**IEEE Access**
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received December 20, 2017, accepted January 23, 2018, date of publication January 30, 2018, date of current version February 28, 2018.

*Digital Object Identifier 10.1109/ACCESS.2018.2799180*

# A Side-Lobe Suppression Method Based on Coherence Factor for Terahertz Array Imaging

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This work was supported by the National Natural Science Foundation of China under Grant 61571011.

**ABSTRACT** Terahertz (THz) arrays can be used to improve the data acquisition speed considerably in real-time imaging applications. However, the THz array imaging usually suffers from the side-lobe artifacts, which leads to a severe decline in the image quality. In this paper, a side-lobe suppression method based on coherence factor is proposed to improve the image quality. The influences of signal-to-noise ratio on the imaging results are analyzed by simulation. Furthermore, the results based on the real-world data validate the effectiveness of the proposed method, which indicates that the side-lobe is suppressed by 29 dB. This paper can benefit the development of THz imaging technique and its applications in real-time imaging realms.

**INDEX TERMS** Coherence factor, side-lobe suppression, terahertz array imaging.

## I. INTRODUCTION

With the increasing threat of terrorism, the security inspection are becoming more and more important on high-security sites, including airports and railway stations. In the past few years, terahertz (THz) imaging has been developed for the security inspection applications due to its distinguished merits, e.g., high spatial resolution, penetration capability and safety characteristics [1]–[3]. Moreover, the array technique is applied to further improve the imaging resolution and the data acquisition speed for real-time imaging [4], [5]. In reality, the sparse array with large spacing between two elements is usually used in THz imaging systems, which can be implemented with low cost. However, the side-lobe and grating lobe artifacts usually arise in the THz sparse array imaging systems, which would severely degrade the image quality [6].

Over the years, many approaches, like window function [7] and array design [8], have been proposed to suppress the side-lobe and grating lobe artifacts in microwave radar imaging. In contrast, for THz radar imaging, the short wavelength, the nonlinear errors of signal and low signal-to-noise ratio (SNR) [2], [9], would lead to higher side-lobe level. Generally, the coherence factor (CF) [10] is defined as the ratio of the coherent power to the incoherent power for a known point in the obtained target image, which has been successfully used to suppress the grating-lobe artifacts of the sparse array for through-wall imaging radars [11], [12] and the THz impulse imaging system [6]. To improve the image quantity of the THz array system, the coherence factor which operates in the image domain, is applied for side-lobe suppression in this paper.

The rest of this paper is organized as follows. In section 2, the imaging method with side-lobe suppression is proposed for THz array imaging. In section 3, simulations are carried out to evaluate the performance of the proposed method. The values of peak side lobe ratio (PSLR) and integrated side lobe ratio (ISLR) are calculated for quantitative comparisons. Furthermore, the proposed side-lobe suppression method is also validated by real-world data obtained from a THz array system.

## II. THEORY

In this paper, the bistatic back-projection (BP) algorithm [13] is adopted, which provides the most direct solution for target reconstruction problem in the imaging scenario. Considering an array with $N_T$ transmitters and $N_R$ receivers, the intensity of a point located at the position $\mathbf{r}$ can be obtained by the coherent sum of echo signals after range compression, which can be given by

$$I(\mathbf{r}) = \sum_{i=1}^{N_T}\sum_{j=1}^{N_R} I_{ij}(\mathbf{r}) = \sum_{i=1}^{N_T}\sum_{j=1}^{N_R} s_{ij}(\|\mathbf{r}_i - \mathbf{r}\| + \|\mathbf{r}_j - \mathbf{r}\|) \quad (1)$$

where $s_{ij}$ is the range-compressed echo signals corresponding to the bistatic round-trip distance. $\mathbf{r}_i$ and $\mathbf{r}_j$ denote the position vector of the $i$th transmitter and the $j$th receiver, respectively. $\mathbf{r}$ represents the position vector of the desired point.

To suppress the side-lobe artifacts, an amplitude weighting coefficient, i.e. CF, is introduced to correct the target image. The spatial coherence of the time-delayed signals across the entire array is measured to calculate the CF. Thus, the CF at a specific image point $\mathbf{r}$ can be written as

$$\mathrm{CF}(\mathbf{r}) = \frac{\left|\sum_{i=1}^{N_T}\sum_{j=1}^{N_R} I_{ij}(\mathbf{r})\right|^2}{N_T N_R \sum_{i=1}^{N_T}\sum_{j=1}^{N_R} \left|I_{ij}(\mathbf{r})\right|^2} \quad (2)$$

As for the side lobes, the incoherent power is higher than the coherent power due to the incoherence of the data channels. The CF is usually smaller than 1. However, the incoherent power and the coherent power of the main lobe are almost the same, which results in a unity ratio. Thus, the imaging method using CF can be used to suppress the side-lobe artifacts, and the corrected image can be obtained as

$$I_{\mathrm{CF}}(\mathbf{r}) = \mathrm{CF}(\mathbf{r}) \cdot I(\mathbf{r}) \quad (3)$$

According to (2) and (3), we can conclude that the CF is an adaptive reconstruction method based on the echo data and no prior knowledge of the object is needed. The proposed imaging method with side-lobe suppression is illustrated in Figure 1.

## III. EXPERIMENTS AND ANALYSIS

The schematic of the THz array imaging system is depicted in Figure 2. The range resolution along the Y axis (line of sight) is achieved by transmitting linear frequency modulated signal at the center frequency of 332.8 GHz with 16 GHz bandwidth. The linear multiple-input-multiple-output (MIMO) array along the X axis is used to realize the cross-range resolution. The THz waves are transmitted from the transmitters sequentially, and the echoes from target are collected by receivers simultaneously. Moreover, a rotating reflector is used to implement the mechanical steering in the Y-Z plane, which provided the imaging resolution along the Z axis. The THz array system operates at a standoff range of about 2.3 meters with respect to the focal point.

The configuration of the linear MIMO array is shown in Figure 3, in which Tx and Rx stand for the transmitters and receivers, respectively. In particular, the MIMO array is consisted of 4 transmitters and 16 receivers with an aperture size of 136 mm. The spacing between two transmitting elements is 4 mm, and the spacing between two receiving elements is 8 mm, which indicates that the element spacing is much larger than the signal wavelength (approximately 0.9 mm). Thus, the side-lobe artifacts will occur and severely degrade the image quality, which should be suppressed.

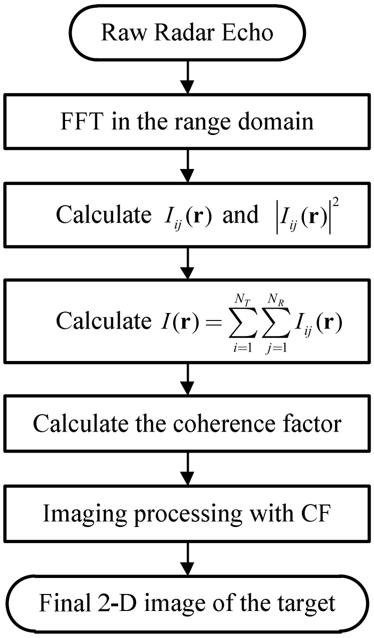


**FIGURE 1.** The proposed imaging procedure with side-lobe suppression.

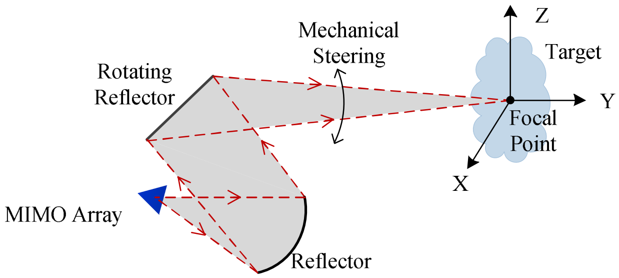


**FIGURE 2.** The schematic of the THz array imaging system.

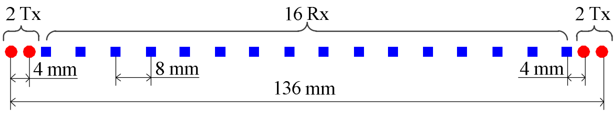


**FIGURE 3.** The configuration of the linear MIMO array.

### A. SIMULATION RESULTS

To evaluate the performance of the proposed method in THz array imaging, the simulation is conducted, based on the aforementioned system schematic and parameters. Firstly, the imaging simulation is carried out without noise contribution. Based on the proposed imaging algorithm in section 2, the imaging results before and after side-lobe suppression are shown in Figure 4. It can be seen from Figure 4 that the side-lobes of the imaging result are greatly suppressed by the processing with CF. Specifically, the PSLR and ISLR values of the imaging result before side-lobe suppression are −12.57 dB and −9.08 dB, respectively. In contrast, the PSLR

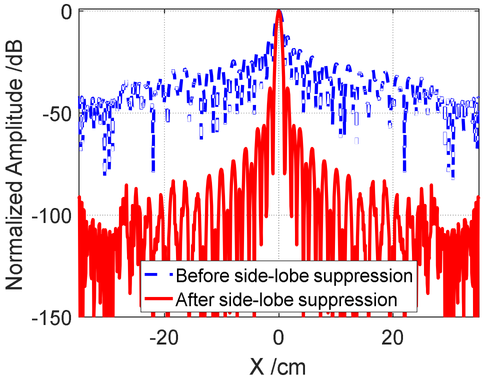
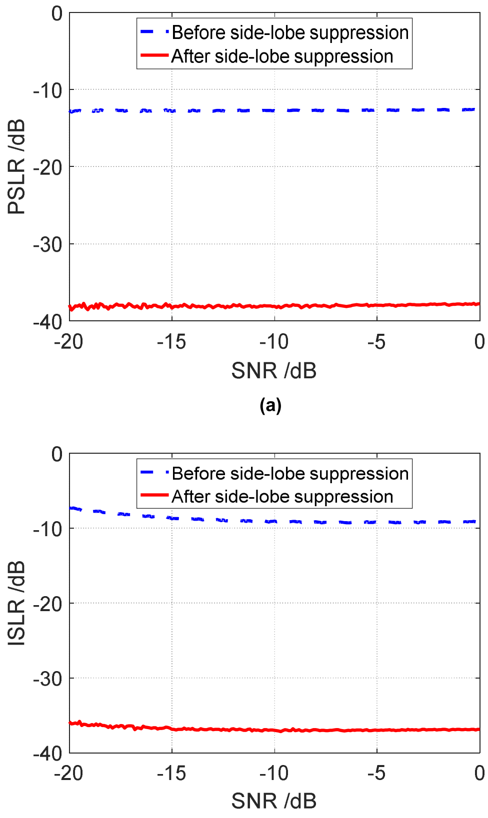


**FIGURE 4.** The simulation imaging results in the X direction (without noise).



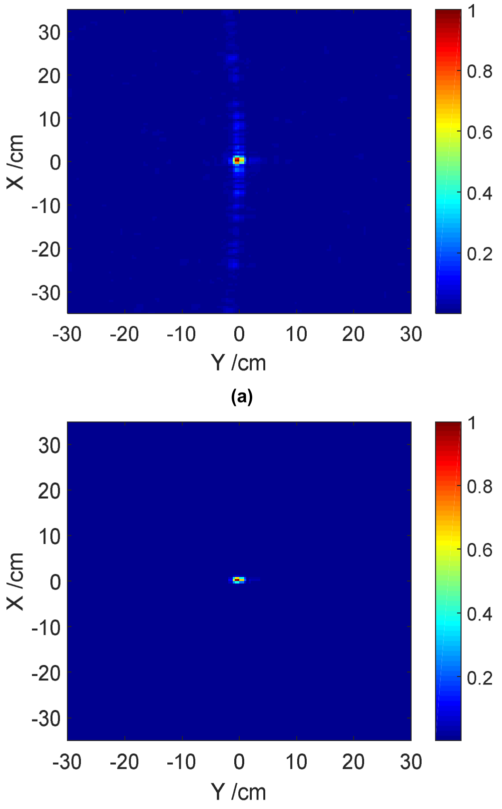
(a)

(b)

**FIGURE 5.** The values of PSLR and ISLR as a function of SNR. (a) PSLR. (b) ISLR.

and ISLR values of the imaging result after side-lobe suppression are −37.7 dB and −36.83 dB, respectively.

Secondly, the quantitative analysis is carried out to further show the good performance of the side-lobe suppression method. The values of PSLR and ISLR of the imaging results in the X direction are calculated with different SNR. In the simulation, 200 Monte Carlo trials are conducted. The PSLR and ISLR curves as a function of the SNR before and after side-lobe suppression are shown in Figure 5. In Figure 5(a), the mean value of PSLR is approximately suppressed by 25 dB, and the mean value of ISLR in Figure 5(b) decreases from −9 dB to −37 dB.



(a)

(b)

**FIGURE 6.** The imaging results on the X-Y plane. (a) Before side-lobe suppression. (b) After side-lobe suppression using the proposed method.

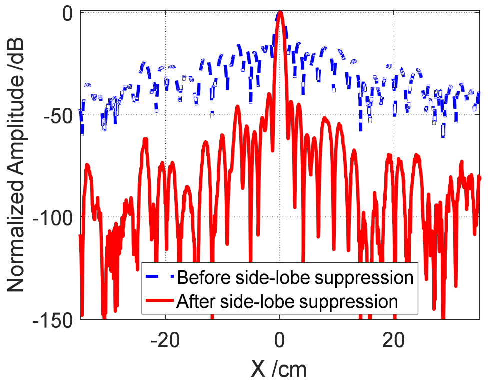


**FIGURE 7.** The imaging results in the X direction.

### *B. IMAGING RESULTS BASED ON REAL-WORLD DATA*

To further show the effectiveness of the proposed method in the THz array imaging, the imaging results based on the real-world data are provided. The echo of a vertically placed metal stick is received by the imaging prototype system described in Figure 2.

The two-dimensional target image on the X-Y plane is reconstructed using the bistatic BP algorithm, shown in Figure 6(a). It can be seen from Figure 6(a) that the side-lobe

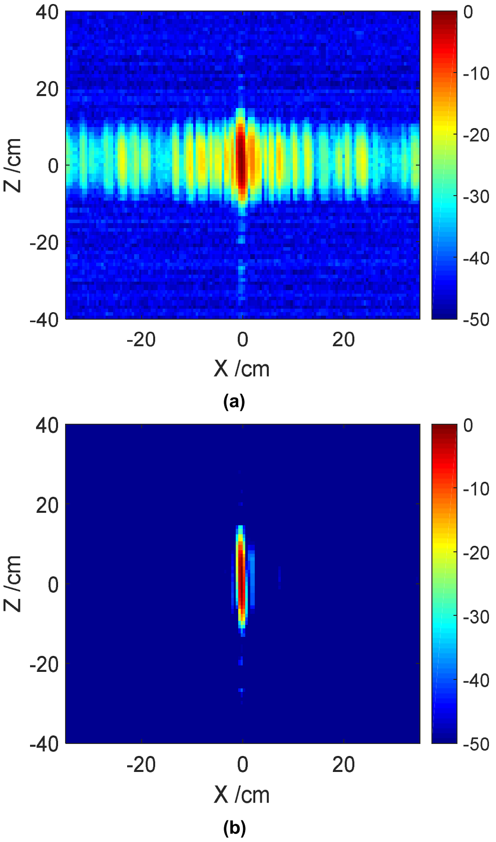


**FIGURE 8.** **The imaging results of the metal stick on the X-Z plane. (a) Before side-lobe suppression. (b) After side-lobe suppression.**

artifacts occur and the image quality is severely degraded in the cross-range dimension. To suppress the side-lobes, the imaging processing with CF proposed in section 2 is applied and the imaging result is shown in Figure 6(b). Results indicate that the target image is well focused and almost has no side lobes in the X direction, i.e., the cross-range dimension. The one-dimensional imaging result in the X direction is displayed in Figure 7, which provides a more quantitative analysis of the side-lobe suppression. The imaging results in the X direction before and after side-lobe suppression are both depicted and the corresponding PSLR values of the two images are −14.49 dB and −43.53dB, respectively. Thus, the side lobe is suppressed by 29 dB. Furthermore, the imaging result of a metal stick on the X-Z plane is shown in Figure 8, which indicates that the image quality has been improved significantly.

## IV. CONCLUSION

In summary, an effective side-lobe suppression method based on the CF has been proposed for THz array imaging, in this paper. The proposed imaging method can adaptively reconstruct the object based on the echo data, and no prior knowledge of the object was needed. Simulation results with different SNR indicated the good performance of the proposed side-lobe suppression method. A practical application processing the real-world data was provided. Experimental results demonstrated that the side-lobe can be suppressed by 29 dB, which can significantly improve the image quality in the azimuth direction. Further improvement on the efficiency of imaging processing will be made to broaden its applications in the real-time scenario.

## V. ACKNOWLEDGMENT

The authors would like to thank the Microsystem and Terahertz Research Center in China Academy of Engineering Physics (CAEP) for providing the prototype system and sharing the experimental data.

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