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Comparison of Clutter Reduction Methods for Buried Object Detection in Heterogeneous Soil

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ABSTRAK

GPR yang dimodelkan dengan menggunakan Vector Network Analyzer (VNA) yang disambungkan dengan dua antena dilakukan pada penelitian ini untuk mendeteksi logam yang terkubur di bawah tanah. Target yang terkubur berada pada 17 cm dari permukaan tanah. Proses pendeteksian dilakukan untuk mendapatkan hasil citra radar, yaitu A-scan dan B-scan. Pengurangan clutter pada penelitian ini dilakukan dengan tiga metode, yaitu weighting method, averaging, dan singular value decomposition (SVD). Penelitian ini mengkaji kinerja dari beberapa metode untuk mengurangi clutter yang diakibatkan oleh tanah heterogen. Secara kualitatif, ketiga metode mampu memperjelas target dan mampu mengurangi clutter pada citra radar. Secara kuantitatif, digunakan perhitungan Signal to Clutter Ratio (SCR) yang didapatkan setelah pengurangan clutter. Pada metode weighting process, SCR meningkat menjadi 28.81 dB, sedangkan metode averaging meningkatkan SCR menjadi 25.31 dB. Sementara itu, metode SVD hanya memberikan peningkatan kecil menjadi 4.45 dB.

***Kata kunci**: GPR, Pemrosesan Sinyal, Weighting process, Pengurangan clutter, SCR*

ABSTRACT

A GPR was conducted in this study using a Vector Network Analyzer (VNA) connected to two antennas to detect buried metals. The target was located 17 cm below the ground surface. The detection process was carried out to obtain radar images, namely A-scan and B-scan. Clutter reduction was performed using three methods: weighting, averaging, and singular value decomposition (SVD). This study reviews the performance of clutter-reduction methods under heterogeneous soil conditions. Qualitatively, all methods clarified the target and reduced clutter in the radar image. Quantitatively, the Signal-to-Clutter Ratio (SCR) is calculated after clutter reduction. In terms of results, the weighting method increased the SCR to 28.81 dB, while the averaging method increased it to 25.31 dB. Meanwhile, the SVD method only provided a small increase to 4.45 dB.

***Keywords**: GPR, Signal processing, Weighting process, Clutter reduction, SCR*

1. INTRODUCTION

Radar technology is a rapidly growing and widely used technology due to its accuracy in detecting objects non-destructively **(Pathirana et al., 2024)(Ye et al., 2026)(Ma et al., 2021)**. The advantages of radar are utilised in various fields, including health **(Imran et al., 2021)**, geology **(Elshaboury et al., 2023)**, agriculture **(Pathirana et al., 2023)**, transportation **(Tang, et al., 2021)**, post-disaster rescue operations **(Wang et al., 2022) (Ramadhamy et al., 2023, 2025)**, and military applications **(Sato, 2025)**. Radar is widely used to detect objects hidden behind walls or buried underground, such as in geology for mapping underground structures and in agriculture for monitoring soil moisture levels **(Machado Brito-da-Costa et al., 2021)**. In transportation, one of these devices is used to detect track deflections, thereby minimizing accidents **(Liu et al., 2022)**. Additionally, for post-disaster victim rescue, it is used to detect small movements of victims to determine whether they are still alive or have died in a particular position **(Ramadhamy et al., 2023)**. It is also used in the military field, specifically to locate an enemy behind cover. It is often used to detect the presence of mines **(Saranya et al., 2024)**.

In addition, radar technology has evolved. Various radars are used in these fields, including Light Detection and Ranging (LIDAR) **(Wang et al., 2023)**, Ultra-Wide Band Radar **(Li et al., 2025)**, Frequency Modulated Continuous Wave Radar (FMCW) **(Baspinar et al., 2023)**, Multi-Frequency Continuous Wave Radar (MFCW) **(Alsharif, 2021)**, and Ground Penetrating Radar (GPR) **(Ramadhamy et al., 2021)**. One widely used method, especially in subsurface detection applications, is GPR. The accuracy of GPR has been demonstrated by numerous studies in detecting objects buried underground. GPR works by transmitting electromagnetic waves from a transmitter antenna to the ground until they penetrate and hit the target. Then, the waves are returned by the receiver antenna. In this case, GPR has been utilized in the military field of mine detection, the archaeological field of detecting hidden artifacts, and geological mapping to visualize the rock layers beneath the ground.

The extensive research on the resolution of GPR has led to the development of this radar as one of the technologies for subsurface exploration. In the detection using GPR, one of the things that interferes with the detection results is the presence of clutter signals. The clutter signal is a signal whose presence covers the object signal, which is the purpose of this research. Research into methods to reduce clutter signals has been widely conducted, including the averaging method **(Ramadhamy et al., 2021)**, Singular Value Decomposition (SVD) **(Zhao et al., 2023)**, Principal Component Analysis (PCA) **(Zhao et al., 2023)**, Weighting Process **(Ramadhamy et al., 2023)**, and others. The use of SVD and PCA methods has been proven in many studies. However, these methods have the disadvantage of high computational complexity and sensitivity, so it is necessary to be cautious when selecting reduced signal data to prevent the decomposition results from being disturbed. The SCR value obtained is low compared to other methods. As for the averaging method, it is a straight forward method for clutter reduction and has a high SCR value. However, this method cannot distinguish between clutter and the desired signal when they have a very close position. For the Weighting Process, this method is excellent for clutter reduction, as it avoids the high complexity of SVD and LTS, but is also not as simple as the averaging method. It can distinguish clutter from other objects and has high estimation accuracy.

Various clutter reduction methods have been developed, such as the method that used in this analyzed. The averaging method are generally effective under stationary condition of clutter, whereas SVD method utilise signal subspace seperation to remove dominant clutter component. Furthermore, weighting process have also been introduced to enhance the ability to reduce the clutter. Nevertheless, most previous studied have evaluated these methods seperately and have not conducted systematic comparisons in the same conditions particularly in heterogenous soil. This soil cause complex variation in dialectric properties that directly affect the propagation of electromagnetic waves. Therefore, this study aims to conduct a comparative analysis of three clutter reducing method based on SCR performance under controlled heterogenous soil conditions.

Based on research **(Ramadhamy et al 2023, 2021)**, some of the methods mentioned are only applied to certain types of data. To compare the performance of each method, the experiment was conducted by collecting data under two conditions, such as applying the clutter reduction method and calculating the increase in SCR obtained by this method for the experimental conditions created to assess the method's accuracy in relation to the experiments conducted. This experiment used comparison This paper is divided into several sections, including Section II, which discusses the research methodology used in this study; Section III, which presents the results and discussion of the study conducted through laboratory experiments; and Section IV, which provides the conclusions.

2. METHOD

Figure 1 shows a diagram of the GPR system. The diagram explains how GPR works to detect objects buried underground. The GPR system consists of a transmitter (Tx) and a receiver (Rx), which connect to two antennas. The transmitter transmits electromagnetic waves towards the target, and the receiver antenna receives reflected signals from the surface and the target. The received signals undergo post-signal processing and are displayed on a screen. Laptops or monitors are commonly used as displays to show the results in the form of radar images.

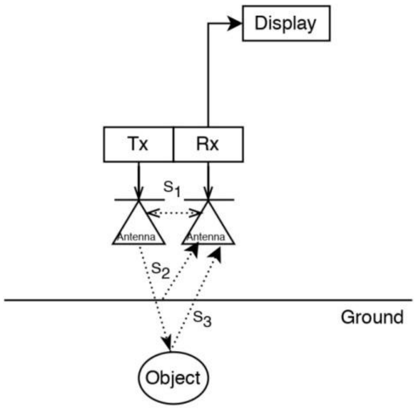

Figure 1. GPR System

In a radar system, there are three received signals, namely S_1, S_2, and S_3. Signal S_1 is a direct signal (coupling) between the transmitting antenna and the transmitter in the air. This signal is one of the most significant sources of interference due to reflections near the antenna. Signal S_2 is a reflection originating from the surface to the ground above the target. Meanwhile, signal S_3 is a reflection signal originating from the target buried in the ground, which is the target of this research detection. The received signal (S_r) is written as (1).

$$S_r = S_1 + S_2 + S_3 \quad (1)$$

Pulses fired into the ground will experience signal attenuation and distortion during propagation. The pulse will first hit the ground surface, and then the signal will be reflected to the radar. If the ground conditions are heterogeneous, the clutter received by the antenna will be greater than that of homogeneous ground. The principle work of GPR is based on measuring electromagnetic waves from the transmitter to the object and back to the receiver. The signal travel time is used to calculate the location and depth of buried objects.

After understanding the general working principles of the GPR system, a laboratory experiment was designed for this study. The flow chart used in this study is shown in Figure 2. The flow chart explains the stages of the GPR experiment conducted in this study to obtain and analyse target signals buried underground. This research began with a literature study aimed at understanding the basic theory of waves used in radar, the characteristics of the GPR system, and the clutter reduction methods used in radar signals. This stage became one of the concepts for designing the experiment. Then, the theories that had been studied were validated.

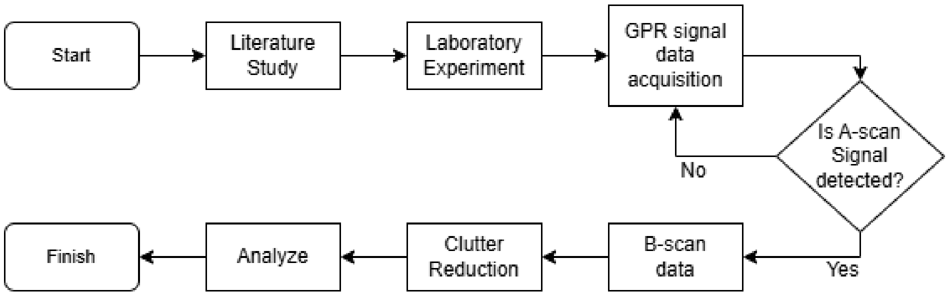

Figure 2. Research Flowchart

Moreover, a laboratory experiment was conducted where the GPR radar system used an antenna connected to a VNA. This modelling is shown in Figure 3. The experimental data for this study were collected in an outdoor sandbox. The type of antenna used was a Vivaldi antenna with an operating frequency range of 1-10 GHz. The distance between the antennas used was 8 cm, and the distance between the antenna and the ground surface was 12 cm. The frequency range used by the VNA was 0.3-8000 MHz. This experiment was tested by detecting a 5 cm x 10 cm diameter can buried 17 cm deep in the ground.

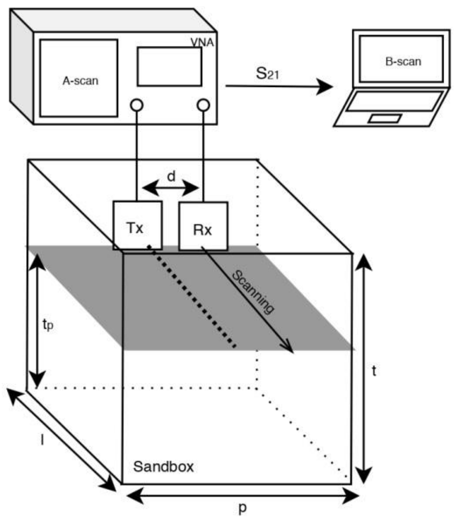

Figure 3. Modelling Experiment

The processing of the acquired signals is carried out using software and represented as radar images. Radar images consist of A-scans, which are one dimension, B-scans, which are two dimensions, and C-scans, which are three dimensions **(Saintenoy et al., 2025).** Data acquisition at a single point in the survey area is referred to as an A-scan signal, which, when placed above the target, shows signal reflections originating from the ground surface and objects buried within it.

This research converts the signals collected into B-scans. If the A-scan data collection at a single point does not produce any signals, the data collection will be repeated until the desired results are obtained. Once the A-scan signal has been successfully obtained for all points along the x-axis, the data is then collected to form B-scan data. The results of the B-scan image are used to analyse the differences between coupling signals, clutter, and targets.

The B-scan image will show the difference in signals produced by clutter and targets, enabling clutter reduction, where these signals are unwanted. Clutter reduction also makes the target signal more dominant. The next step is clutter reduction. The clutter method can reduce clutter and improve the SCR ratio in detection results. The methods used in this study for clutter reduction are Weighting Process, Averaging, and SVD. The weighting process is a method that uses cross-correlation to determine the weighting factor **(Pramudita et al., 2022)**. The weighting process method can be expressed as follows in (2). The weighting process is implemented using a cross-correlation approach to measure the degree of similarity between the received signal and the clutter signal. This approach enables adaptive reducing the clutter by giving the greater weight to components with high correlation.

The averaging method can be written in (3). The averaging method assumes that clutter remains relatively constant accros multiple measurement. An estimate of the clutter is obtained by calculating the average, and then substracting it from the main signal. SVD is a factorization of a matrix into U and V, as well as S, a diagonal matrix. SVD can be calculated using (4). The SVD method used for seperated signal and clutter components based on the distribution of energy across subspace. S contains singular value which means signal energy. In this signal, that dominant values known as clutter are removed and signal then reconstructed using the ramining components. However, thw effectivity of this method depend of selection of appropriate rank. GPR performance can be analysed using signal processing results and clutter reduction. Finally, the analysis results obtained in this study are used to conclude the performance of the GPR system. They can serve as a basis for further study on methods for reducing clutter. Illustrations of the A-scan and B-scan signals are shown in Figures 4 and 5.

$$Wp = S_r \times cross\ correlation \tag{2}$$

$$S_{raveraging} = \frac{1}{n}\sum_{a=1}^{n} S_{clutter} \tag{3}$$

$$X = UVS^T \tag{4}$$

where Wp is weighting process, S_r is receive signal, $S_{raveraging}$ is receive signal for averaging method, n is number of measurements, X is matrix B-scan decomposition svd method, $S_{clutter}$ is clutter signal, U and V is matrixes factorization and S diagonal matrix.

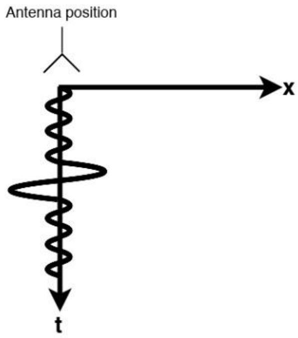

Figure 4. A-scan Signal

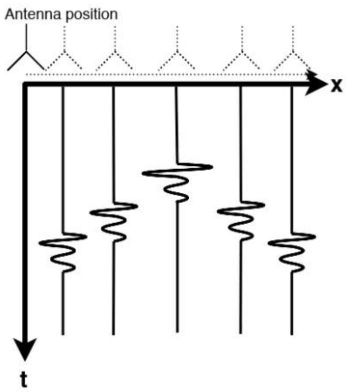

Figure 5. B-scan Signal

3. RESULT AND DISCUSSION

3.1 Qualitative and Quantitative Analysis

The signals obtained in this experiment were analysed quantitatively and qualitatively. In this study, A-scan and B-scan signals were used for qualitative analysis. Clutter reduction in B-scan affects the clarity of the hyperbolic pattern of the target. Therefore, the method used for clutter reduction can enhance data readability, making the qualitative results of this study more visible. The A-scan and B-scan results of this experiment are shown in Figure 6 and Figure 7, respectively. The A-scan displays different signal magnitude values based on the depth obtained from the coupling reflection, the ground surface, and the target. The data was collected in the time domain to demonstrate that the position matched the actual target location. Figure 1 shows three peaks marked S_1, S_2, and S_3. Peak S_1, corresponding to the antenna coupling, is recorded at 1.329×10^{-8} seconds.

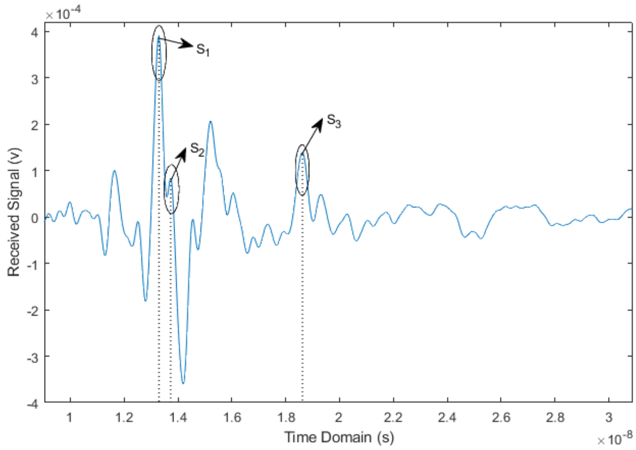

Figure 6. A-scan Result

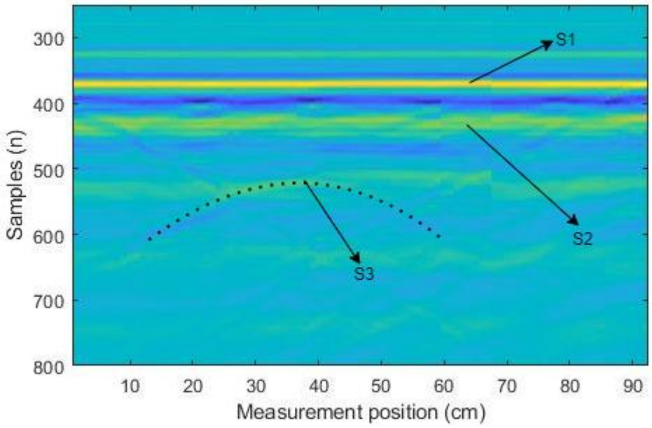

Figure 7. B-scan Result

In contrast, peak S_2, representing the ground surface, is recorded at 1.376×10^{-8} seconds, and peak S_3, originating from the target, is recorded at 1.8661×10^{-8} seconds. The time difference in this measurement is multiplied by the wave propagation speed and divided by two to calculate the distance in this study. The difference between the antenna and the ground surface is 0.47×10^{-9} seconds, and the difference between the ground surface and the target is 4.85×10^{-9} seconds.

The (4) calculation is used for quantitative analysis. For the first step, the velocity and the propagation time must be known so that it can be calculated. The velocity used was 144.07 x 10^6 m/s, and the propagation time was 10.64 x 10^-9 s. The result for the position was 17.003 cm, while the actual depth was 17 cm. In this study, data were collected in several times under the same conditions to ensure the reliability of the results obtained. The detection accuracy rate between after reduction and the actual depth reached 99.728%. it means that clutter reduction method for this experiment did not change the position target. The wave velocity value used was for heterogeneous soil, which affects the wave velocity.

3.2 Analysis Result

The experimental results show that the presence of targets affects the distance of the reflected signal. The clutter reduction process was carried out by comparing three methods, namely the weighting process, averaging, and SVD. Figure 8 shows the results of clutter reduction using the weighting process. This method reduces clutter caused by antenna coupling and surface clutter. Figure 9 shows the results of clutter reduction using the averaging method, which only reduces the ground surface portion. Figure 10 shows the results of clutter reduction using SVD.

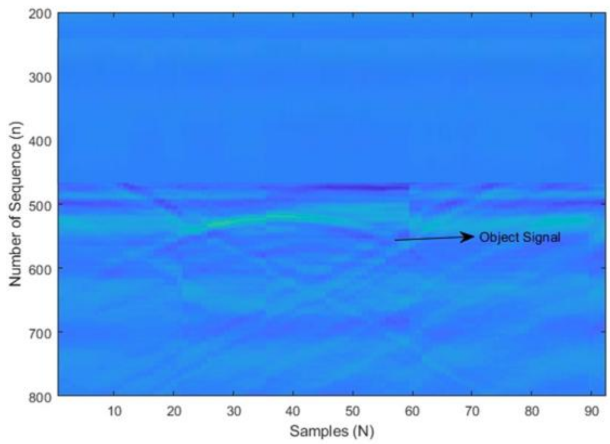

Figure 8. Clutter Reduction using Weighting Process

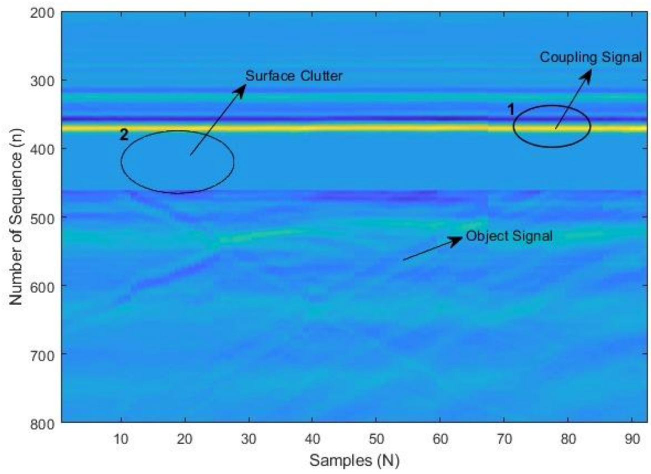

Figure 9. Clutter Reduction using Averaging

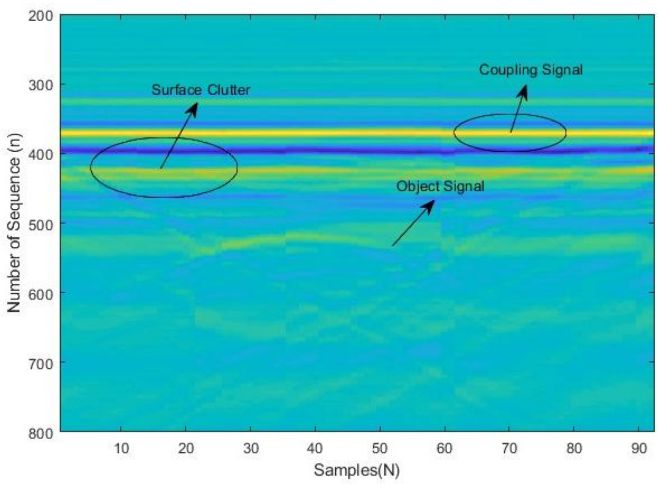

Figure 10. Clutter Reduction using SVD

From the three clutter reduction method experiments, qualitatively better results were obtained using the weighting process. Qualitatively, clutter reduction can be seen from the increase in SCR. The SCR calculation results in this study are shown in Table 1.

Table 1. SCR Result

Before clutter reduction	After clutter reduction		
	Weighting process	**Averaging method**	**SVD**
-27.37 dB	28.81 dB	25.31 dB	4.45 dB

A method can be successful when the SCR increases by 1-30 dB. From the table, it can be concluded that the SCR calculation in this experiment is -27.37 dB. After clutter reduction, a different SCR value was obtained. For the weighting process, the SCR value becomes 28.81. This value indicates that the increase in SCR obtained after reducing clutter using this method exceeds 10 dB. For averaging method is 25.31 dB. The increase in SCR obtained is more than 10 dB. Meanwhile, for SVD, this method achieves an SCR value of 4.45 dB and exhibits an SCR increase of less than 10 dB. Therefore, the weighting process is effective at reducing clutter, as evidenced by the increase in SCR obtained.

The experiment results show that weighting process generates the highest increasing the SCR values compared to others method. This is due to the adaptive nature of the weighting process, which is capable of adjusting clutter reduction based on signal similarity. Alternativelty, the averaging method has limitations as it relies on the assumption that clutter is stationary. This causes it to be less effective in heterogeneous terrain conditions. Meanwhile, the SVD method exhibits sensitivity to rank selection, an incorrect separation between the signal and clutter subspaces can lead to the loss of target information or the persistance of clutter.

4. CONCLUSION

This study concludes that GPR radar, which is assumed to use VNA and two antennas, is capable of detecting targets buried 17 cm below the ground surface. This detection is divided into two radar images, namely A-scan and B-scan. These two images are used to analyse qualitative results. After reducing clutter using three methods, namely the weighting process, averaging, and SVD, good qualitative results were obtained. Quantitatively, the increase in SCR obtained by the three methods was quite good, especially the weighting process and averaging methods. The weighting process increased the SCR from -27.37 dB to 28.81 dB, while the averaging method increased the SCR from -27.37 dB to 25.31 dB. SVD only slightly increased the SCR from -27.37 dB to 4.45 dB. This could be due to the complex selection of U and V, resulting in less-than-optimal results.

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