University of Sindh Journal of Information and Communication Technology (USJICT)
Volume 7, Issue 2

ISSN-E: 2523-1235, ISSN-P: 2521-5582
Website: http://sujo.usindh.edu.pk/index.php/USJICT/

Simulation and Signal Transmission of Through-Wall Detection/Imaging of Metallic Target Using UWB Monostatic Radar

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Abstract: This paper introduces a simulation and signal transmission approach for through-wall target detection/imaging using a monostatic UWB radar. The investigation encompasses the detection and imaging of metallic targets through the application of signal processing techniques. For this purpose, a UWB-balanced antipodal Vivaldi antenna (BAVA) with high gain and standard signal transmission has been designed. Through wall simulation model using monostatic RADAR configuration has been developed in CSTMWS. Through through-wall simulation model has the capability of producing received signals in the time domain for through-wall target detection that are further processed to obtain 2D images. MATLAB programming techniques were employed to process the simulated data at various scan positions. The 2D image of the objects was produced based on the respective scanning positions and distances.

Keywords: UWB, Signal processing, Simulation, Through-Wall, Radar, BAVA, Monostatic

I. Introduction

Through-wall object detection and imaging have garnered significant attention due to their potential applications in various fields, including search and rescue operations, surveillance, and security [1-3]. Ultra-wideband (UWB) radar systems have emerged as promising tools for through-wall sensing, offering advantages such as high resolution, robustness against clutter, and the ability to penetrate non-metallic obstacles. UWB technology is a promising wireless technology used in communication systems, radar systems, and imaging applications [4-6]. Its main applications include Ground Penetrating Radar (GPR), diagnostic medical imaging, and through-wall detection for hidden metallic objects [7-9].

Various methodologies and techniques have been proposed for through-wall object detection using UWB radar systems. Time-domain and frequency-domain approaches are commonly employed for signal processing and target detection.

The UWB signal, consisting of short pulses separated by time, enhances spatial resolution and short-range capability. When applied in radar applications, the increased bandwidth allows the system to obtain more target information, thereby improving its overall performance. UWB systems utilize a larger spectrum, lower power, and pulsed data for improved data transmission speed, low intercept and detection probability, multi-path immunity, and precision ranging and localization [10-11]. UWB radar is widely used in through-wall detection and imaging by radiating electromagnetic waves into structures and analyzing reflected signals to acquire information about obstacles behind them [12].

Antennas serve as the interface between the radar system and the environment [13] transmitting UWB signals into the surrounding space and receiving the reflected signals from targets behind walls. The design and characteristics of the antenna directly influence the radiation pattern, polarization, and bandwidth of the transmitted and received signals, thus affecting the system's overall performance. UWB radar systems are designed to penetrate through walls and other obstacles to detect objects on the other side. The antenna's design plays a crucial role in maximizing signal penetration while minimizing losses due to wall absorption and scattering [14]. Antennas with suitable radiation characteristics and polarization ensure efficient signal propagation through various wall materials, thereby enhancing detection sensitivity and range.

The Balanced antipodal Vivaldi antenna is a wide-bandwidth antenna designed for UWB radar systems. Its wide bandwidth allows for efficient transmission and reception of UWB signals, enabling high-resolution imaging and accurate detection of targets behind walls [15]. Its design minimizes dispersion effects, enhancing precision in UWB radar applications. The antenna's directional radiation patterns provide enhanced spatial coverage and sensitivity, improving signal penetration and target detection performance. Its compact size and low profile make it suitable for portable and lightweight UWB radar systems [16]. Its design simplicity and broadband nature ensure consistent performance across different operating conditions.

Despite significant progress, several challenges and limitations remain in through-wall object detection using UWB radar systems. Multipath propagation, wall penetration losses, and signal attenuation degrade the quality of received signals, leading to reduced detection range and accuracy. Moreover, environmental factors, such as building materials and structural interference, pose additional challenges to reliable through-wall sensing. Addressing these challenges requires interdisciplinary research efforts encompassing electromagnetics and signal processing.

The paper discusses the numerical simulation and signal transmission of UWB antenna for through-wall detection and imaging of metallic targets. The simulation model is developed using a Balanced antipodal Vivaldi antenna design in CST MWS, which uses the Finite Integration Technique (FIT) method to simulate target response in time domain signal. In addition, the extracted time domain signal is processed using a signal processing technique for 2D imaging.

II. ANTENNA DESIGN, SIMULATION MODELING AND SIGNAL TRANSMISSION

This section is further categorized into three sub-sections. Section A is about UWB antenna design, while Section B discusses the through-wall simulation model designed using CST-MWS and Section C. discusses the signal transmission of UWB antenna for through-wall target detection.

A. *UWB ANTENNA DESIGN*

The balanced antipodal Vivaldi antenna (BAVA) is designed using an RT/Duroid 5880 substrate, featuring rectangular slots and circular slots on both of its arms as shown in Figure 1. The radiating element features seventeen rectangular slots of varying lengths and six circular slots distributed along both arms, each characterized by specific parameters. The antenna design features a thickness of 1.58 mm, a loss tangent (δ) of 0.004, and a dielectric constant (εr) of 2.2. For the excitation port of the antenna, a microstrip line with a width (Wc) of 4.60 mm and an impedance of 50 Ω is employed. The Rogers 5880 material, chosen for its tangential loss properties, is known to contribute to achieving favorable gain [17]. The antenna comprises two fundamental components: the feed line and the radiating flared wings. The incorporation of the AVA slot structure is instrumental in enhancing the antenna's performance [18]. In theory, the Vivaldi antenna's high-frequency range should be infinite, whereas the low-frequency range can be determined through the antenna's width and the effective dielectric constant (εeff), as outlined in equations (1) to (4) [19]. The optimized dimensions, obtained through CSTMWS, are detailed in Table 1.

$$fmin = \frac{c}{2w\sqrt{\varepsilon_{eff}}} \tag{1}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+\frac{12h}{w}\right)^{-1/2} \tag{2}$$

$$z_o = \frac{60}{\sqrt{\varepsilon_{eff}}} ln\left(\frac{8h}{w}+\frac{w}{4h}\right) for \left(\frac{w}{h}\right) < 1 \tag{3}$$

$$z_o = \frac{120\pi}{\sqrt{\varepsilon_{eff}}\left[\frac{w}{h}+1.393+\frac{2}{3}ln\left(\frac{w}{h}+1.444\right)\right]}$$

$$for \left(\frac{w}{h}\right) \geq 1 \tag{4}$$

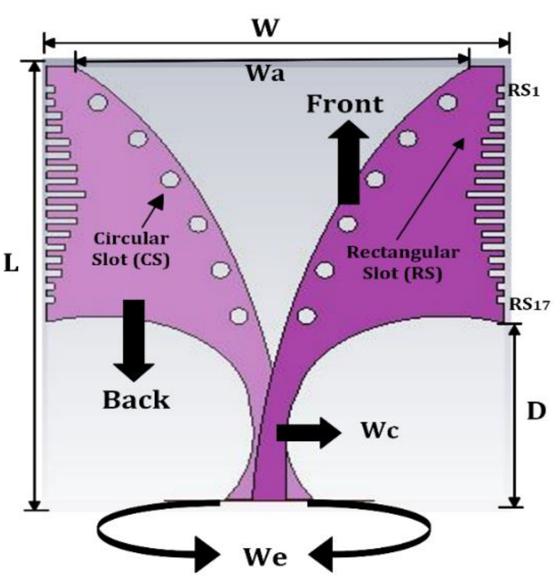


Figure 1. Antenna Geometry

Table 1. Optimized dimensions of BAVA

Parameters	Value (mm)
W	61
L	65.50
D	13.50
Wa	55
Wc	4.60
We	11.80
CS (1-6) (L & W)	2.50
RS (W) (1-17)	1
RS (L) (1, 2, 16, 17)	1
RS (L) (3, 4, 14, 15)	2
RS (L) (5, 6, 13, 12)	3
RS (L) (7,8, 11, 10)	4
RS (L) (9)	5

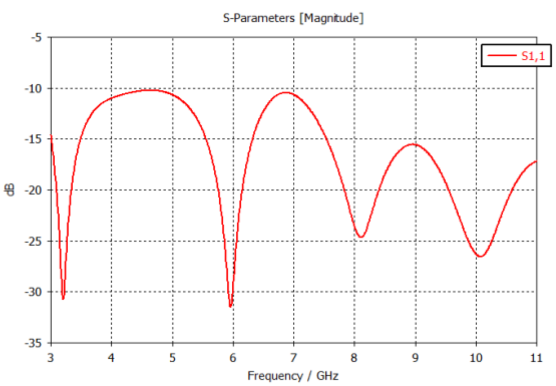


Figure 2. Reflection coefficient (S_{11})

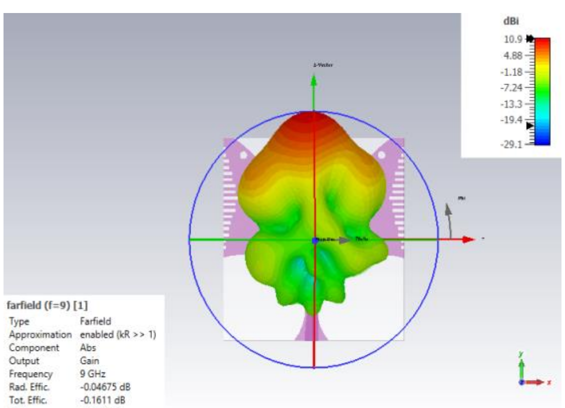


Figure 3. 3D far-field radiation pattern

Figure 2 shows the simulated S_{11} of the BAVA. The BAVA antenna demonstrates acceptable S_{11} values of the designed BAVA. At a frequency of 9 GHz, Figure 3 displays the 3D far-field radiation pattern of the designed BAVA. The depicted pattern reveals that the BAVA has attained a maximum gain of around 11 dB.

B. THROUGH WALL SIMULATION MODEL

The methodology for simulating the through-wall detection/imaging system using CST software involves several key steps:

i. **Model Setup:** The simulation begins with setting up the model in the CST software. This involves defining the geometry and material properties of the components involved, including the BAVA antenna, the concrete wall, and the metallic object.

ii. **Antenna Configuration:** The electromagnetic signal is transmitted from the BAVA antenna in a monostatic RADAR configuration. This means that the same antenna is used for both transmission and reception of the signal. The parameters of the antenna, such as frequency, polarization, and radiation pattern, need to be configured appropriately for the simulation.

iii. **Wall Parameters:** The concrete wall is modeled with specific dimensions - 300 x 300 mm² in size and 100 mm thickness. The distance between the antenna and the wall (Wd) is set to 200 mm.

iv. **Target Placement:** The metallic object, representing the target behind the wall, is introduced into the simulation model. Its dimensions (100 x 100 mm² and 20 mm thickness) and position relative to the wall are specified. The target is placed at various distances (Od) from the wall - 200 mm, 400 mm, and 600 mm - to simulate different scenarios.

v. **Simulation Execution:** Once the model is set up with all the necessary parameters, the simulation is executed. This involves solving Maxwell's equations to simulate the propagation of electromagnetic waves through the environment, including their interaction with the wall and the target object.

vi. **Data Analysis:** After the simulation is complete, the collected data, such as the reflected signals, are analyzed to extract relevant information. This may include detecting the presence of the target, estimating its distance from the wall, and reconstructing an image of the target behind the wall.

vii. **Validation:** The results obtained from the simulation are validated against known theoretical principles or experimental data to ensure the accuracy and reliability of the simulation model.

By following this methodology, the performance of through-wall detection/imaging systems can effectively be simulated and evaluated using CST software.

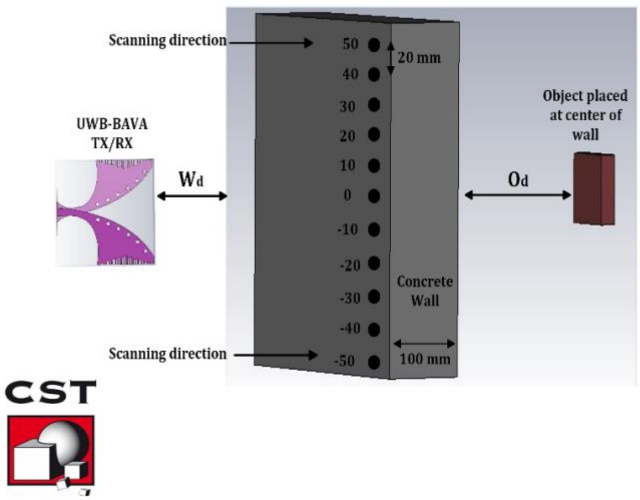


Figure 4. Through wall simulation model

This methodology outlines a systematic approach to developing an image of an object behind a wall using scanning techniques as shown in Figure 4.

i. **Scanning Setup:** The setup involves positioning an antenna to scan the wall at various positions. The scanning direction starts from the 0 scan position and extends to both positive (0 to 50) and negative (0 to -50) positions, covering a wide area.

ii. **Antenna Positioning:** The antenna is primarily positioned in the horizontal plane to ensure maximum coverage of the wall area. This ensures that the antenna scans across the entire width of the wall to capture potential signals reflected from the object behind it.

iii. **Scanning Positions**: A total of 11 scanning positions are utilized. These positions are likely strategically chosen to cover the wall comprehensively and minimize blind spots. Additionally, there's a 20 mm gap between each position, indicating a systematic and uniform scanning approach.

iv. **Target Placement:** The object of interest (metal target) is placed in the middle behind the wall. This central positioning likely helps optimize the scanning process and ensures that the antenna captures reflections from the target from various angles.

v. **Data Collection:** As the antenna scans the wall at different positions, it collects data on the signals it receives. This data would include information about the intensity and direction of the signals reflected from the object behind the wall.

vi. **Image Development:** The collected data is then processed to develop an image of the object behind the wall. This could involve sophisticated signal processing techniques to reconstruct the object's image based on the reflected signals.

Overall, this methodology provides a structured approach to effectively scan and develop an image of an object behind a wall using antenna scanning techniques. It ensures comprehensive coverage of the wall area and systematic data collection to accurately reconstruct the object's image.

C. *SIGNAL TRANSMISSION*

Figure 5 displays the UWB BAVA antenna response in the time domain, presenting both the transmitted signal and the received signal. Both signals originate from zero, exhibit resonance, and ultimately converge towards zero. This indicates the potential for processing the received antenna signal for purposes such as detection and imaging.

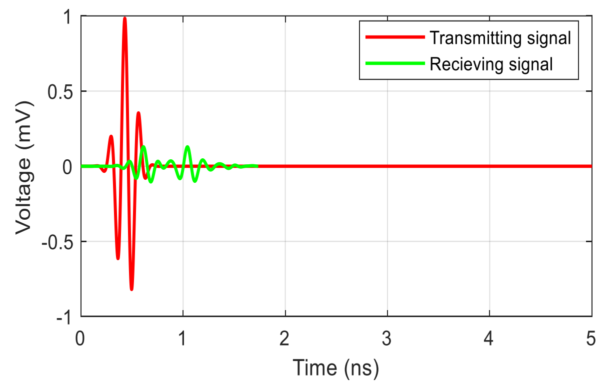


Figure 5. Transmitted and received signal of UWB BAVA antenna

In Figure 6, the UWB BAVA antenna's response to being positioned in front of a wall is depicted. Notably, a substantial wall reflection is observed at 2.5 ns.

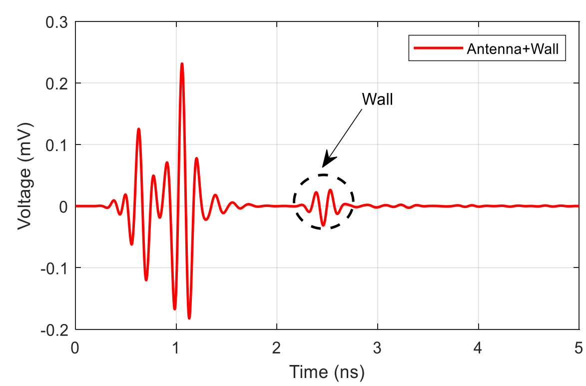


Figure 6. Response of UWB BAVA antenna in front of wall

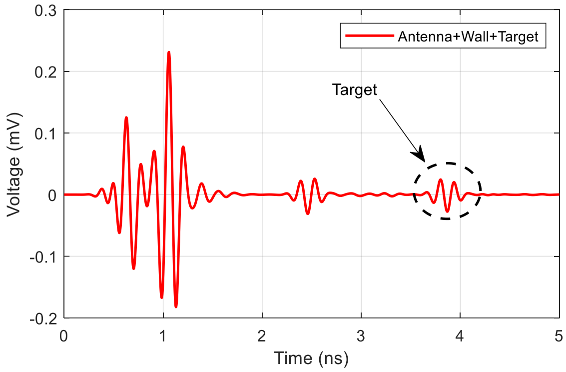
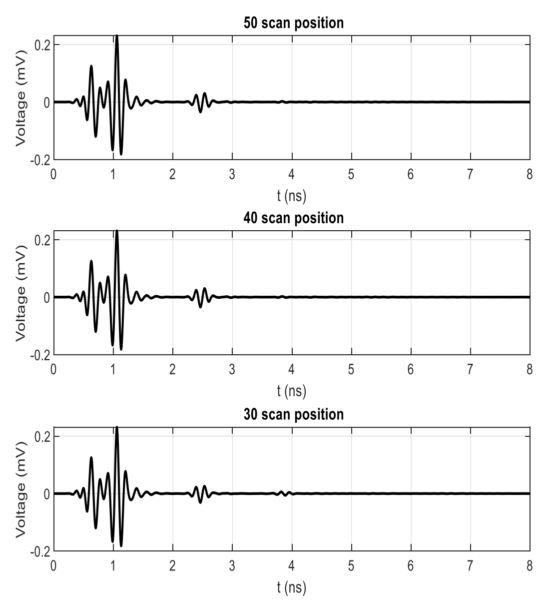


Figure 7. Response of UWB BAVA antenna in front of Wall and target

Conversely, Figure 7 illustrates reflections when both the antenna and the target are centrally positioned on the wall. This configuration is crucial as it unveils object reflections around 3.8 ns, followed by notable wall reflections. To detect objects located behind a wall, the received signals undergo analysis at 11 scanning positions. Figure 8 illustrates the received signals from the monostatic through-wall radar system at these 11 scanning positions, ranging from 0 to 50 and -50 positions. The fluctuations in the received signal over time at all scanning positions, ranging from approximately 0.6 to 1.1 ns, are identified as antenna reflections. Additionally, variations occurring at 2.4 to 2.5 ns are attributed to wall reflections. Conversely, the fluctuations observed between 3.83-3.95 ns represent scattered reflections from the iron object. These reflections are primarily reported at central positions, including 0, 10, 20, -10, and -20, with minor reflections noted at 30 and -30 scanning positions. Notably, no reflections from the iron object are detected at 40, 50, -40, and -50 scanning positions.



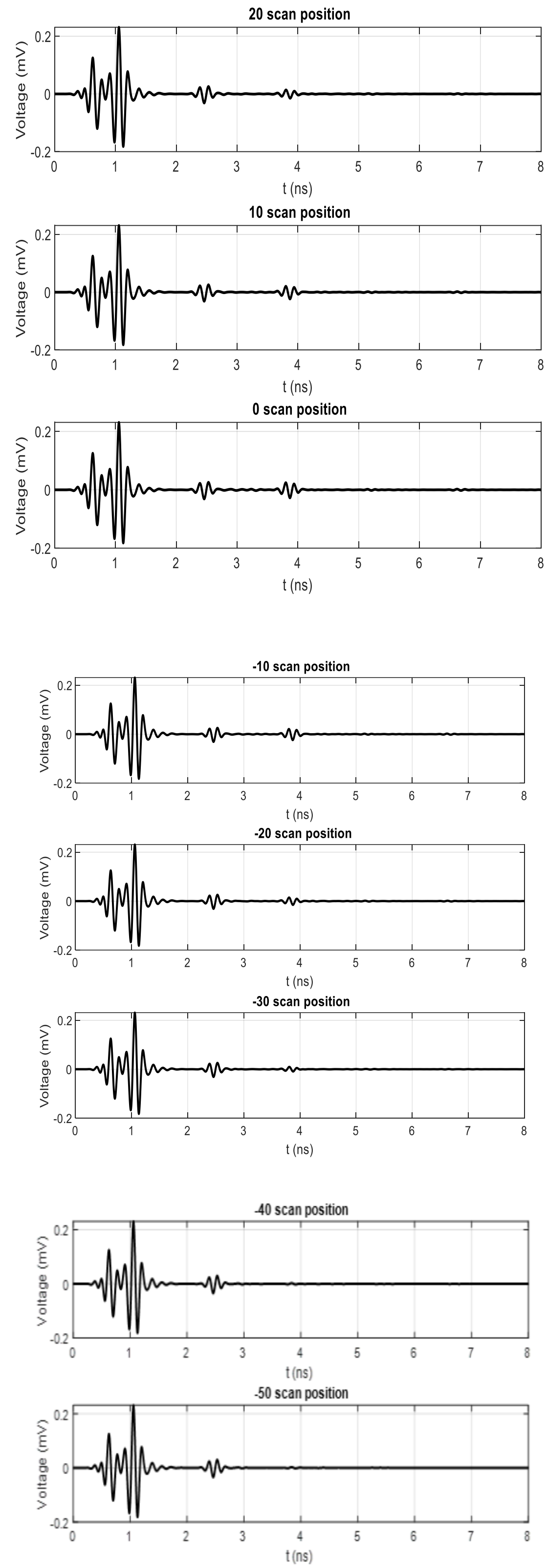


Figure 8. Received signals of 11 scan positions for iron detection at 200 mm

III. RESULTS AND DISCUSSION

Table 2 presents the outcomes of metallic object detection through a wall using a monostatic through-wall RADAR configuration. The results reveal that the designed simulation system is capable of detecting metallic objects, such as iron, within a range of 600 mm.

Table 2: Through wall detection of metallic objects using monostatic RADAR configuration

Object Type	Object distance (O_d) 200 mm	Object distance (O_d) 400 mm	Object distance (O_d) 600 mm
Iron	Detected	Detected	Detected

To generate an object image, the wall is systematically scanned at various positions using a monostatic RADAR configuration, aiming to create a 2D representation of the object. As depicted in Figure 7, the antenna scanning commenced from 0 scan position to 50 scan positions and from 0 scan position to -50 scan positions. To cover the maximum wall area, the antenna was horizontally positioned. A total of 11 scanning positions were employed, with a 20 mm gap between each position. The metallic target was centrally located behind the wall. Following the completion of the simulation for each scanning position, the simulated data in XLS format for each scan position was exported from CST MWS to MATLAB software. Subsequently, the algorithm was applied to generate 2D images of metallic targets. Figure 9 displays the flow chart of the object detection algorithm.

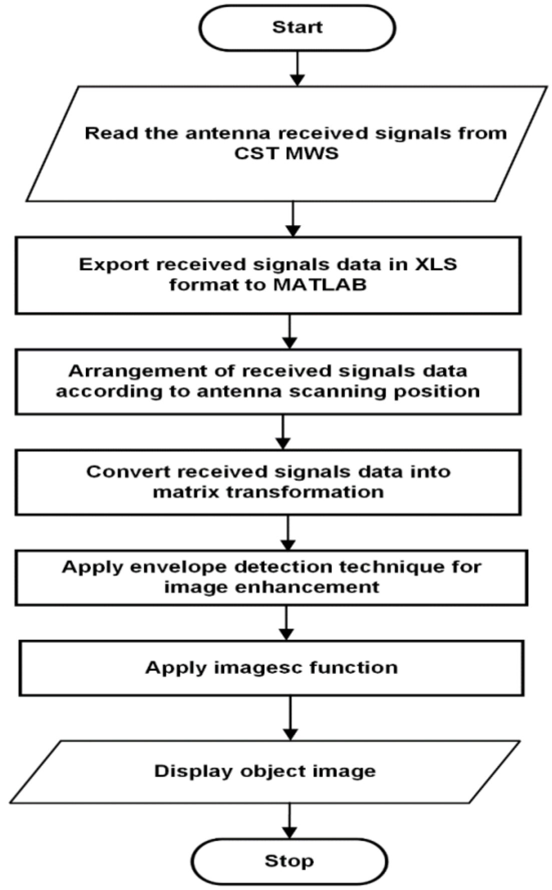
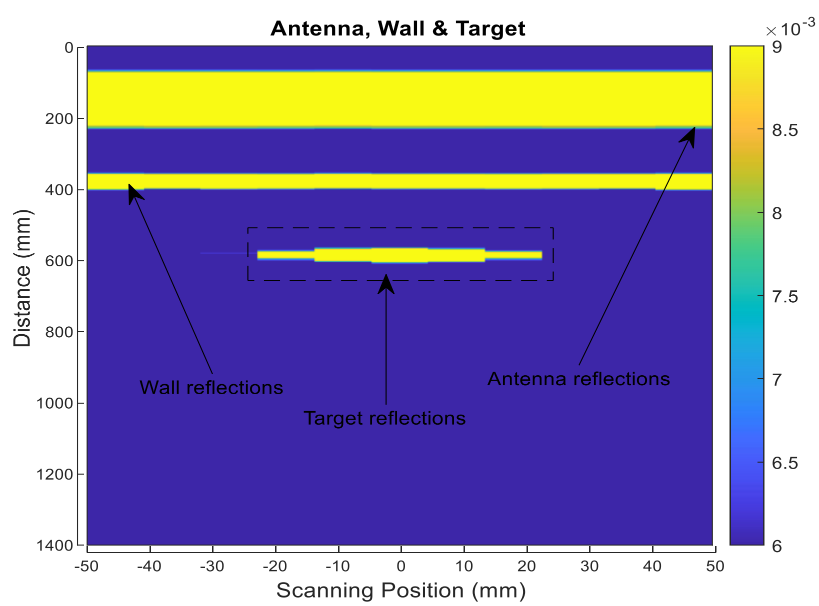
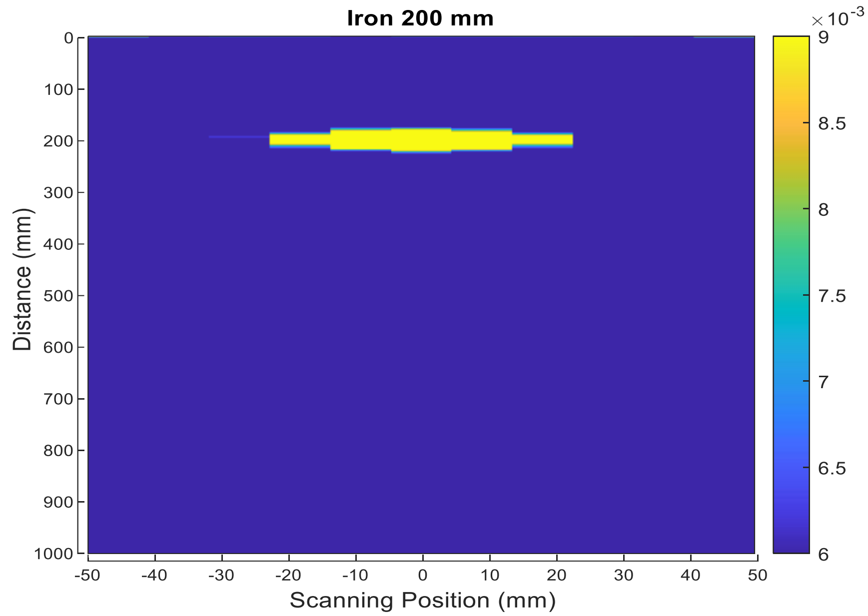


Figure 9. Algorithm for construction of object image using MATLAB software



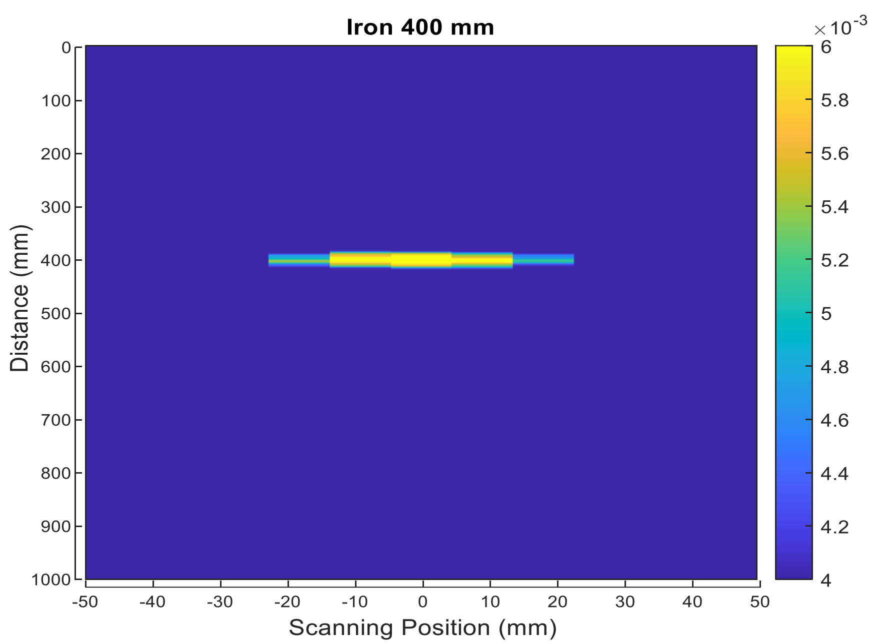
(a)



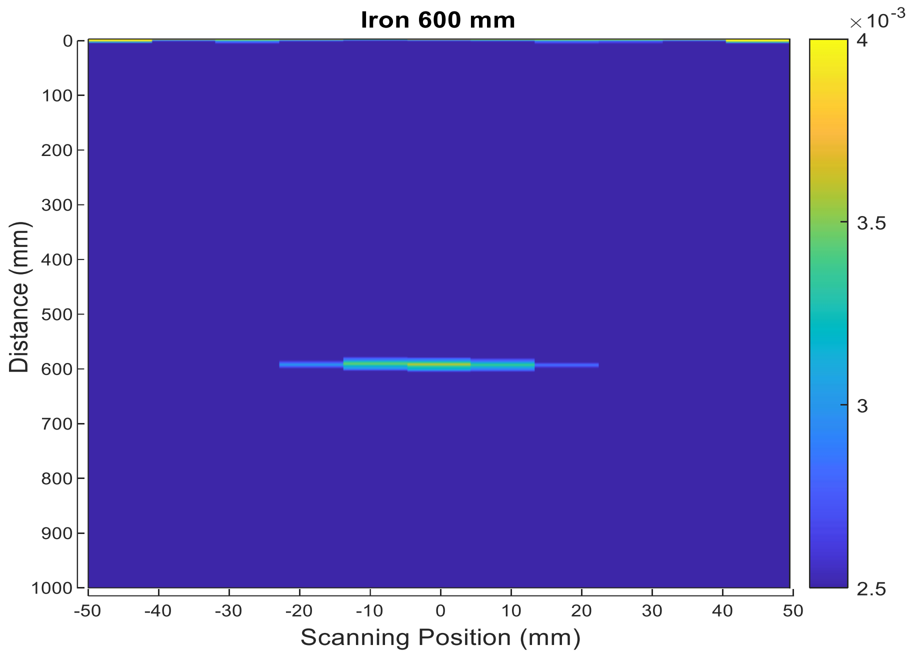
(b)

Figure 10. Through wall imaging at 200 mm (a) Antenna, wall, and object (b) iron object

Figure 10 displays a 2D image of an iron object located 200 mm behind a wall, utilizing a monostatic RADAR configuration. The object's distance is represented along the y-axis, while the scanning positions are illustrated along the x-axis. In Figure 10(a), the initial representation depicts the antenna reflection, followed by the wall reflection, and eventually, the appearance of the object's reflection positioned at the wall's center to the antenna scanning positions. Figure 10(b) exclusively presents the object's image after subtracting the reflections of the antenna and the wall. It is observed that the iron object is situated at 200 mm, precisely at the center concerning the scanning positions.



(a)



(b)

Figure 11: Through wall imaging (a) iron object 400 mm (b) iron object 600 mm

In Figure 11(a), the imaging of an iron object is presented at a distance of 400 mm about the scanning position of an antenna. Simultaneously, Figure 11(b) displays the imaging of an iron object located 600 mm away concerning the scanning position of the antenna. As the distance from the object increases, the antenna receives fewer reflections.

IV. CONCLUSION

In this paper, simulation, and signal transmission of through-wall target detection/imaging using a monostatic UWB radar configuration has been demonstrated. The UWB BAVA antenna has been simulated in the frequency range (3.1 GHz - 10.6 GHz) and tested through a wall detection/ imaging simulation model for metallic targets. The received signals in the time domain were obtained at each scanning position in through through-wall simulation model. An algorithm based on signal processing techniques has been developed using MATLAB software to produce 2D images of targets. The findings indicate that the detection and imaging of metallic targets, such as iron, is achievable at distances of up to 600 mm.

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