# An Experimental Study on Multi-static Ultra Wideband Radar Imaging with SEABED and Synthetic Aperture

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**Abstract:** This paper presents a comparison study on the application of two electromagnetic inverse scattering algorithms, SEABED [1] and the synthetic aperture method, to experimental multi-static UWB (Ultra Wide-Band) radar data. A linear UWB antenna array with a wideband frequency (1.5-8 GHz) was used for the multi-static radar measurement in a realistic environment. The results clearly show the advantage and disadvantage of the algorithms. The synthetic aperture method is more stable but has poor resolution whereas the SEABED has a higher resolution but gives false images or poor resolution for multiple targets located close together.

**Keywords:** UWB radar, inverse scattering, SEABED

## 1. Introduction

Electromagnetic backscattering techniques have been of great interest in radar systems due to their wide range of applications including security systems, rescuing operations and landmine detection. Although various algorithms have been developed for this purpose, it is not clear what their advantages and disadvantages are.

Amongst all these algorithms, the SEABED has been seen as a promising candidate due to its high-speed processing property. SEABED employs a simplified model of the target shape instead of the conventional pixel/voxel-based tomographic target models. Because most targets in the air have clear boundaries, conventional models are unnecessarily complicated with too many degrees of freedom. Previous work [1] developed a high-speed radar imaging algorithm, SEABED, with a simplified target model. The SEABED algorithm estimates the target image using a reversible transform between the target shape and the observed data, assuming that all targets have clear boundaries.

In this paper, we show some experimental imaging results by employing two algorithms, SEABED (Shape Estimation Algorithm based on BST and Extraction of Directly scattered waves) and the synthetic aperture method, establishing each algorithm's performance for different target configurations.

## 2. System Model and Experimental Setup

We assume a linear antenna array radar system with 8 wide-band antennas. For simplicity, the 2-dimensional problem in $x-y$ Cartesian coordinate space is assumed for imaging, and all the antennas are assumed to be located on the $x$ axis. We define $(x, y)$ as a point on the target boundary, and $(X_{\mathrm{T}}, 0)$ and $(X_{\mathrm{R}}, 0)$ as the position of the transmitter and receiver. The pair of $X_{\mathrm{T}}$ and $X_{\mathrm{R}}$ are sequentially selected by a switch, producing $8 \times 8$ echo signals $s(X_{\mathrm{T}}, X_{\mathrm{R}}, Y)$, where the normalized delay time $Y = ct/2\lambda$ is defined by the propagation speed $c$, the elapsed time $t$ and the center wavelength $\lambda$.

The radar system used in this study consists of a multi-static radar system with an 8-element UWB antenna array connected to an 8-port Rohde & Schwarz ZVT multi-port VNA (Vector Network Analyzer) with a frequency band of 1.5-8GHz. Targets are placed in the air, which is modeled as free space for simplicity. The antenna array consists of 8 ETSAs (Exponential Tapered Slot Antennas) based on Vivaldi antennas [2] at intervals of 8 cm. In our previous work, it was shown that this system can provide a clear image by using the time-reversal and DORT method [3-5].

## 3. Synthetic Aperture and SEABED Method

The synthetic aperture method [6] is a conventional inverse scattering algorithm which is expressed as:

$$S(x, y) = \int s\left(X_{\mathrm{T}}, X_{\mathrm{R}}, Z_0\left(X_{\mathrm{T}}, X_{\mathrm{R}}; x, y\right)\right) \mathrm{d}X_{\mathrm{T}} \mathrm{d}X_{\mathrm{R}}, \tag{1}$$

where $Z_0(X_{\mathrm{T}}, X_{\mathrm{R}}; x, y)$ is defined to be the normalized delay time between the transmitter and the receiver via the point $(x, y)$ as:

$$Z_0\left(X_{\mathrm{T}}, X_{\mathrm{R}}; x, y\right) = \left(\sqrt{\left(x - X_{\mathrm{T}}\right)^2 + y^2} + \sqrt{\left(x - X_{\mathrm{R}}\right)^2 + y^2}\right) / \lambda \cdot \tag{2}$$

Although this method gives stable images regardless of the experimental configurations, the resolution is strictly limited by the wavelength and the baseline of the antenna array.

The SEABED algorithm is based on a reversible transform between the target shape and the received data suited to imaging with the UWB radar. The SEABED algorithm can directly estimate the target shape with the inverse transform, which is the strict mathematical solution of the inverse scattering problem.

In the SEABED, we apply the matched filter to the signals and pick up the maximum peak points, where the matched filter is constructed as the Fourier transform of the reference signal measured previously. The curved line $(X_{\mathrm{T}}, X_{\mathrm{R}}, Y)$ called a quasi-wavefront is estimated by connecting the peak points. For multiple targets, we extract the other quasi-wavefronts as follows [7]. We subtract the reference signal from the received signals by changing the delay time and the amplitude as estimated when extracting the first quasi-wavefront. We apply the same method to the residual signals to obtain other quasi-wavefronts.

After these procedures, we apply the IBBST (Inverse Bi-static Boundary Scattering Transform)

[8] expressed as:

$$\begin{cases} x = X - \dfrac{2Y^3 Y_X}{Y^2 - d^2 + \sqrt{(Y^2 - d^2)^2 + 4d^2 Y^2 Y_X^2}}, \\ y = \dfrac{\sqrt{Y^2 - d^2}}{Y} \sqrt{Y^2 - (x - X)^2} \end{cases} \quad (3)$$

where $X = (X_{\mathrm{T}} + X_{\mathrm{R}})/2$ and $d = (X_{\mathrm{T}} - X_{\mathrm{R}})/2$ are assumed and $Y_X = dY/dX$. This transform can obtain the image without any iteration or repetition process only if the quasi-wavefront is accurately estimated.

## 4. Imaging Results for the Experimental Data

Figure 1 shows the comparison between the synthetic aperture and SEABED for three targets with only the S11 data, which corresponds to the mono-static radar configuration, or $d = 0$ for Eq. (3). For this measurement, we placed a bottle of salted water with the radius of 5 cm, a metallic cylinder with the radius of 2.5 cm, and a bottle of water with the radius of 5 cm, at 60 cm, 90 cm, and 110 cm from the array respectively. The transmitted pulse has a frequency band of 1.5-8GHz. The image obtained from the synthetic aperture has a lot of artifacts caused by the interference between echoes from different targets. By contrast, the image obtained from SEABED is clearer although the furthest target is not accurately estimated. Figure 2 shows the same comparison with the same data set combined with the S11 and S21 data, which corresponds to the full multi-static radar configuration. In this figure, both the images successfully reconstruct the three targets although the SEABED has a better resolution. Figure 3 shows the received signals and extracted quasi-wavefronts for the data used to generate the images in Figure 2. Three curved lines corresponding to the targets are clearly estimated, because the three quasi-wavefronts are separated without any interference from each other.

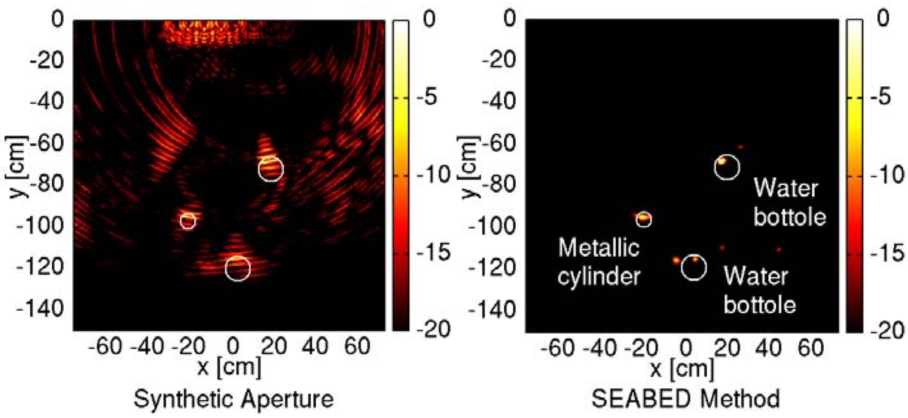


Fig. 1. Images by synthetic aperture and SEABED for mono-static radar data with 3 targets.

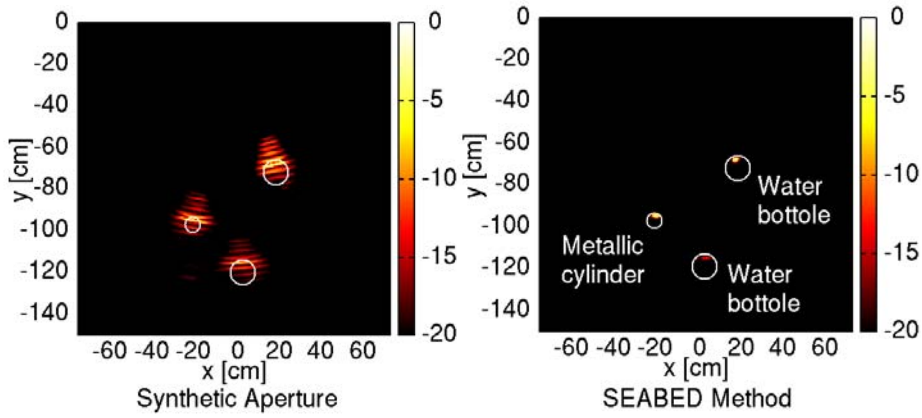

Fig. 2. Images by synthetic aperture and SEABED for multi-static radar data with 3 targets.

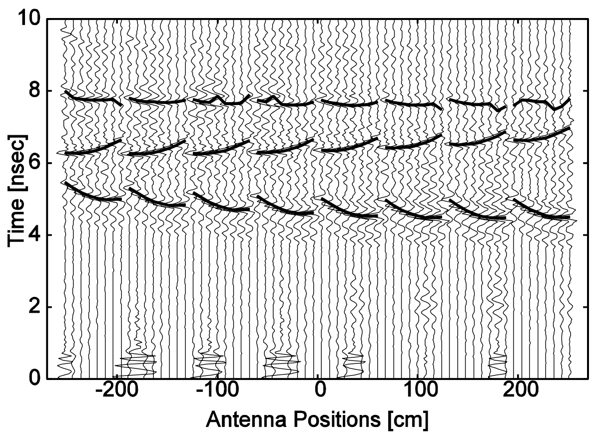

Figure 3 Received signals and the extracted quasi-wavefronts for the data in Fig. 2.

Figure 4 shows the comparison with a different data set in a multi-static radar configuration. For this measurement, we placed two bottles of water with the radius of 5 cm at 70 cm from the array and 40 cm apart from each other. In this case, the SEABED does not work adequately, while the synthetic aperture gives a clear image with two targets. This is because the two targets are located close together and the echoes are suffering interference from each other, leading an inaccurate quasi-wavefront extraction using the above-mentioned procedures. Figure 5 shows the images obtained for targets located even closer together. For this measurement, we placed a metallic cylinder with the radius of 2.5 cm and a bottle of water with the radius of 5 cm at 100 cm from the array and 25 cm apart from each other. We see that the SEABED does not work at all in this case due again to the interference of the quasi-wavefronts. Figure 6 shows the received signals and extracted quasi-wavefronts for the data used to generate the images in Figure 5. The two waveforms are almost completely overlapped and hardly visible as two independent curves where the estimated curved lines are severely degraded by the effect of the interference. This issue is critical to applying the SEABED method to general target configurations and an important future task regarding this approach.

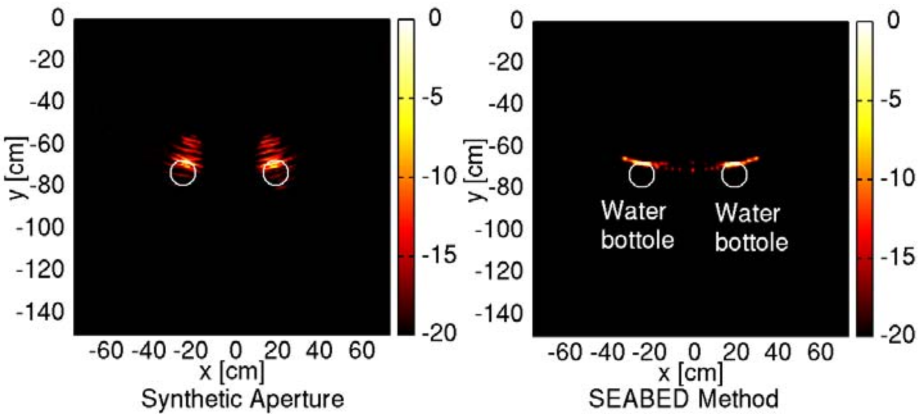


Fig. 4. Images by synthetic aperture and SEABED for multi-static radar data with 2 targets located close together.

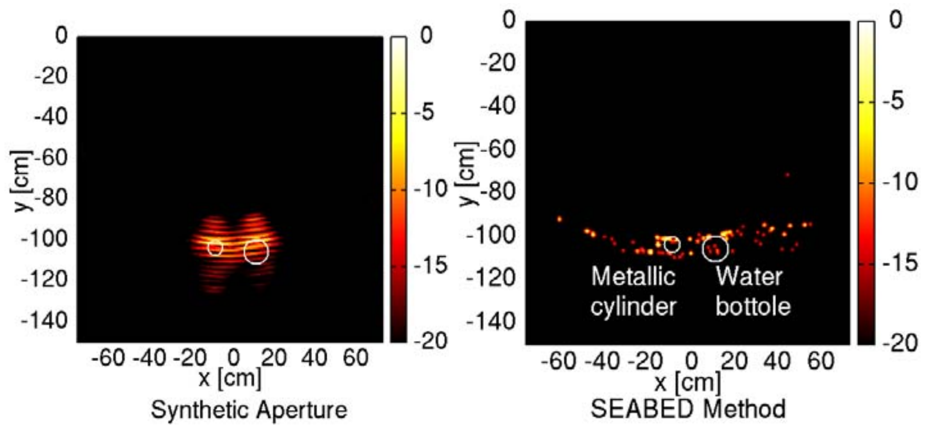


Fig. 5. Images by synthetic aperture and SEABED for multi-static radar data with 2 targets located very close together.

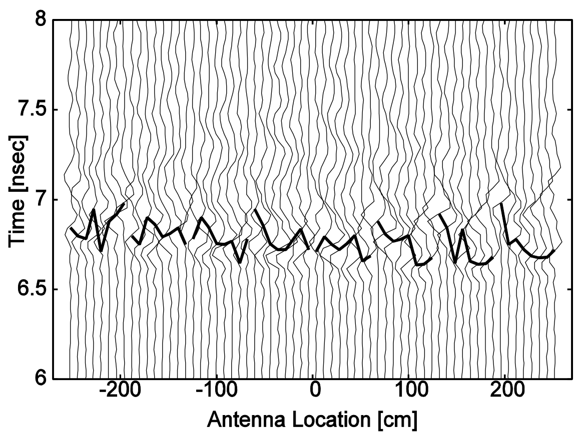


Figure 6 Received signals and the mistakenly extracted inaccurate quasi-wavefront.

## 5. Conclusions

In this paper, we showed some inverse scattering imaging results by comparing the SEABED method and the conventional synthetic aperture method, using experimental data with an 8-element UWB antenna array multi-static radar system. The results showed that the synthetic aperture method gives stable images regardless of the target configuration. In contrast, the SEABED method gives a high-resolution image under certain conditions, but can give a poor image for targets close together. To make the SEABED method applicable to a variety of data sets and considering the interference effects it will be imperative to develop a reliable method to extract the quasi-wavefronts.

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