A 3-D SAR Imaging Method Based on Back Projection Algorithm

Qian Han, Pengbo Wang*, Xinkai Zhou, Xinchang Hu, Yanan Guo
School of Beihang University, Beijing, China

*Corresponding author e-mail: hanqian@buaa.edu.cn

Abstract. 3D back projection (BP) algorithm is an imaging algorithm based on time domain echo data, which effectively solves the overlapping mask problem existing in 2D SAR. It can complete the imaging processing of echo signal under any geometry configuration, and has the advantages of high target focusing accuracy and high phase preservation. However, the high complexity and low efficiency of 3D BP imaging algorithm limit its application and development. In this paper, a 3d imaging method based on improved back projection algorithm is proposed. Aiming at the problem that existing imaging algorithms need 2D imaging first and then 3D imaging, an improved 3D BP algorithm is proposed to directly 3D imaging, which avoids 2d imaging processing. The proposed method simplifies the steps of the traditional 3D BP algorithm and improves the efficiency of the algorithm. The validity and effectiveness of the proposed method are verified by the 3d imaging results of simulated lattice targets.

1. Introduction
The concept of synthetic aperture radar (SAR) was first proposed in 1951. SAR is an all-day and all-weather microwave imaging radar with strong penetration and independent of light source [1]. Therefore, SAR has been widely used in national economy and national defense construction. Traditional 2D SAR can only imaging in range direction and azimuth direction. Therefore, it can only reflect part of the information of the scene, and one dimension of information will be lost. While interferometry can only provide surface elevation information, 3D imaging can provide richer and more comprehensive information. The 3D SAR imaging technology can meet the current requirements for multi-dimensional and high-precision radar imaging, and can obtain more comprehensive ground scene information.

Multi-baseline tomography SAR imaging is an emerging technology which applies computer-aided Tomography (CAT) to SAR imaging. Research on it began in the mid-1990s and has attracted many research institutions at home and abroad, including German Aerospace Center, Xidian University, Beihang University, etc. It shows the research interest. Compared with other 3D SAR imaging methods, Multi-baseline Tomographic SAR has the advantages of simple implementation, small computation and no need to change the existing imaging system and imaging algorithm. It has a wide application prospect in target classification and recognition, vegetation cover measurement, urban area reconnaissance and other aspects, and has a high research value.

Back Projection (BP) is a common 3D SAR imaging algorithm. Compared with the 3d imaging algorithm based on Tomographic FFT algorithm, it has the advantage of independent baseline interval, and can achieve high precision 3D imaging under non-uniform navigation. However, the traditional BP
algorithm needs to generate some two-dimensional images first and then imaging on the height dimension. This results in high implementation complexity and low imaging efficiency. Therefore, it is of great significance to improve 3D BP imaging algorithm. To solve this problem, some relevant algorithms have been proposed, such as Locality Back Projection (LBP) algorithm [2], Fast Back Projection (FBP) algorithm for polar subaperture processing [3] and Fast Factorized back-projection (FFBP) algorithm based on factorization [4].

To sum up, the high complexity and low efficiency of the traditional 3D BP algorithm seriously limit its development. Therefore, this paper proposes a method of BP imaging processing directly from 3D, which optimizes the algorithm complexity and improves the efficiency.

2. Space geometry configuration and principle analysis of 3D BP algorithm

2.1. Space geometry configuration

The structure of the multi-baseline SAR echo model is shown in Figure 1. First of all, it can be analyzed from the figure that if only one radar platform obtains echo signals, that is, for the traditional single-channel SAR imaging system, only 2d images with high resolution in range and azimuth directions can be obtained, while SAR images are essentially the result of target scattering distribution projected on 2d plane in 3D space. The value of each pixel unit is the sum of the scattering coefficients of all scatterers located at the same distance but at different heights. Point A and point P in the figure will fall in the same distance gate. Therefore, overlapping mask phenomenon exists in two-dimensional SAR images.

In addition, when the radar shines on the target with a certain height, there will be problems such as top-bottom inversion and shadow. These problems make the traditional 2D SAR images unable to meet the requirements of practical application, which requires that the SAR platform can not only obtain the target range and azimuth information, but also to obtain the target height distribution, so as to achieve the three-dimensional reconstruction of the scene area.

![Figure 1. Geometric structure diagram of multi-baseline SAR imaging.](image)

2.2. Analysis of algorithm Principle

Back-projection algorithm (BP) is an imaging algorithm based on time domain echo data, which can complete the imaging of echo data signals in any geometry configuration [5]. At the same time, it has the advantages of high target focusing precision and high phase preservation. Its basic idea is to calculate the time delay of the platform relative to the reference point according to the distance between the grid points and the flight platform in the imaging region, and then find the corresponding echo data in the time domain, and coherent accumulation to get the imaging results. In this paper, the traditional BP algorithm is improved, and imaging is directly performed from three dimensions. Compared with the traditional method of first generating some two-dimensional images and then performing three-dimensional reconstruction based on the two-dimensional images, the complexity of the algorithm is reduced.

The following figure is the flow chart of BP algorithm imaging:
Echo preprocessing and imaging region meshing

Start looping in height

Calculate The delay $\tau$ relative to the nearest distance reference point

Calculate the corresponding echo value and perform coherent superposition

Is all height are traversed

yes

next height

no

Is all pixels are traversed

yes

Complete the imaging

Figure 2. Flow chart of 3D BP imaging algorithm.

The main steps of the algorithm proposed in this paper are as follows:

Step 1: Range compression

First of all, the range echo signal is processed by matched filtering technology. Here, the frequency domain compression method is used, and the matched filter is:

$$H(f) = \exp\left(j \pi f^2 / K_p \right)$$ (1)

The signal after distance matching filtering can be expressed as:

$$s_{rc}(\tau, \eta) = p_r(\tau - t_d) \cdot \exp\{-j 2\pi f_0 t_d\}$$ (2)

Where $p_r(\tau)$ is the sinc function.

Step 2: Calculation of echo delay of scenic spots

The delay of echo from each observation point arriving at the array element in the observation scene can be expressed as:

$$\tau(n; P_a) = \frac{2R(P_c, P_a)}{c}$$ (3)

where $n$ represents the $N$th element in the array antenna, $R(P_c, P_a)$ represents the Euclidean distance between the phase center point and the scene target point, and $c$ represents the speed of light.

Step 3: Interpolate the distance direction data

The sinc function is used to interpolate and resample the echo after distance compression.

Step 4: Use a compensation factor to compensate for the remaining phase (phase correction)

The compensation factor can be calculated by $R(P_c, P_a)$ in Formula (3):

$$h(n; P_a) = \exp\left(j 4\pi R(P_c, P_a) / \lambda \right)$$ (4)
Step 5: Coherent accumulation
For each pixel element, the array element uses sinc function to interpolation and resampling, and compensates the Doppler phase, and carries out coherent accumulation of echo amplitude value, then we obtain the echo amplitude value of the target point:

$$\sigma = \sum_{n=1}^{N} A(n; P_a)$$  \hspace{1cm} (5)

Step 6: Image the entire scene space
Repeat the above steps for each pixel to obtain the final result of 3D imaging.

3. Simulation imaging results
The system parameters used in the simulation experiment are shown in Table 1:

| parameters                  | value  |
|-----------------------------|--------|
| signal bandwidth (MHz)      | 43.3   |
| pulse width (s)             | 0.000002 |
| signal sampling rate (MHz)  | 86.6   |
| number of flights $N$       | 75     |
| pulse repetition frequency (Hz) | 100     |
| carrier frequency (GHz)     | 2      |
| wavelength (m)              | 0.15   |
| radar height (m)            | 1732   |
| radar speed (m/s)           | 200    |

Figure 3(a) shows the original spatial relationship diagram of the point targets in the simulation scene. It can be seen from the figure that there are 27 point targets in the simulation scene. The height is divided into 3 layers, and the distance between adjacent points is 50m. The baseline distribution is uniform and meets the maximum unambiguous height, the baseline interval is set to 1m, and the number of radar passes is 75.

Figure 3(b,c) shows the result of imaging with 3D BP and the result of tomography imaging with FFT. It can be seen from the figure that both algorithms can clearly present 27 point targets, and the geometric relationship is not distorted, but the imaging results based on the 3D BP algorithm are clearer and the reconstruction effect is better. Figure 4 shows the profile of the 3D BP imaging results in the distance, azimuth, and height directions, as well as the profile in the height direction. It can be seen from the figure that the signal has been successfully compressed in all three dimensions.

To quantify the focusing performance, the point target analysis results in the height direction are listed in Table 2. Here we select the center point and other three edge points for measurement. The ideal PSLR and the integrated sidelobe ratio (ISLR) are 13.26 dB and 9.68 dB, respectively. According to Table 2, it can be seen that the values of PSLR and ISLR in height directions are within the error range. All these indicate that the corresponding algorithm can meet the imaging requirement of the SAR effectively.

| PSR(dB) | ISLR(dB) |
|---------|----------|
| 1       | 13.29    | 9.38    |
| 2       | 13.29    | 9.38    |
| 3       | 13.10    | 9.66    |
| 4       | 13.11    | 9.88    |
4. Conclusion
The 3D back projection (BP) algorithm is an algorithm for imaging processing based on time-domain echo data, which effectively solves the overlap problem of two-dimensional SAR, and has the imaging advantages of high target focusing accuracy and high phase preservation. However, the high complexity and low efficiency of the 3D BP imaging algorithm severely limits the application and development of 3D BP imaging. Therefore, this paper proposes an improved 3D back projection imaging method. The algorithm directly performs imaging from a three-dimensional perspective. Finally, a simulation verification is carried out, and the result shows the correctness and effectiveness of the method proposed in this paper.
References
[1] L. G. Cumming. Digital Processing of Synthetic Aperture Radar Data: Algorithms and Implementation [M]. Norwood: Artech House, 2005.
[2] Mccorkle J W. Focusing of synthetic aperture ultra wideband data [A]. IEEE International Conference on Systems Engineering [C]. Dayton, OH, USA: IEEE, 1991. 1-5.
[3] Yegulalp A F. Fast backprojection algorithm for synthetic aperture radar [A]. Radar Conference, 1999. The Record of the 1999 IEEE [C]. Waltham, MA, USA: IEEE, 1999. 60-65.
[4] Ulander L M H, Hellsten H, Stenstrom G. Synthetic-aperture radar processing using fast factorized back-projection [J]. IEEE Transactions on Aerospace and Electronic Systems, 2003, 39(3): 760-776.
[5] Xingyue Zhang. Research on 3D Imaging Algorithm of Multi-Baseline Tomography SAR [D]. University of Electronic Science and Technology of China, 2020.