A Fast Imaging Algorithm for Near Field SAR

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Abstract: Millimeter-wave synthetic aperture radar which is a well developed technique for producing high resolution images, because of its large amount of data, generally requires a relatively expensive and complex server to perform calculations in order to reduce time, and therefore the system costs is very high. In this paper, based on the traditional range migration algorithm, a new millimeter-wave SAR fast imaging algorithm is given. This algorithm proposes to intercept the echo data according to the characteristics of the target, so as to improve the operation efficiency on the origin, greatly reduce the operation time and cost. At the same time, the principle and algorithm flow of the method are given in combination with mathematical derivation. Finally, the feasibility and effectiveness of the technology are verified through experiments and the results show that the imaging time of the improved algorithm is shortened several times under the same data quantity and hardware and software condition.

Keywords: data interception; synthetic aperture radar; range migration algorithm; fast imaging.

1. Introduction

In recent years, the development of SAR imaging has become increasingly mature, and there are various algorithms, such as Range-Doppler algorithm\cite{1}, Chirp-Scaling algorithm\cite{2}, Range Migration algorithm\cite{3}. The Paper [4][5] compare the imaging performance of the algorithms mentioned above, the results show that the Range Migration algorithm under the condition of near field is the most accurate, because in the near field case, Fresnel plane-wave assumption is no longer set up, and the Range Doppler algorithm and Chirp Scaling algorithm is only partially compensated bend, so the imaging results cannot be fully focused, eventually even fuzzy and defocusing. The algorithm in this paper mainly aims at compensating the distance bending completely
under the condition of near field and improving the Range Migration algorithm which can make the imaging speed faster by using FFT. The echo data in SAR imaging process is often very large. In addition, most redundant information is often found in echo data. In terms of data processing, compressive sensing proposes to use part of the data to obtain images that are not too different from the original image. However, the compressed sensing usually takes a long time in the process of reconstruction. If a large number of echo data want to be fast, on the one hand, it can be considered to improve the hardware conditions, but the system cost will increase correspondingly, on the other hand, it is to make improvements in the algorithm. On the basis of the traditional distance migration algorithm, this paper proposed to complete the interception of echo data by considering the distance range of the target, greatly reduce the amount of imaging data, reduce the operation time, and fundamentally improve the efficiency of imaging.

2. Principle

We can take the planar 3D scanning imaging of traditional synthetic aperture imaging as an example. Planar scanning imaging refers to scanning a two-dimensional plane of the target at a time, and then performing data analysis and imaging to obtain the reflectivity image of the target scene. In addition, in order to reduce the cost to a certain extent, linear array antenna is generally adopted in hardware to form the plane aperture of the antenna through the combination of electrical scanning and mechanical scanning, so as to obtain echo data representing the target information. The geometric model of imaging is shown in figure 1. The transmitted signal is a linear frequency modulation signal, the plane \((x'; z')\) parallel to plane \((x, z)\), The vertical radial distance between the two planes is \(R_0\), we can define the X-axis direction as the azimuth dimension, the Y-axis is the range dimension, and the Z-axis is the height dimension.

Assuming that \((x, y, z)\) is the position of any point on the target. Its reflectivity is \(\sigma(x, y, z)\), Without considering the propagation loss of free space and antenna mode, the measured backscattering data \(s(x, k_z, z_w)\) can be expressed as:

\[
s(x, k_z, z_w) = \sigma(x, y, z) \cdot e^{i\omega R} \cdot e^{-j\omega R} \tag{1}
\]

where \(R\) is the range between the antenna to the point scatterer \((x, y, z)\):

\[
R = \sqrt{(x - x_e)^2 + (y + R_e)^2 + (z - z_w)^2}
\]

\(R_0\) is the reference distance between the target and the antenna array plane. The total wave number \(k_z = 2k = 4\pi f / c\), \(\omega\) is the instantaneous angular velocity, \(c\) is the propagation speed of electromagnetic wave in free space.
Figure 1 The geometric model of millimeter wave plane scanning imaging

Since the distance dimension is sampled in the frequency domain, only the Fourier transform of the other dimension and the height dimension is used to obtain the representation of echo data in the wavenumber-number domain:

\[ S(k_x, k_y, k_z) = \sigma(x, y, z) \cdot e^{j\beta R_0} \cdot E(k_x, k_y) \]  \hspace{1cm} (3)

Where \( E(k_x, k_y) \) represents the two-dimensional Fourier transform processing of phase history in azimuth and height dimensions.

\[ E(k_x, k_y) = \iint e^{j \beta R_0} \cdot e^{-j k_x x - j k_y y} \, dx \, dz \]  \hspace{1cm} (4)

We can use the stationary phase theorem[8] to solve the integral, and the final arrangement can obtain the expression of echo data in the wavenumber field as follows:

\[ S(k_x, k_y, k_z) = \sigma(x, y, z) \cdot e^{-j \left( k_x^2 R_0^2 + k_y^2 R_0^2 - k_0^2 \right)} \cdot e^{j \beta x} \cdot e^{-j \beta y} \cdot e^{-j \beta z} \]  \hspace{1cm} (5)

The function of the target image can be obtained by moving the term in equation (5) to the left side of the equation:

\[ \sigma(x, y, z) = S(k_x, k_y, k_z) \cdot e^{j \left( k_x^2 R_0^2 + k_y^2 R_0^2 - k_0^2 \right)} \cdot e^{j \beta x} \cdot e^{-j \beta y} \cdot e^{-j \beta z} \]  \hspace{1cm} (6)

The conjugate expressions of partial functions of matched filtering are obtained from the first term in formula (6). At the same time, the nonlinear operation in the second term shows that the echo data is not uniformly distributed in the y direction. However, the Fourier transform or inverse Fourier transform requires that the echo data must be uniformly distributed, so STOLT interpolation is required before the three-dimensional inverse Fourier transform \( \sqrt{k_x^2 + k_y^2 + k_z^2} \) to interpolate the data into uniform data and represent it as \( k_y \). Three sets of linear relations \( k_x - x \), \( k_y - y \), \( k_z - z \) can be obtained and they are Fourier transform pairs of each other. Finally, the target image reconstruction can be completed by three-dimensional inverse Fourier transform.
Frequency domain sampling echo data

Azimuth and height FFT

Matched filtering

Stolt interpolation $k_r \rightarrow k_y$

$3D \text{ IFFT}$

Target image $(x, y, z)$

**Figure 2** Range migration algorithm three-dimensional imaging flow chart

To sum up, the flowchart of Range migration algorithm three-dimensional imaging is shown in figure 2. Since SAR imaging is antenna movement and the target remains stationary to obtain the imaging mechanism of relative motion, what is really needed in echo data is the echo data near the reference distance $R_0$, and the rest is unnecessary redundant information such as noise. Therefore, the improved fast imaging algorithm proposed in this paper proposes to complete data interception of the target before two-dimensional Fourier transform to reduce the data volume. The flowchart of the improved part is shown in figure 3.

Because we're sampling the range dimension data in the frequency domain. Therefore, the echo data is firstly processed into the time domain by IFFT, and then converted into the frequency domain for processing after interception. If the echo data is sampled in the time domain, the operation of Fourier transform is not required. A certain distance range can be directly selected according to the location of the target at $R_0$ to intercept the target data within the range. This method can fundamentally solve the problem of
the amount of data, and then directly improve the speed of imaging, the following is through the computer simulation verifies the validity of the improved fast imaging algorithm.

3. The experimental results
In this imaging experiment, the human body was taken as the test target, and the positive and negative images of the human body were completed at the same time. The experimental parameters in table 1 were used to reconstruct the image of the target according to the principles and steps in the previous section. The software and hardware platform models and parameters of imaging processing are shown in table2.

Table1 The experimental parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
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<tbody>
<tr>
<td>Center frequency</td>
<td>35GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>5GHz</td>
</tr>
<tr>
<td>Frequency sampling number</td>
<td>219</td>
</tr>
<tr>
<td>Azimuth dimension sampling points</td>
<td>127</td>
</tr>
<tr>
<td>High dimensional sampling points</td>
<td>350</td>
</tr>
<tr>
<td>Sampling interval</td>
<td>0.005m</td>
</tr>
</tbody>
</table>

Table2 Hardware and software platform model and parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Mode &amp; Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Software</td>
<td>MATLAB 2017b</td>
</tr>
<tr>
<td>Memory</td>
<td>8GB</td>
</tr>
<tr>
<td>Processor</td>
<td>Intel(R) Core(TM) i7-7820X</td>
</tr>
<tr>
<td>CPU</td>
<td>8核 @3.60 GHz 3.60 GHz</td>
</tr>
</tbody>
</table>

The imaging results of the traditional RMA algorithm and the improved algorithm are respectively shown in Figure. 4 and Figure. 5.

![Figure 4 The traditional RMA algorithm for front and back images of human body](image.png)
Figure 5 The improved algorithm for front and back imaging of human body

It can be seen from the comparison between figure 4 and figure 5 that the improved algorithm is basically consistent with the traditional RMA algorithm in terms of imaging effect. The improved RMA algorithm can also obtain high-quality imaging results, which verifies the feasibility of the algorithm.

In terms of imaging time, the average imaging time processed by traditional RMA algorithm is about 6.365 seconds. However, the average imaging time processed by the improved algorithm after data interception on the same hardware and software platform is about 2.273 seconds, which is only one third of that of the traditional RMA algorithm and several times shorter. This proves the effectiveness of the fast imaging algorithm proposed in this paper.

4. Conclusion

In this paper, a fast synthetic aperture imaging algorithm based on the traditional RMA algorithm is improved by fundamentally reducing the amount of data, and the simulation of human body as a test target is carried out, finally proving the feasibility and effectiveness of the improved algorithm.

References


