Development of Ground Penetrating Radar Hybrid System Using Vivaldi Antenna for Buried Object Detection

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Abstract – *Ground penetrating radar (GPR) is categorized based on the number of antenna and modulation technique used for buried object detection. GPR systems that were often studied are the GPR of amplitude modulation and GPR of frequency modulation. Based on these two types of GPR system, the GPR of frequency modulation which is known as Stepped Frequency Continuous Wave (SFCW) is easy to be developed using only antenna and vector network analyzer (VNA). This study combined the Pulse modulation and SFCW GPR to form the GPR Hybrid. The combination was made in order to develop Pulse modulation GPR system of amplitude modulation GPR type using VNA. Discussion on this developed Hybrid GPR using the CST studio Suite 2014 software, included the design of a GPR antenna called the Vivaldi antenna of patch types, the design on simulation system of GPR Hybrid system, and the implementation of GPR Hybrid system using vector network analyzer. After the validation process, the developed GPR Hybrid system equipment was able to successfully detect a metal object that was buried in a wooden chamber containing dry sand.*

Keywords*: ground penetrating radar, Vivaldi antenna, reflection signal parameter, amplitude modulation, frequency modulation*

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I. Introduction

GPR system is a radar system used to detect objects buried in the earth. The technique used in the GPR system is to detect the reflected electromagnetic wave signal by objects that are embedded underground. There are several methods used in GPR systems that have been classified into different types of modulation such as amplitude modulation, frequency modulation and spatial modulation [1], in addition to GPR system without modulation, known as pulse GPR.

In studies conducted on GPR system that uses modulation technique, there are two types of GPR system that is often used, namely the amplitude modulation GPR [2] and frequency modulation GPR [3]. Besides referring to the type of modulation, the GPR system has also been categorized into the number of antennas used in the system, such as monostatic GPR system which uses only one antenna for transmitting and receiving signals of electromagnetic waves such as those used by Di Donato [4], Ozdemir et al. [5] and Comite [6]. The bi-static GPR system is a GPR system that uses two antennas, one as a receiving antenna and one as a transmitting antenna, as used by Yakubov [7] and Kong et al. [8]. On the other hand, the multi-static GPR system is a GPR system that uses multiple antennas arranged in parallel and divided into transmitter antenna and receiver antenna as has been used by Counts et al. [9] and Feng and Sato [10]. All these types of GPR system with different antennas configuration used are for detecting buried objects in several types of material such as sand, rock and concrete.

A. GPR System

A GPR system that uses pulse signal is known as a GPR system that operates in time domain [1]. The GPR system of this type, which emits a pulse of electromagnetic wave signal, is called GPR system without modulation while a GPR system that radiate signal of electromagnetic waves in Gaussian shape is known as GPR system of pulse modulation also known as Amplitude Modulation GPR (AM GPR).

On the other hand, GPR system of frequency domain emits electromagnetic wave signal with a variable frequency is called chirp signal. One of the GPR system types in this category that is frequently used is the Stepped Frequency Continuous Wave (SFCW) GPR. Researches involving GPR system of SFCW type used vector network analyzer as receiver system and transmitter system, as reported by Goodman et al. [11] and Shrestha, Miwa and Arai [12].

In this study, the GPR Hybrid system which is the mixture of AM GPR and SFCW GPR was developed. The main objective is to facilitate the development of the AM GPR system using SFCW signal which can be developed using VNA equipment as the transmitter and receiver systems but still have the advantages of the AM GPR system. One of the advantages of AM GPR system in comparison to the SFCW GPR system is that the AM GPR system can detect an embedded object which is located deeper in the earth. Previous work on the SFCW GPR system revealed that VNA was one of the instrumentation that was always used as a receiver system and transmitter system of the electromagnetic wave signal. However, the use of VNA produced the reflected signal parameter S_{11} if monostatic GPR system is used and S_{21} for bistatic GPR system. In vector network analyzer readout, which provides the reflection signal parameter S_{11} or S_{21}; the convolution between the input signal and S_{11} signal in the time domain must be performed by the GPR system to get the signal reflected from the embedded object.

In this study, a digitally generated Gaussian-shaped input signal was used in the development process of the GPR system. This is an important feature in the AM GPR system. The measurement of the S_{11} signal in this GPR Hybrid system however, was based on the vector network analyzer equipment that emits electromagnet wave signal in the shape of SFCW.

The proposed GPR hybrid system began with the design of patch type Vivaldi antenna using the CST studio Suite 2014 software. The Vivaldi antenna design simulation was then extended to the GPR system simulation. In this GPR system simulation, this designed antenna was used to scan the sand packed cube with iron block embedded inside. Then the Vivaldi antenna was fabricated and packaged in GPR hybrid system which was developed using the vector network analyzer Rohde & Schwarz, zvB14. For validation purposes, this GPR hybrid system was tested by conducting scan process on a wooden chamber containing a metal object planted in a dry sand.

II. Vivaldi type of patch antenna design using CST Studio Suite

The Microstrip Vivaldi antenna design which was developed in this study is shown in Figure 1. The parameter of this antenna is as shown in Table 1. This antenna was chosen due to its wideband property as shown in Figure 2 and having unidirectional of radiation as illustrated in Figure 4.

TABLE 1
MICROSTRIP VIVALDI ANTENNA PARAMETERS

Length	Width	Thick
63mm	40mm	1.74mm

In Figure 1, the curve parameter of the Microstrip Vivaldi antenna is presented in Table 2.

TABLE 2
MICROSTRIP VIVALDI ANTENNA DESIGN PARAMETERS

curve	Clock wise (cw) / anti-clock wise (acw)	center point	point 1	Angle
A	cw	(0,-80)	(0,2)	21.460128
B	cw	(0,-20)	(0,-2)	90
C	acw	(0,-33)	(0.-2)	65.206138
D	cw	(0,33)	(0,2)	65.206138

As presented in Table 2 and in the CST Studio Suite software, the *c* curve of this Microstrip Vivaldi antenna is required to be rotated at 180 degrees on the *y*-axis. Next, in order to form this Microstrip Vivaldi's antenna petal, the antenna curves which were marked with *a*, *b*, *c* and *d* in Figure 1 needed to be joined immediately at the end of the curve to form a closed antenna petal. Finally, this enclosed petal was extruded to form a thickness of 0.07 mm. The second petal, which is located at the back of the Microstrip Vivaldi antenna as depicted in Figure 1 was made by duplicating the first petal and was subsequently set to the coordinates under the antenna substrate.

In order to find the suitable operating frequency the antenna, the simulation CST of Vivaldi antenna was conducted with the frequency range of 0 GHz until 10 GHz. The simulation result of the designed Vivaldi antenna is shown in Figure 2. It can be seen that the designed Vivaldi antenna was able to radiate an electromagnetic wave signal at a frequency of 6.5 GHz with amplitude of approximately -7.5 dB. To obtain the simulation result of the designed Vivaldi antenna to operate at the frequency of 6.5 GHz with a bandwidth of 3 GHz, the simulation must be carried out again in the frequency range of from 5 GHz until 8 GHz.

The follow-up simulation result for the frequency range of 5 GHz to 8 GHz is shown in Figure 3. It can be concluded that the designed Vivaldi antenna was able to emit an electromagnetic wave signal in the frequency range from 5 GHz until 8 GHz with amplitude less than -6 dB.

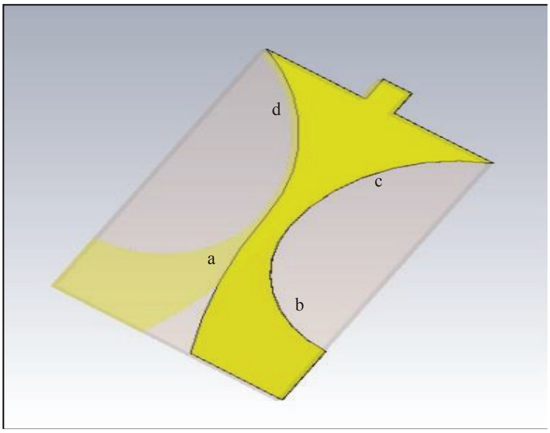

Fig. 1. Vivaldi antenna of patch type

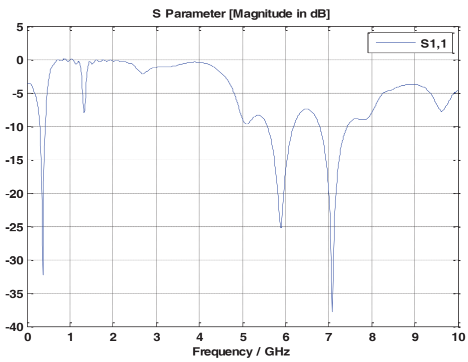

Fig. 2. Simulation result of the designed Vivaldi antenna for range of frequency 0 GHz to 10 GHz

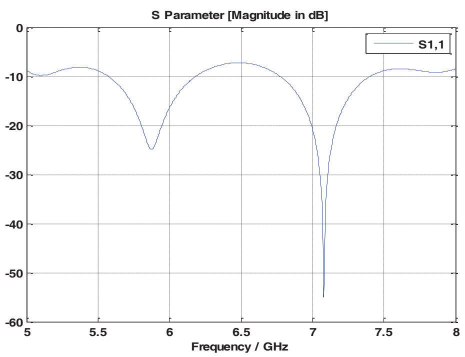

Fig. 3. Simulation result of the designed Vivaldi antenna for range of frequency 5 GHz to 8 GHz

Beside producing S_{11} signal, another important antenna's characteristic in designing a GPR antenna is to ensure that the radiation pattern is unidirectional. However, if the antenna does not have a unidirectional pattern, shielding method may be applied. Figure 4 shows a Vivaldi antenna radiation pattern which was designed in this study. The designed Vivaldi antenna's radiation pattern produced a unidirectional radiation pattern with a magnitude in the main lobe equivalent to 3.98dBi in the direction of 0 degrees.

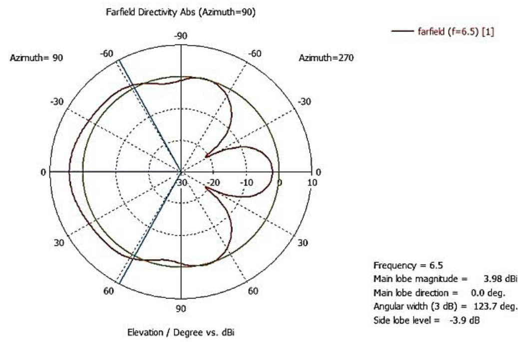

Fig. 4. Simulation result of the designed Vivaldi antenna for range of frequency 5 GHz to 8 GHz

III. Design of the simulation of GPR hybrid system using CST Studio Suite

Designing the Vivaldi antenna enables the monostatic GPR Hybrid system to be simulated using CST Studio Suite. Figure 5 shows the simulation design of the GPR Hybrid system that was created in this study.

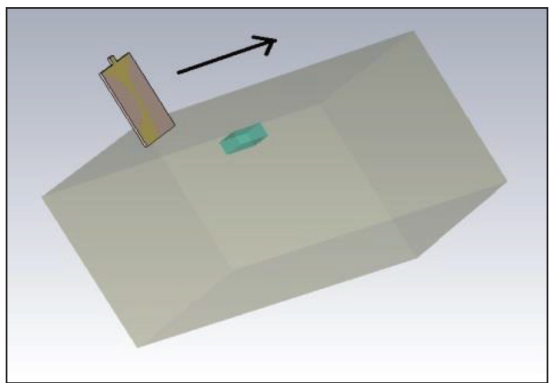

Fig. 5. Simulation design of the GPR Hybrid system

The design of the GPR Hybrid system simulation was made using the designed Vivaldi antenna, a cube containing dry sand with the dimension of 180 mm high, 140 mm wide and 200 mm long, and an object (iron) of 50 mm high, 20 mm wide and 20 mm long. In this simulation, the object was planted at a distance of 5 mm from the surface of the cube.

The simulation of the designed GPR hybrid system was conducted by changing the position of the antenna from one position to another in the direction from left to right as shown in Figure 5. In this study, the position of the Vivaldi antenna was moved from one position to another position at a distance of 10 mm which produces 9 measurements of S_{11} signal at each position.

IV Processing Algorithm

Each of the S_{11} signal obtained from one position of the antenna was processed by applying the Inverse Fast Fourier Transform (IFFT) method and then convoluted with the generated input signal of Gaussian type with a signal spectrum from 5 GHz to 8 GHz. The processing algorithm flowchart is illustrated in Figure 6. Figure 7 shows the input signal used in this study.

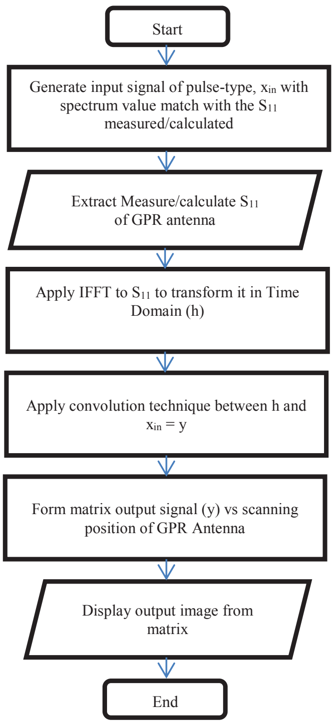

Fig. 6. Processing Algorithm Flow Chart for GPR Hybrid System

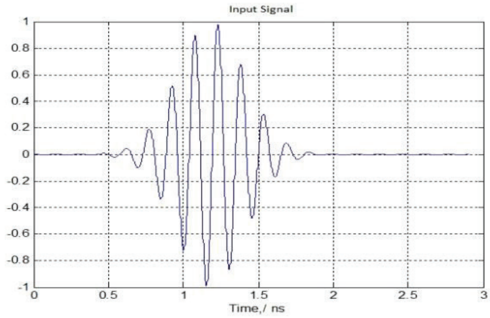

Fig. 7. Input signal which was used for the convolution with the measured S_{11} signal

The result of the convolution of the reflected signal parameter S_{11} with the input signal was arranged in a matrix form against the position of the antenna. The visualization of this matrix is shown in Figure 8.

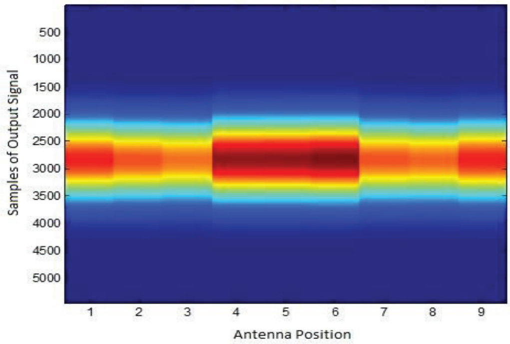

Fig. 8. Result of simulation of GPR Hybrid system

The position of the object was fixed at position 4, 5 and 6 prior to the detection process. As observed in Figure 8, the position of the object in the simulation of GPR Hybrid system can be accurately estimated to be in the position of 4, 5 and 6.

IV. Development of GPR Hybrid system using Vector Network Analyzer (VNA), ZVB14

With promising simulation results for the GPR Hybrid system, the designed Vivaldi antenna was fabricated and packaged. Figure 9 shows a Vivaldi antenna that was fabricated and packaged. The material used to package the Vivaldi antenna is a paper box. The reading of the reflection signal parameter S_{11} of the Vivaldi antenna and GPR Vivaldi antenna are as shown in Figure 10 and Figure 11. These readings which were the reflection signal parameter S_{11}, were measured using Vector Network Analyzer, zvB14.

Fig. 9. Vivaldi antenna which has been fabricated and packaged

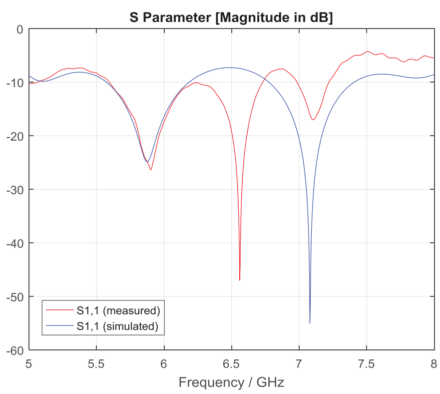

Fig. 10. The reflection signal parameter S_{11} of Vivaldi antenna simulation (blue) and measured (red) using the VNA zvB14

As depicted in Figure 10, the S_{11} parameter of the Microstrip Vivaldi antenna was shifted where the second operating frequency of the fabricated antenna (measured) is at about 6.5 GHz in comparison to simulation result which was recorded at approximately 7 GHz. The measured S_{11} signal of the packaged Microstrip Vivaldi antenna also produced amplitude readings of less than -5 dB in the frequency range of 5 GHz to 8 GHz as portrayed in Figure 11. It may be noted here that the paper used to package Vivaldi antenna have modified the reading of S_{11}.The fabricated GPR Vivaldi antenna was able to produces S_{11} signal which was better than the designed Vivaldi antenna.

Validation of the GPR Hybrid system was performed by scanning a wooden chamber which has been filled with dry sand. An iron object was planted inside the box at a depth of 5 mm. The dimension of the wooden chamber was 600 mm in length, 600 mm in width and 100 mm in height. The size of the iron object is 110 mm in length, 110 mm in width and 15mm in height. Figure 11 shows the GPR Hybrid system developed with the validation equipment and a diagram of iron object that had been used.

The scanning process of the developed GPR Hybrid system equipment was made based on the direction of the arrow shown in Figure 12. The distance between two points of the GPR sensor device in the scanning process was set at 5 mm starting from the position marked by A until B. The scanning process by the GPR system equipment on the wooden chamber filled with sand produced 115 measurements of the **S_{11}** parameter.

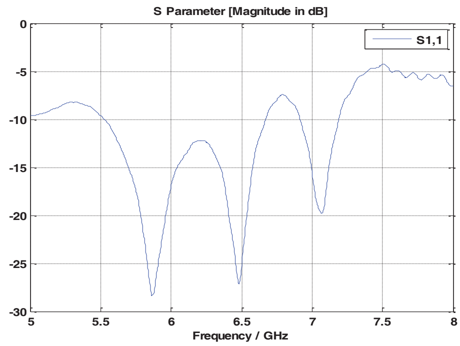

Fig. 11. The reflection signal parameter S_{11} of the GPR Vivaldi antenna measured using VNA zvB14

Fig. 12. The process of testing the GPR Hybrid system using a wooden chamber containing dry sand and iron object

In the earlier simulation of the GPR hybrid system, the results of the testing process of the GPR Hybrid system obtained from the VNA, zvB14 was in matrix form. The corresponding matrix that was produced based on the results of processing the measurements made using zvB14 during the validation process were visualized as shown in Figure 13. It can be estimated that the position of the iron object in the wooden chamber containing dry sand is at position 10 to 20. This result is in line with the position of iron object which was planted in the wooden chamber when the validation equipment was prepared.

The results of the scanning process using GPR Hybrid system in both simulation and validation test were very consistent as depicted in Figure 8 and Figure 13 respectively. Based on the two images, the reflection of iron object which is colored in red can be detected by the GPR system clearly.

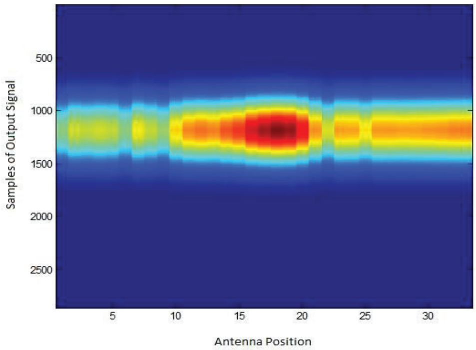

Fig. 13. The result of detecting a buried iron object using the developed GPR hybrid system

V. Conclusion

In this study, a GPR Hybrid system which is a mix of the AM GPR and the SFCW GPR was proposed, simulated, tested and produced. The simulation results of the GPR Hybrid system emulating an object detection showed accurate detection of the object in the CST software. Subsequently, the validation test of the physical GPR Hybrid system determining the position of a buried iron object showed an accurate detection. These results were promising to warrant extended validation process in the future work. An example of such validation is to scan the wooden chamber contains dry sand and a non-metal object. Furthermore, the development of the GPR Hybrid system can be studied using other antennas other than the Vivaldi antenna.

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