Space Group Targets Detecting and Resolving Algorithm via Ultra-low Sidelobe Filtering

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Abstract. Detecting and resolving the space group targets in the main beam of radar is an urgent requirement for the air-defense and anti-missile radar system. Ground-based radar, as an important instrument for space surveillance, can be used to detect and track the space targets like grouped aircrafts, warheads and the decoys of the missiles. However, it is difficult to detect and resolve the dense targets due to the limit of the radar resolving power. To solve this problem, a space group targets detecting and resolving algorithm based on ultra-low sidelobe filtering is proposed. By exploiting the convex optimization into the pulse-Doppler radar, the problem of ultra-low sidelobe is converted into the problem of optimization. The key of this algorithm is to minimize the peak to sidelobe level (PSL) of the range sidelobes with a constraint of signal to noise ratio (SNR) loss. Then the ultra-low sidelobe filtering results are used to detect and resolve the space group targets in the main beam. Numerical and experimental results demonstrate the effectiveness of the proposed algorithm.

Keywords: Group targets · Ultra-low sidelobe · Convex optimization

1 Introduction

In modern war, formation flying is usually an important means of sudden attacks. In this case, the targets always appear in the form of groups (i.e., group targets) [1–4]. When the group targets are illuminated with the same radar beam, the group targets fall into the same beam of the radar. Different from single target, the returns of the group targets superpose with each other. Moreover, conventional pulse compression usually produced high range sidelobes, which may makes it difficult to detect all the group targets. Especially, the maiblobe of the weak one may be masked by the sidelobes [1, 4–6] of the strong one among the group targets, and miss alarm will occur. The sidelobes of the group targets interact with each other, which makes it difficult for group targets detecting and resolving.

To solve this problem, many techniques have been studied. The existing group targets detecting and resolving algorithms can be approximately grouped into two sorts: micro-Doppler (m-D) effect analysis and waveform design method. The m-D

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characteristics can be regarded as a unique signature of the target and provides additional information for target recognition applications [2–4]. To decrease the mutual interference between the group targets in adjacent range cell, low correlation peak sidelobe level (PSL) deign methods are considered. In [5], the simulated annealing algorithm is used in the polyphase code design. The linear programming method and the reiterative minimum mean-square error algorithm are discussed in [6] and [7], respectively.

In this paper, a group targets detecting and resolving approach using ultra-low sidelobe filtering is proposed. Based on the criterion that minimizes the PSL with a constraint of signal-to-noise ratio (SNR) loss with respect to the conventional matched filtering, the convex method is introduced in the pulse compression process to suppress the sidelobe level, which is quite helpful to decrease the interactions between the group targets. After that, different group targets can be easily detected and resolved from the ultra-low sidelobe filtering results. Numerical and experimental results verify the effectiveness of the proposed algorithm.

2 Signal Model

High range resolution can be achieved by the pulse compression technique, however, high sidelobes always occur. Windowing may be an effective tool to suppress the sidelobe, but it is at the expense of broading the mainbeam and SNR loss [1]. In this section, we will introduce an alternative approach to suppress the sidelobes.

Assuming that the transmitted signal sequence can be expressed as $\mathbf{x} = (x_0, x_1, \ldots, x_{N-1})^T$, where $(\cdot)^T$ denotes the transpose operator, N is the length of transmitted signal sequence.

The ultra-low sidelobe filter is given as $\mathbf{w} = (w_1, w_2, \ldots, w_M)^T$, where M is the length of the ultra-low sidelobe filter, and usually $M \geq N$. To simply the analysis, we usually add zeros to the beginning and end of the transmitted signal to make it extend to signal $\mathbf{s}$, then we can get the new signal $\mathbf{s}$ as

$$\mathbf{s} = (0, \ldots, 0, x_0, x_1, \ldots, x_{N-1}, 0, \ldots, 0,)^T \tag{1}$$

Let the signal $\mathbf{s}$ pass through the ultra-low sidelobe filter $\mathbf{w}$, then the output results can be expressed as

$$y_n = \sum_{i=k_1}^{k_2} w_i^* s_{n-i}, n = 0, 1, 2, \ldots, 2M - 2 \tag{2}$$

Where y_n denotes the filtered results, and $k_1 = \max(0, n - M + 1), k_2 = n - k_1$, $(\cdot)^*$ denotes conjugate operation.

To facilitate derivations, we define the a matrix S as

$$S = \begin{bmatrix} s_0 & \cdots & s_{M-2} & s_{M-1} & 0 & \cdots & 0 \\ 0 & \cdots & s_{M-3} & s_{M-2} & s_{M-1} & \cdots & 0 \\ 0 & \cdots & s_{M-4} & s_{M-3} & s_{M-2} & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & s_0 & s_1 & \cdots & s_{M-1} \end{bmatrix} \quad (3)$$

Then Eq. (2) can be rewritten in the following form:

$$\mathbf{y} = \mathbf{w}^H S = [y_1, y_2, \ldots, y_M, \ldots, y_{2M-1}] \quad (4)$$

When $\mathbf{w} = \mathbf{s}^*$, the ultra-low sidelobe filter becomes the classical matched filter. The matched filter is optimal to the peak response, but not optimal in terms of the sidelobe level. High sidelobe may deduce the mask phenomenon, where the mainlobe level of the weak targets may be blurred in the high sidelobe level of the strong ones among the group targets. In order to suppress the sidelobes to decrease the mutual interference among the group targets, ultra-low sidelobe filter is quite essential.

There are two famous criteria can be used to decrease the sidelobes, the peak to sidelobe ratio (PSLR) and the integrated sidelobe level (ISL). The first criteria to minimize the maximum value of the sidelobe while the second one to minimizing the integrated sidelobe level of filtered results. In the proposed algorithm, minimizing the PSL after the ultra-low sidelobe filtering is used to design the ultra-low sidelobe filter.

For the further analysis, the PSLR the of the signal $\mathbf{s}$ after the ultra-low sidelobe filtering can be defined as

$$PSL = -20 \log 10 \left(\max_{k \neq M}(|y_M|) \right) \quad (5)$$

Assume that the signal $\mathbf{s}$ is filtered by the ultra-low sidelobe filter, then the SNR_{loss} of the signal $\mathbf{s}$will occur compared with the matched filter. Then the SNR_{loss} is defined as the ratio between the SNR provided by the ultra-low sidelobe filter and the optimal SNR provided by the matched filter, which can be defined as

$$SNR_{loss} = 10 \log 10 \left(\frac{|\mathbf{w}^H \mathbf{s}|^2}{(\mathbf{w}^H \mathbf{w})(\mathbf{s}^H \mathbf{s})} \right) \quad (6)$$

In order to suppress the sidelobe, we can construct the following optimization

$$\begin{aligned} &\min_{w} \ \text{PSL} \\ &s.t. \, \mathbf{w}^H \mathbf{s} = \mathbf{s}^H \mathbf{s} \end{aligned} \quad (7)$$

It should be noticed that the constraint $\mathbf{w}^H \mathbf{s} = \mathbf{s}^H \mathbf{s}$ guarantees that the trivial solution $\mathbf{w} = 0$ will be discard

Based on the definition of PSL, Eq. (7) can be transformed as

$$\begin{gathered}\min_{w} \max|y|_i, i = 0, 1, 2, M-2, M, M+1, \ldots, 2M-2, i \neq M-1 \\ s.t.\ \mathbf{w}^H \mathbf{s} = \mathbf{s}^H \mathbf{s}\end{gathered} \tag{8}$$

If the constrained matrix T is defined as

$$T = \begin{bmatrix} s_0 & \cdots & s_{M-2} & 0 & \cdots & 0 \\ 0 & \cdots & s_{M-3} & s_{M-1} & \cdots & 0 \\ 0 & \cdots & s_{M-4} & s_{M-2} & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & s_1 & \cdots & s_{M-1} \end{bmatrix} \tag{9}$$

Then the ultra-low sidelobe problem can be further expressed as

$$\begin{gathered}\min_{w} \max\left|\mathbf{w}^H T\right|_\infty \\ s.t.\ \mathbf{w}^H \mathbf{s} = \mathbf{s}^H \mathbf{s}\end{gathered} \tag{10}$$

Where $|\cdot|_\infty$ denotes the infinity norm.

The above constrained infinity norm problem cannot be solved analytically. Many existing solutions consist of weight ISL method or L_p-norm optimization problem with p sufficiently large [6, 7].

In order to solve the constrained infinity norm problem, we convert Eq. (10) as follows

$$\begin{gathered}\min_{w}\ t \\ s.t.\ \mathbf{w}^H \mathbf{s} = \mathbf{s}^H \mathbf{s} \\ \max|\mathbf{w}^H T|_\infty \leq t\end{gathered} \tag{11}$$

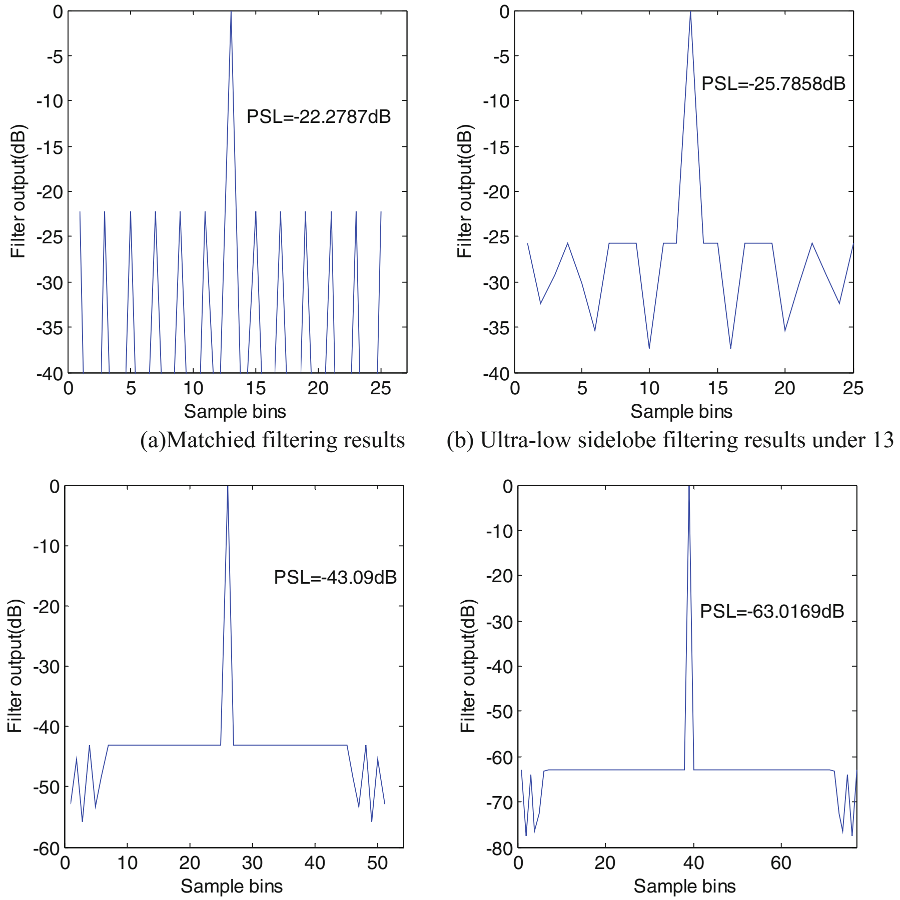
Obviously, Eq. (11) can be considered as a quadratically constrained quadratic program (QCQP). The QCQP problems can be solved with the interior point methods [8–10].

3 Numerical Results

In this section, we will present the first example to demonstrate the ultra-low sidelobe performance of the proposed algorithm. Baker code waveform is considered, and the ultra-low sidelobe filter length is 13, 39 and 65, respectively. Meanwhile, the single target velocity is set as 0 m/s and 10 m/s, respectively. In the simulation, the radar works in the S band.

3.1 Stationary Target Scenery

Figure 1 gives the compared results of matched filter and ultra-low sidelobe filter in the case of stationary target scenery.



(a)Matchied filtering results (b) Ultra-low sidelobe filtering results under 13

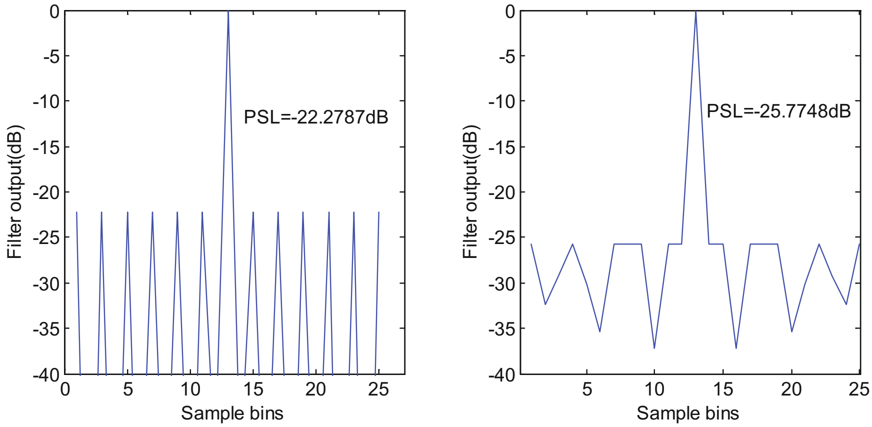
(c) Ultra-low sidelobe filtering results under 39 (d) Ultra-low sidelobe filtering results under 65

Fig. 1. Results of matched filter and ultra-low sidelobe filter for stationary target

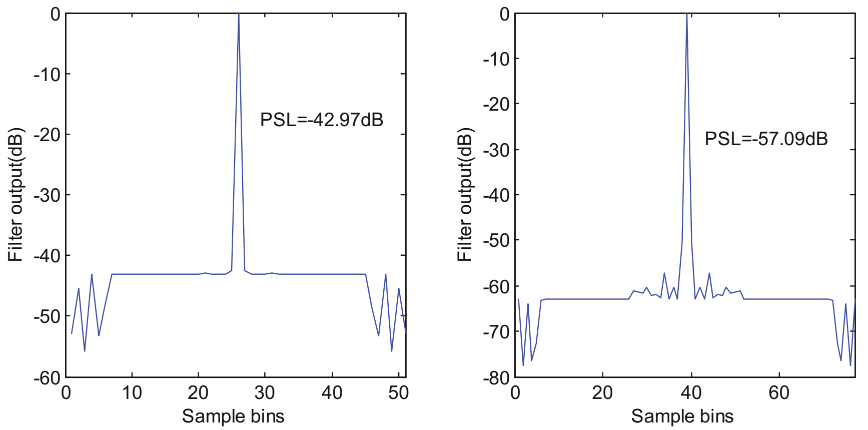
In Fig. 1, matched filter and ultra-low sidelobe filter with the length of 13, 39 and 65 is introduced. From Fig. 1, we can know that the PSL of the matched filter is −22 dB, while the ultra-low sidelobe filtering results are −25.79 dB, −43.09 dB and −63.02 dB, respectively. We can find that there is a substantial gain improvement in PSLR with the increase of the ultra-low sidelobe filter length.

3.2 Moving Target Scenery

For further analysis, the moving target scenery is considered. Assume that the velocity of the target is 10 m/s, and the sample frequency is 1 MHz, the simulation result is illustrated in Fig. 2.



(a)Matchied filtering results (b) Ultra-low sidelobe filtering results under 13



(c) Ultra-low sidelobe filtering results under 39 (d) Ultra-low sidelobe filtering results under 65

Fig. 2. Results of matched filter and ultra-low sidelobe filter for moving target

From Fig. 2, we can know that sidelobe level of the ultra-low sidelobe filtering results are −25.77 dB, −42.97 dB and −57.09 dB, respectively. And, an interesting phenomenon can be seen that the sidelobe level of the moving target is a little high than the case of stationary target, which may result from the Doppler effect of the moving target. Therefore, the Doppler compensation is necessary in the ultra-low sidelobe filtering algorithm. It will be further investigated in our future work.

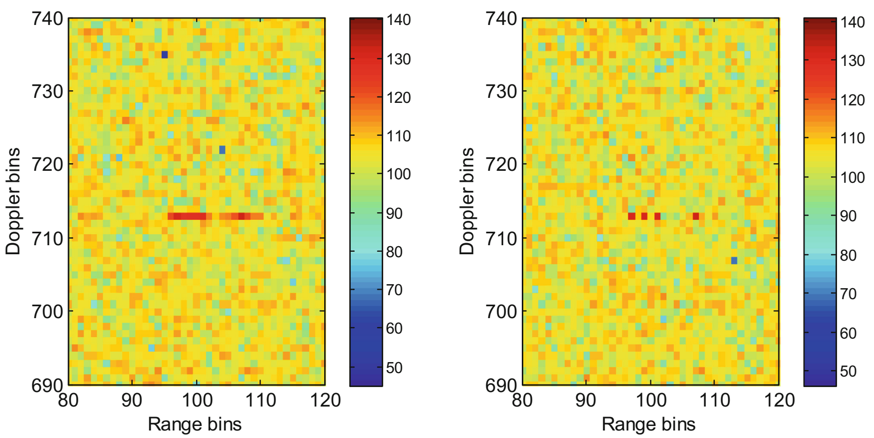
4 Experimental Results

To demonstrate the effectiveness of the proposed algorithm in the group targets scenery, in this section, experimental data collected from real radar is utilized to verify the proposed algorithm. Part of the radar system parameters are listed in Table 1.

Table 1. Parameters used in the experiments

Parameters	Value
Time width	50us
Band width	18 MHz
Platform velocity	8 m/s
Range gate number	512
Coherent pulses	1024
Scanning area	−45°–45°
Coherent pulses	1024
Pitching angle	5°

As is shown in Fig. 3, the targets to be studied can be classified as 2 cases. Case 1 is for the first three group targets (T1, T2 and T3) with the same beamwidth in the azimuth and range closed spaced cells. Case 2 is for the single target with the same beamwidth as the first group targets but different range cells. The SNR for both targets is about −19.5 dB, and the velocity is about 152 m/s. To better testify the improvement of the proposed algorithm, the conventional matched filtering algorithm in [1] is performed for comparison.

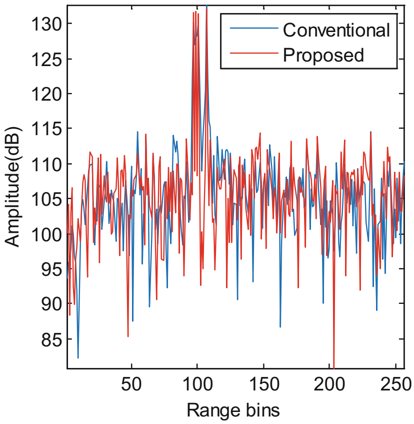


(a) Matchied filtering results (b) Ultra-low sidelobe filtering results

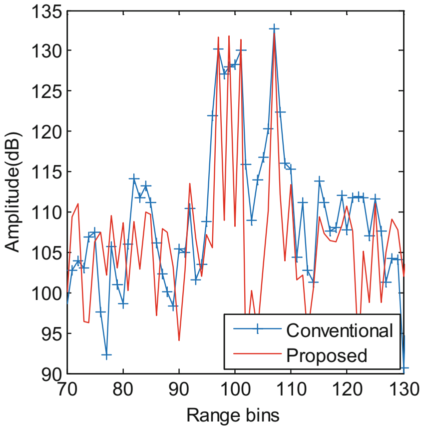
Fig. 3. Results of matched filter and ultra-low sidelobe filter in the RD domain

In the experiment, the length of ultra-low sidelobe filter is 5 times longer than transmitted signal sequence. The results with the conventional matched filtering algorithm and the proposed algorithm in the Range-Doppler (RD) domain are shown in Fig. 3.

From Fig. 3, we can find that conventional matched filtering results can hardly resolve and distinguish the first group targets, and all the targets in group 1 mutually interact with each other. In this case, false alarm will occur. However, the group targets in Fig. 3(b) can be well distinguished, and it is quite useful for further target detecting and resolving if CFAR detector is followed. To further illustrate the effectiveness of the proposed algorithm, the range profile at the 713 Doppler cell is shown is Fig. 4.



(a) Range profile comaprision of different methods



(b) Zoomed in results of the range profile

Fig. 4. Results of matched filter and ultra-low sidelobe filter in the range profile

From Fig. 4, it can be seen that the two groups can be resolved based on both the conventional method and the proposed one. The three group targets in group 1 can be well distinguished in the proposed algorithm, while the conventional method fails to distinguish them. Especially in Fig. 4(b), there are three obvious peaks, which are corresponding to the three targets in group 1. Based on the experimental results, the proposed ultra-low sidelobe filtering algorithm can be used to detect and resolve the group targets.

5 Conclusion

In this paper, a space group targets detecting and resolving algorithm using the ultra-low sidelobe filtering is proposed. Firstly, the problem of ultra-low sidelobe filtering is converted into the problem of convex optimization by exploiting the optimal PSL criteria, then the ultra-low sidelobe filtering results are used to detect and resolve the space group targets in the main beam. Since the ultra-low sidelobe filter can decrease the mutual interact between group targets, it is useful to distinguish space group targets. Numerical and experimental results demonstrate the effectiveness of the proposed algorithm.

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