MIMO imaging algorithm for single-frequency data processing based on bi-static range migration

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Abstract —A bi-static range migration algorithm for 2-D multiple input multiple output imaging for single-frequency data processing is investigated in this paper. On the basis of considering the near field electromagnetic wave attenuation, the imaging algorithm formulae are deduced in detail by applying the Method of Stationary Phase strictly which leads to a key filter factor for 2-D single-frequency imaging algorithm as a consequence. Image can be focused or not depends on a Phase item of the filter factor while it is influenced by amplitude item slightly which can be ignored under certain conditions. In order to verify the performance of the algorithm, a simple 2-D sparse array is designed for the imaging experiments in a complex electromagnetic environment. The focusing results are excellent which shows that the MIMO imaging algorithm discussed in this paper can be used for short-range, high-resolution and real-time imaging system.

Keywords—Range Migration Algorithm, Filter Factor, Real-time Imaging, Multiple Input Multiple Output Array.

I. INTRODUCTION

Design of imaging algorithm is a key point for the MIMO radar imaging technology. Hardware cost is able to be reduced and side-lobes can be inhibited to improve the quality of imaging results with a reasonable algorithm design. Wang Huajun[2] put forward a MIMO radar imaging method based on spatial spectral-domain filling to achieve a high imaging resolution of targets in the air. A 3-D imaging method for L-type MIMO radar based on sparse array was proposed by Gu Fufei[3] to reduce the number of antenna elements when imaging for moving target with single snapshot. Charvat[4-6] did research on a one dimension MIMO array imaging technology at S wide band. He designed an array about 2.24m long and composed of 21 antennas, which can be used for through-wall imaging with frequency modulation continuous wave. An equivalent error is introduced by adopting bi-static radar theory which will influence on the imaging quality. In order to solve the above problem, Xidong Zhuge and Alexander G.Yarovy[7-10] put forward a 3-D MIMO imaging algorithm based on Range Migration. According to the modified imaging algorithm, a sparse MIMO array with 12 transmitting antennas and receiving antennas. The 3-D imaging time with sweep frequency data is about two minutes which is far from real-time imaging. A bi-static range migration algorithm for 2-D MIMO imaging for single-frequency data processing will be researched in this paper to further reduce time for real-time radar imaging.

II. IMAGING ALGORITHM FORMULATION

As is shown in figure 1, the transmitting location is \((x_{tx}, y_{tx})\) and the receiving location is \((x_{rx}, y_{rx})\) while the location of an ideal scattering point for imaging is \((x, y)\). The distance between the point and the array plane is \(R_0\). The imaging function of the point is \(f(x, y)\).

![Fig.1. The principle of MIMO imaging algorithm](image)

The receiving signal is represented by equation (1) considering the spreading losses of electromagnetic wave transmitted for \((x_{tx}, y_{tx})\) after scattering.

\[
s(x_{tx}, x_{rx}, y_{tx}, y_{rx}) = \frac{1}{4\pi R_{tx} R_{rx}} \cdot f(x, y) \cdot e^{-\frac{jkR_{tx}}{c}} \cdot e^{-\frac{jkR_{rx}}{c}}
\]

where \(k = \frac{\omega}{c}\) represents the frequency-wavenumber that is directly related with the angular frequency \(\omega\), and \(c\) denotes the speed of propagation. \(R_{tx}\) and \(R_{rx}\) are the distances from the transmitter and receiver to the target, respectively, and

\[
R_{tx} = \sqrt{(x_{tx} - x)^2 + (y_{tx} - y)^2}
\]

\[
R_{rx} = \sqrt{(x_{rx} - x)^2 + (y_{rx} - y)^2}
\]

From (1), we transform the signal into the spatial Fourier domain over the four spatial dimensions for the transmitting and receiving apertures, respectively, as follows,
\begin{equation}
S(k_x, k_y, k_{x_R}, k_{Y_R}) = \frac{1}{4\pi} f(x, y) \cdot e^{-j(k_x x + k_y y)}
\end{equation}

\begin{equation}
S_S(k_x, k_y, k_{x_R}, k_{Y_R}) = \int \frac{1}{\sqrt{(x-x_0)^2 + R_0^2 + (y-y_0)^2}} e^{-j(k_x x + k_y y)} dx dy
\end{equation}

\begin{equation}
S_R(k_x, k_y) = \int \frac{1}{\sqrt{(x-x_0)^2 + R_0^2 + (y-y_0)^2}} e^{-j(k_x x + k_y y)} dx dy
\end{equation}

By applying the Method of Stationary Phase (MSP), the evaluation of the Fourier transforms (4) results in the following expression,

\begin{equation}
S_S(k_x, k_y, k_{x_R}, k_{Y_R}) = \frac{1}{4\pi} f(x, y) \cdot e^{-j(k_x x + k_y y)}
\end{equation}

And (5) results expressing in a similar way,

\begin{equation}
S_R(k_x, k_y) = \frac{1}{4\pi} f(x, y) \cdot e^{-j(k_x x + k_y y)}
\end{equation}

By utilizing the expressions in (6) and (7), the expression (3) can be formulated as

\begin{equation}
b(k_x, k_y) = \frac{1}{4\pi} f(x, y) \cdot e^{-j(k_x x + k_y y)}
\end{equation}

Where \( FFT^{-1} \) indicates 2-D inverse Fourier transformation, the filter factor is defined in the following:

\begin{equation}
\text{filter factor} = \frac{k_x R_0^1}{\pi \left[ \frac{k_x^2 - k_{x_R}^2 - k_{y_R}^2}{k_x^2 - k_{x_R}^2 - k_{y_R}^2} \right]^{\frac{1}{2}}}
\end{equation}

In (15), the filter factor is composed of two items, the first which is called amplitude filtering factor which influences on the amplitude of focus image while the second item is a key point which determines whether the image can be focused. The effect on MIMO imaging at single frequency of the two items will be discussed briefly in the next section through simulation.

Based on the formulation above, the image reconstruction procedure can be separated into several sequential steps in the following. In order to avoid aliasing, the Nyquist criteria must be met for all four spatial frequencies before FFT operation as in (4) and (5); then, the sampling data can be 4-D Fourier transform; Variable substitution as in (9); Interpolation among the frequency-wavenumber domain to get the
same grid of data; Filtering with the filter factor as in (15); The last step, 2-D IFFT in (14). The image can be reconstructed in the end with the above steps finish.

III. ARRAY DESIGN AND MEASUREMENT RESULT

A. Array Design

A simple sparse MIMO array has been designed as shown in figure 2 in order to verify the imaging algorithm discussed above. The work states of antennas will be control through an electronic switch module in practical use. Sapling data is collected mainly by a multi-channel amplitude-phase receiver and will be stored in a master computer for imaging processing. The array working frequency is 18GHz, and the unit interval between adjacent transmitters (or receivers) are one wavelength and a half.

B. Filter Compensation Factor and Imaging Simulation

The influence of filter compensation factor as in (15) on the focusing effect of image is reviewed here. It can be separated into three parts: only considering amplitude filtering factor, only considering phase filtering factor, and considering amplitude filtering factor and phase filtering factor. Three ideal scattering points are as the targets for imaging, their locations are: (0.0, 0.0), (0.05, 0.05), (-0.05, -0.05). The distance between the target and the array plane is 0.5m. The results of imaging simulation in a 20dB dynamic range using the above MIMO array are shown in figure 3.

Figure 3(a) shows that the image can’t focused only considering the amplitude filtering factor while Figure 3(b) shows it is able to be focused only considering the phase filtering factor. The only difference between figure 3(b) and figure 3(c) is the amplitude, which reveals the amplitude filtering factor can be ignored under some condition. To summarize, it is able to get a focused image with normalizing amplitude of imaging result when only consider the phase filtering factor.

C. Measurement Result

A calibration for hardware phase of MIMO array system must be implemented before testing. Hardware phase error mainly comes from the differences between cables and between different states of switch controlling modules and can be minimized by calibration with a metal ball. In addition, the high-performance absorbing material will be pasted on the tablet for holding antenna array to reduce coupling between the very close antennas. The target center is located at 0.5m from the MIMO array. A 2-D imaging experiment of a plane model as in figure 4 was carried out at 18GHz.
The total time including data acquisition and algorithm implementation is only about 1.2s. The excellent imaging result in figure 4 shows that this MIMO imaging algorithm for single-frequency data processing based on bi-static RMA can be used for near-field, high resolution and real-time imaging.

IV. CONCLUSION

A bi-static range migration algorithm for 2-D MIMO imaging for single-frequency data processing has been discussed in detail. Influence of the filter compensation factor including amplitude filtering factor and phase filtering factor on imaging accuracy has been analyzed through simulation. The measurement result of a plane model proves that the algorithm can be used for high resolution and real-time imaging.

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REFERENCES


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