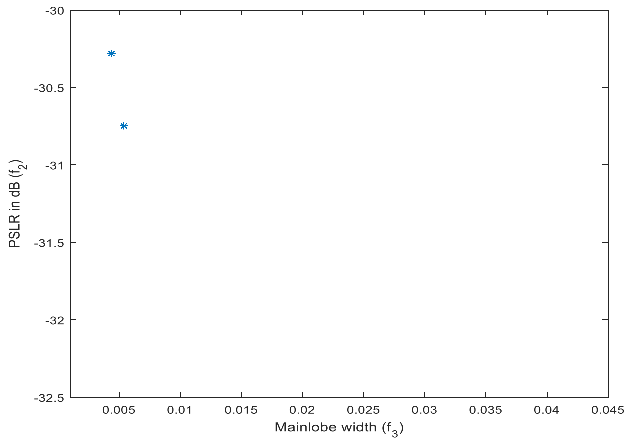

Figure 11. Pareto front obtained using MOGWO for $t_b\Delta f \in [5, 30]$, $c \in [2, 10]$, $\mathcal{E} < 0.01$ and N = 8.

Table 1. PSLR values for the SFPT parameters obtained from the MOGWO problem 1.

Range of $t_b\Delta f$	Range of 'c'	MOGWO
		PSLR in dB
[2 - 10]	[2 - 10]	-32.006
[2 - 10]	[2 - 5]	-31.639
[5 - 30]	[2 - 10]	-30.782

Table 2. PSLR values for the SFPT parameters obtained from the MOGWO for problem 2.

Range of $t_b\Delta f$	Range of 'c'	MOGWO
		PSLR in dB
[2 - 10]	[2 - 10]	-32.156
[2 - 10]	[2 - 5]	-31.787
[5 - 30]	[2 - 10]	-30.747

The PSLR values for the SFPT parameters obtained from the MOGWO algorithms are shown in table 1 and 2. It is clear that for the given SFPT parameters, the maximum PSLR -32.006 dB is obtained in the range $t_b\Delta f \in [2, 10]$, $c \in [2, 10]$ for problem 1. For problem 2, the maximum PSLR is obtained as -32.156 dB when compared to remaining ranges.

6. Conclusions

The basic demerit of Stepped frequency pulse train technology is the appearance of the grating lobes. In this paper, Multi-objective Grey wolf optimizer is suitable to determine the parameters to minimize the grating lobes and reduce sidelobes at the matching point. The maximum PSLR -32.006 dB is obtained with MOGWO for the SFPT parameters $t_b\Delta f$ = 7.226 and t_bB = 42.186 in the range $t_b\Delta f \in [2, 10]$, $c \in [2,10]$, $\mathcal{E} < 0.01$ and N = 8. Comparing with NSGA- II, the value of PSLR is improved by -0.274 dB and For $t_b\Delta f \in [5, 30]$, $c \in [2, 10]$, $\mathcal{E} < 0.01$ and N = 8, the PSLR is improved to -1.961 dB for problem 1. For problem 2 the maximum PSLR -32.156 dB is obtained in the range $t_b\Delta f \in [2, 10]$, $c \in [2, 10]$. In the range $t_b\Delta f \in [2, 10]$, $c \in [2, 5]$ and N = 8, the PSLR is improved by - 0.028 dB when compared to NSGA-II. The MOGWO based approach provides improved PSLR for acceptable trade-off solutions between the objective functions using Pareto fronts for problem 1 and problem 2 than the NSGA-II.

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