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Comparative Analysis of Singular Value Decomposition and Linear Trend Subtraction for Stationary Clutter Reduction

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Abstract—Detecting people under rubble using FMCW radar is a more efficient approach than conventional methods. This FMCW radar system detects small movements associated with inhalation and exhalation. However, one challenge in searching for people buried in rubble is the debris clutter. Therefore, clutter reduction is necessary. In this paper, two clutter-reduction methods are used: Singular Value Decomposition (SVD) and Linear Trend Subtraction (LTS). The results show that both methods can reduce clutter caused by wall obstructions. Performance evaluation in this study was based on improvements in the Signal-to-Clutter Ratio (SCR), which indicates how effectively the methods reduced clutter. The analysis results show that the SCR obtained with the LTS method was higher than SVD method across the scenarios tested. Furthermore, the breathing rate detected after clutter reduction showed a slight difference compared to the initial measurement.

Keywords: Singular value decomposition, Linear Trend Subtraction, Clutter Reduction, FMCW Radar, Small Movement .

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1. Introduction

Radar is used in a variety of applications, including post-disaster response, due to its ability to detect small movements beneath rubble, estimate distances, and consume relatively low power. Several types of radar, such as Doppler radar [1], ultra-wideband (UWB) radar [2], ground penetrating radar [3], [4], and frequency-modulated continuous-wave (FMCW) radar [5], [6], [7], have proven capable of detecting hidden targets. In this study, data acquisition was performed using FMCW radar due to its superior range resolution [8]. All radars, including FMCW radars, face challenges detecting targets behind debris caused by obstructing walls, commonly referred to as clutter, which degrades system performance. This issue becomes increasingly complex in dynamic and non-stationary environments. Therefore, clutter reduction is necessary to process the signals acquired by the FMCW radar system.

Conventional methods, such as filtering, are effective in homogeneous environments but less accurate in heterogeneous environments. Consequently, this experiment was conducted using alternative methods. Several methods in several study already used to reduce the clutter [3], [4], [5], [6], [7]. One method that has been widely used in recent years is singular value decomposition (SVD), which decomposes the received signal into a set of dominant and residual components [9]. Although SVD is widely used and has many advantages, it involves highly complex computations, and the selection of components to be decomposed must be very strict to ensure the resulting decomposition is more accurate. To address the limitations of SVD, an alternative method, Linear Trend Subtraction (LTS), is proposed because it is computationally simpler. LTS removes the linear trend from the signal, thereby reducing clutter more simply than SVD.

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A clutter reduction method based on a weighting process was presented in earlier paper [5], [6]. That preliminary work was restricted to complicated circumstances with irregularly arranged clutter, regardless of the observation that it performed SVD and LTS in reducing debris clutter from FMCW radar. Those basic methods fared badly under such circumstances, leaving the basic operational limitations and spatial dependency of LTS unused. In addition a consequence, it presents a crucial research gap on the underlying capabilities and particular boundary circumstances under which basic methods like LTS operates at their best.

This study demonstrated performance of SVD and LTS under structured, flat-positioned stationary debris as clutter. The primary contribution of this study is establishing that the simpler LTS method can match the performance of the sophisticated weighting process under specified spatial clutter configurations, and this method will compare with SVD. In order to set a standard for the operational limits of basic clutter reduction methods in radar processing. Therefore, the main objective of this study is to reduce the partial clutter conditions to establish the clutter reduction. The performance evaluation of the methods was based on their ability to improve the Signal-to-Clutter Ratio (SCR) and enhance the accuracy of respiratory signal extraction.

2. Method

The detection of objects within a radar system's field of view is achieved by transmitting electromagnetic waves into the environment and receiving the returning signal, which contains the desired information. Generally, a radar system comprises a transmitting antenna, a receiver, and a signal processing module [10]. In this study, Frequency Modulated Continuous Wave (FMCW) radar was used. This radar was chosen for its ability to measure distance and its sensitivity to detecting small movements, including chest movements caused by breathing [11], [12]. The small movements detected by the radar range from millimeters to centimeters. This detection is based on changes in the phase of the reflected signal during breathing [13].

FMCW radar is a radar system that continuously transmits electromagnetic signals at a frequency that varies over time and within a specific bandwidth range [14]. The frequency variation at the core of this radar is used to detect the presence of objects. This frequency variation is obtained by mixing the transmitted signal with the received reflected signal [15]. Generally, FMCW radar uses a chirp signal that is frequency-modulated using frequency modulation techniques [5]. This causes the signal frequency to increase gradually over a specific time interval. This modulated signal is transmitted to the target and reflected, enabling further processing to obtain the desired information.

This radar comprises a ramp generator that produces a chirp signal [16]. After being amplified by a power amplifier, the chirp signal is transmitted via the transmit antenna. The reflected signal from the target and clutter is received by the receiving antenna, amplified by a low-noise amplifier, and then correlated with the transmitted signal in the mixer. The signal is then filtered, and a low-pass filter is used to produce an intermediate frequency (IF) or beat frequency, which is the difference between the transmitted and received signals. This signal is used to determine the parameters of range, velocity, and angle of arrival of the reflected signal.

The IF signal is used to detect objects and estimate distance, and to estimate Doppler shifts via fast Fourier transform (FFT) calculations [17]. The FMCW radar system for detecting human respiration beneath rubble operates based on the received echo signals. The received echo signals consist of reflections from obstacles, the target, and other objects surrounding the target. Clutter reflections are the most dominant signals and have the highest amplitudes; they result from the radar's proximity to obstacles, which causes the target reflection to be very small and obscured. Reflections produced by obstacles and other objects tend to have a constant, unchanging phase. In contrast, reflections originating from the target have a phase component that changes over time due to human respiratory activity.

AIJASET – Vol. 06, No. 03, November 2026. 348-358
https://doi.org/10.25077/aijaset.v6i3.348

In the resulting signal, the signal is divided into wall and target components. Signals originating from the target enter the region of interest (ROI) [18]. After that, signals originating from obstacles are ignored, and the portion of the ROI signal is further investigated. This process is carried out at a single A-scan point to determine whether the target is detected. Meanwhile, to reduce clutter, obstacle signals are still included. To this end, data were collected across the entire observation area. After obtaining signals at each point in the observation area, the signal data is compiled into a B-scan matrix. The point with the maximum amplitude within the observation area is selected as the target point. Clutter from surrounding objects is reduced, enabling the target to be identified. The block diagram radar is shown in Figure 1.

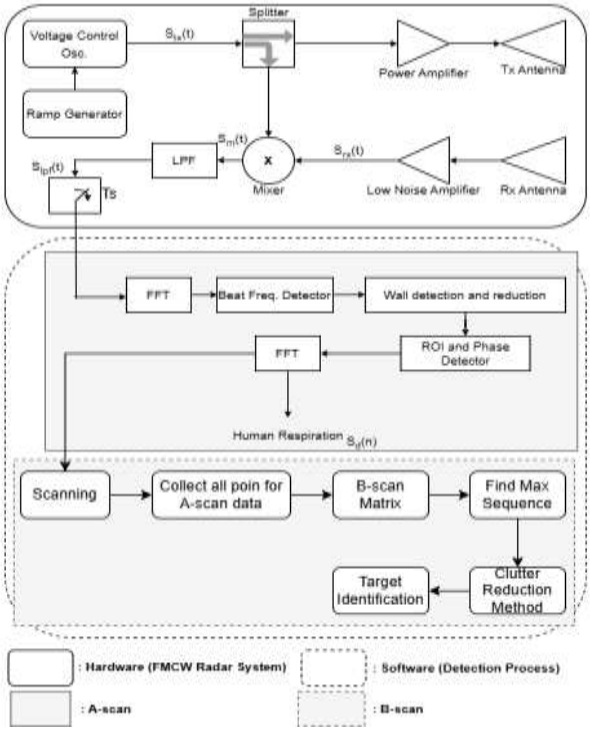


Figure 1. Block Diagram FMCW Radar System

2.1 Clutter Reduction

The SVD method is a matrix decomposition technique that has been widely used previously in signal processing and clutter reduction in radar signals [19]. This method was chosen for its ability to separate a signal's main components based on their energy. This method is divided into three matrix components, namely the orthogonal U, the diagonal S, and the orthogonal V^T [9]. The diagonal S matrix contains singular values that indicate the energy or contribution of data components to the overall signal. Generally, the largest singular value indicates the most dominant component, and conversely, the smallest value indicates noise components or weaker signals [20].

In this study, the SVD method was applied to the B-scan matrix before clutter reduction. The B-scan matrix is denoted by $\theta_{(n,m)}$, where m is the number of scan points and n is the number of data samples at each scan point. The matrix decomposition using the SVD method is given by (1).

$$\theta_{(n,m)} = USV^T \quad (1)$$

where U is an m×m orthogonal matrix, V is an n×n orthogonal matrix, and S is an diagonal matrix containing non-negative singular values. The values in matrix S are arranged in descending order, from the largest to the smallest. Singular values typically indicate reflections from clutter, objects, noise, or low-energy signal information. In practice, the matrices U and V are obtained from the singular vectors resulting from the decomposition of the matrices $[\theta_{(n,m)}\ \theta^T_{(n,m)}]$ and $[\theta^T_{(n,m)}\ \theta_{(n,m)}]$.

When applying the SVD method, clutter reduction is achieved by analyzing the distribution of singular values and identifying the singular component that represents the dominant clutter. Subsequently, clutter reduction is performed by reducing the contribution of the dominant singular value, followed by reconstruction [21]. This enables separating the target signal from the clutter component based on their signal energies. This method is widely used to identify the dimensions or directions in which data varies. Previous studies [5], shown that SVD can reduce clutter by eliminating the first singular value, which is often caused by debris with a dominant signal. However, other studies have shown better results when the reduction is applied to the third singular value or a combination of specific singular values. Consequently, the evaluation and selection of singular values must be carefully carried out to achieve good clutter-reduction performance and obtain the desired target information.

The second method is LTS, a technique that estimates the static component and the linear trend in the radar scan data matrix [22], [23]. This static component is subtracted from the raw data to obtain a signal that better represents the dynamic target. This method effectively reduces the influence of fixed reflections from the environment, such as obstacles that obscure the target. In the LTS method, a linear least-squares fitting approach is applied to the received data matrix along the scanning direction. This is used to estimate the linear trend of the static clutter signal. Once the linear trend is obtained, the component is subtracted from the original data matrix, leaving only the signal component that varies with time or target position. The LTS method equation is shown in (2).

$$s_{lts} = \theta_{(n,m)} - X(X^T X)^{-1} X^T \theta_{(n,m)} \quad (2)$$

where $\theta_{(n,m)}$ is the original data matrix received from the radar, etc. In (2), the matrix X represents the linear trend model for the scanned data. The component $X(X^TX)^{-1}X^T \theta_{(n,m)}$ is an estimate of the linear component of the clutter signal, whilst the result of subtracting the original matrix yields the signal after clutter subtraction. In (2), $X \in \mathbb{R}^{mxp}$ represents the design matrix modeling the background linier trend across slow-time scan traces, where p=2 corresponds to a constant baseline and a first-order linier ramp.

The advantage of the LTS method lies in its relatively simpler implementation compared to SVD, without requiring high computational complexity. Furthermore, this method is effective in environments where reflections are predominantly static, as it can separate signal changes caused by moving targets from the linear trends of the environmental signal. Consequently, the LTS method is widely used for flat, static environments in radar detection.

2.2 Clutter Configuration and Processing Procedure

The clutter in this experiment is arranged in a structured, flat-positioned orientation relatives to the radar scanning direction, in contrast to earlier investigation [5], which looked at randomly distributed debris. In order to evaluate how LTS accommodates uniform linier trends in comparison to energy-based SD decomposition, this setup isolates the spatial features of stationary clutter. Several consecutive steps represent the entire signal processing procedure, which include collection of raw B-scan data and representation as matrix $\theta_{(n,m)}$, clutter reduction using SVD and LTS method, phased extraction of the respiratory signal of the target, and quantitative evaluation. The Signal to Clutter Ratio (SCR) enhancement is computed as follows to assess the effectiveness of the clutter reduction. The increasing of SCR equation is shown in (3).

$$SCR = s_{target} / s_{clutter} \quad (2)$$

where s_{target} and $s_{clutter}$ represent the signal from target respiration and sum of clutter signal, respectively.

3. Result and Discussion

In this study, a 24 GHz FMCW radar mounted on a concrete block was used, operated remotely via a laptop. The target was a man lying beneath the rubble. The concrete was 20 cm thick, and data collection lasted 1 minute. An illustration of the radar and subject positioning is shown in Figure 2. The

radar was placed on top of a stack of concrete bricks positioned over the target's chest and abdomen to test the accuracy of the radar. Data was then collected across the desired area. The distance between the radar and the floor was 50 cm. The bricks covering the target were arranged flat, with no steps or other bricks around the target.

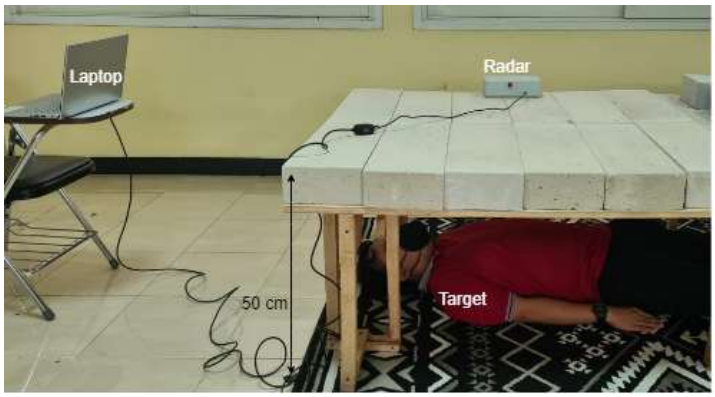


Figure 2. Illustration of radar and subject positioning

A radar operating at 24 GHz has approximately 10 times the sensitivity of a radar at 2.4 GHz, thereby enhancing the amplitude of small movements by about 20 dB. Radar sensitivity offers an advantage in detecting target movement. For this purpose, the fast Fourier transform (FFT) is applied to the beat frequency sample, yielding a spectrum with peaks associated with the target position, commonly referred to as the FFT index. In this study, FFT index 5 indicates clutter, and the target region of interest (ROI) is 6–16. The maximum ROI area is determined based on the original experimental depth of 50 cm. This distance is derived from radar calibration data collected prior to the experiment. A-scan data shown is Figure 3.

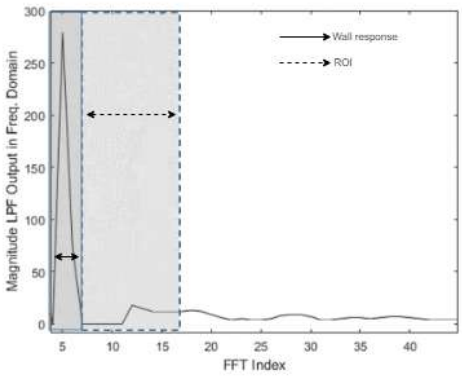


Figure 3. A-scan response

Following this, signal processing is carried out, specifically unwrapping to remove the DC offset and applying a low-pass filter (LPF) to smooth the signal. Both steps are performed to determine whether a human is present, based on the normal human respiratory rate range of 0–40 breaths per minute [24], [25], [26]. To determine the human respiratory rate, the signal, which was originally in the time domain, is converted to the frequency domain using a second FFT. Following this, a scanning process is carried out to determine the target's position; in this experiment, there are 36 observation points spaced 3 cm apart. Figure 4 and Figure 5 shows the B-scan results with and without target under rubble prior to clutter reduction.

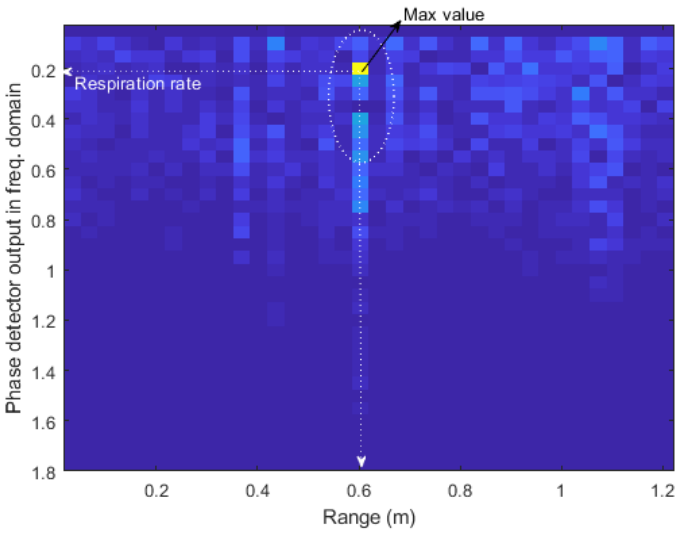


Figure 4. B-scan result with target

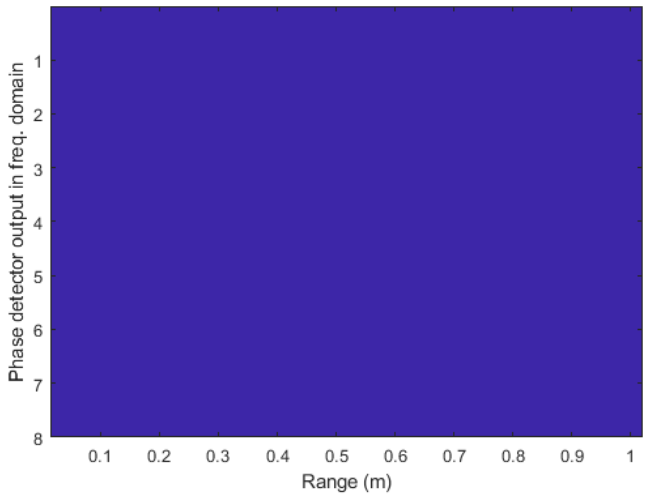


Figure 5. B-scan result without target

Next is the clutter reduction process using the SVD and LTS methods. In the SVD method, the matrix is m × n, where m is the number of scan points (36), and n is the number of data samples (140). Each single-point scanning process produces 512 frames with a scan time of 140 seconds. The SVD method proceeds by first calculating the U and V matrices, then forming the diagonal S matrix. After that, the eigenvalue and eigenimage calculations are performed. The clutter-reduction process is performed by subtracting the eigenimage result from the B-scan matrix prior to the reduction. This was then carried out using the LTS method. The LTS method estimates the static component and the linear trend in the observation area. The initial stage of this method involves constructing a linear trend matrix using a [k/n] matrix, where k is the number of points in the B-scan matrix (36). Once the linear trend matrix has been obtained, the clutter reduction process is performed by subtracting the initial B-scan matrix from the result of processing the linear trend matrix, which involves matrix transposition and inversion.

The clutter-reduction process using the SVD method decomposes the data matrix into several eigenimage components. Selecting the eigenimage ordering is a crucial step for achieving optimal clutter-reduction results in the first scenario. Based on the test results, the first eigenimage provides the best reduction, followed by the second and third eigenimages, as shown in Figures 6, Figure 7, and Figure 8. Therefore, the first eigenimage is used in the clutter reduction process in this study. For the

AIJASET – Vol. 06, No. 03, November 2026. 348-358
https://doi.org/10.25077/aijaset.v6i3.348

LTS method, linear trend reduction is applied to the scanned data matrix. This process aims to eliminate static components and linear trends present in the observation data. The clutter-reduction results from the LTS method in the first scenario are shown in Figure 9. Based on this visualization, the LTS method produces an image with a dominance of dark blue around the target, whilst the target itself appears in bright yellow. This indicates that both methods are capable of reducing clutter quite effectively, as the darker the background color in the B-scan image, the fewer clutter components remain. Furthermore, the area around the target also appears cleaner, with minimal occurrence of other colors resembling the target.

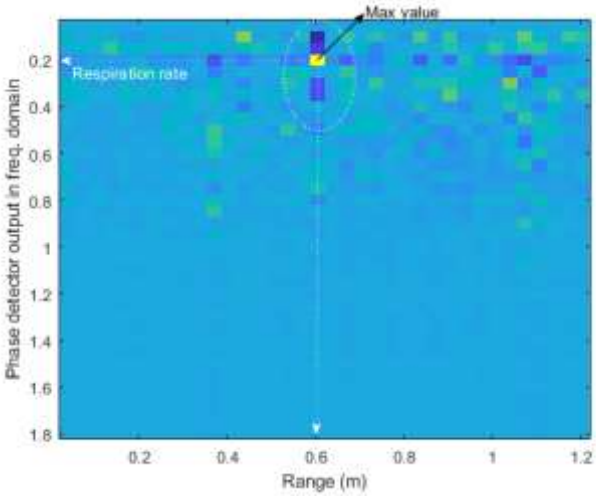


Figure 6. The result of reducing clutter using Eigen 1 of SVD method

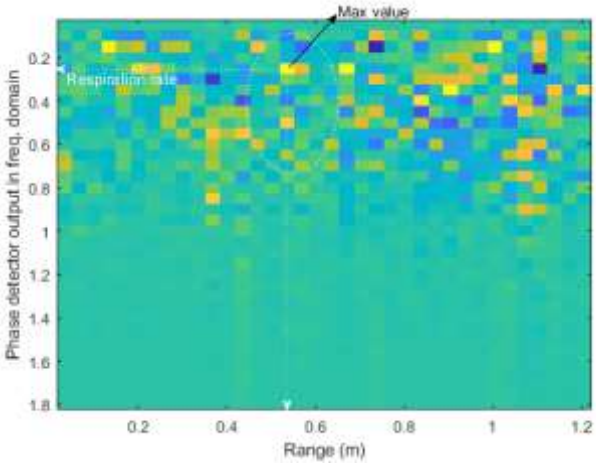


Figure 7. The result of reducing clutter using Eigen 2 of SVD method

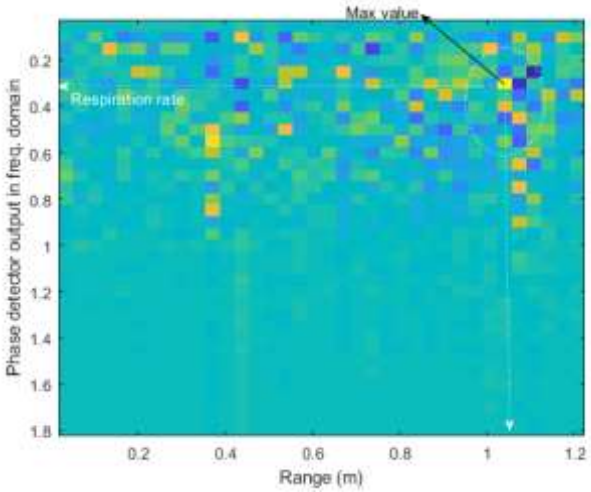


Figure 8. The result of reducing clutter using Eigen 3 of SVD method

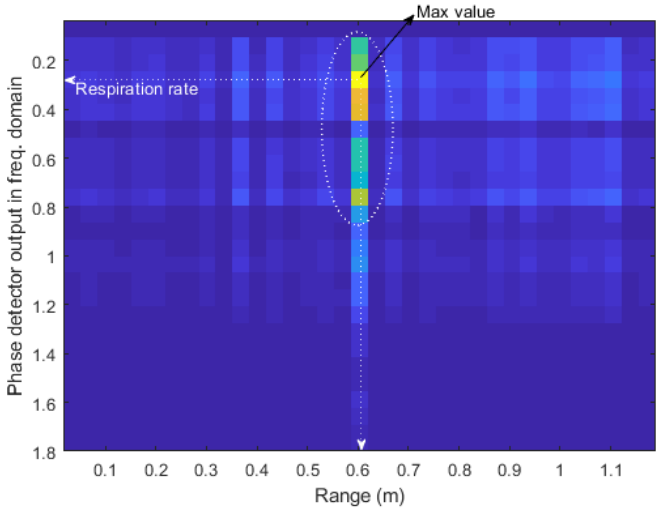


Figure 9. The result of reducing clutter using LTS method

Conversely, the results of the reduction using the SVD method still show a predominance of light blue, with several other colors around the target that are close to the main target color. This indicates that the SVD method in the first scenario still leaves significant clutter, indicating that the separation between the target and its surroundings is not yet optimal. Based on the detection results after the clutter reduction process, both methods successfully identified the target's position at approximately 0.6 m. Furthermore, the target's respiration rate was determined to be 0.2 Hz, equivalent to approximately 12 breaths per minute. Next, the accuracy of the methods was verified by calculating the increase in the signal-to-clutter ratio (SCR). Based on the resulting increase in the ratio, SVD improved it by approximately 3 dB, whilst LTS produced a larger increase. According to [5], the SVD and LTS methods yield nearly identical results; however, under the conditions of this study, LTS showed a greater increase than SVD. It can be concluded that the LTS method is superior in reducing clutter when the bricks are arranged evenly. A comparison of the SCR for each method is shown in Table 1.

Table 1. Comparison of SCR

Before Clutter Reduction	**After Clutter Reduction**	
	SVD	**LTS**
-16.62 dB	3.24 dB	14.81 dB

After calculating the SCR enhancement for each clutter reduction method, the maximum value in the B-scan image was used to determine the target's respiratory rate. The results of the respiration rate detection are shown in Table 2. Based on these results, the SVD and LTS methods did not change the respiration rate following the clutter reduction process. Meanwhile, in [3], the LTS method did result in a change in the respiration rate value. However, in the process of evacuating disaster victims, the most important information is the presence of the target's respiration, not the exact details of the respiration rate.

Table 2. Result of the respiration rate detection

FFT (actual)	SVD	LTS
0.2685 Hz	0.2 Hz	0.2 Hz

Based on the results in both tables, it can be concluded that the LTS method performs better than SVD, as it increases the SCR value by a greater amount without altering the respiratory rate detection results. The increase in SCR using the SVD method was 3.24 dB. Meanwhile, the LTS method produced an increase of 14.81 dB. For respiratory rate detection results, both SVD and LTS produced a maximum value of 0.2 Hz. Based on these results, the LTS method has a fairly good clutter-reduction capability, as it increases the SCR value more significantly than the SVD method. However, according to research [3], this method lacks stability in SCR improvement and causes changes in respiratory rate detection results following clutter reduction when the detected conditions become complex. On the other hand, the SVD method demonstrates stability in respiratory rate detection. However, the resulting increase in the SCR value remains relatively low, indicating its clutter-reduction capability is less than optimal.

4. Conclusion

Based on the test results, the LTS method demonstrated better clutter-reduction performance than the SVD method, improving the Signal-to-Clutter Ratio (SCR). The LTS method produced an increase in SCR of 14.81 dB, whilst the SVD method produced only 3.24 dB. Furthermore, both methods yielded the same respiratory rate detection value, namely 0.2 Hz, indicating that the clutter-reduction process did not affect respiratory rate detection under the test conditions. These results indicate that the LTS method is more effective at mitigating clutter than the SVD method. However, the LTS method exhibits performance fluctuations under more complex environmental conditions, which may affect respiratory rate detection results after clutter reduction. Meanwhile, the SVD method yields more stable respiratory detection results; however, the resulting increase in SCR remains relatively low, indicating its clutter-reduction capability is not yet optimal. Thus, the LTS method is superior at improving signal quality by increasing SCR values, whilst the SVD method is better at maintaining the stability of respiration detection results.

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