Frequency 3D slice image visualization for GPR applications

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Abstract. Ground Penetrating Radar (GPR) is an efficient tool for the detection of the underground utilities. However, most data collected by GPR are in the spatial/time domain, the information in frequency domain is sometimes neglected. Joint Time-frequency Analysis (JTFA) methods are widely used to deal with the problem. In this paper, we propose a further application based on JTFA method to reconstruct the frequency 3D slice image visualization (frequency C-scan) to represent the distributions of the main frequency components of the surveying area. The experiments are conducted in our sandbox with a PVC pipe buried in. After employing the proposed signal processing flow, the frequency C-scan can be re-constructed. By segmenting the frequency C-scan, frequency distribution over a surface at particular radar time/depth can be obtained. The results exhibit the capability of the proposed method to show the spatial and frequency signatures of the buried objects at certain depth.

1. Introduction
The rapidly expanding underground utility network has become one of the most complicated artificial networks in the world. It is of great significance to obtain the information of underground utilities, such as buried pipes. As one of the most efficiency non-destructive testing (NDT) methods, GPR has been widely used in assessing the condition of the buried utilities [1], detecting water leakage [2][3] etc. However, the data directly collected by GPR mostly shows the information in time domain, the information in frequency domain is sometimes neglected. The analysis of the frequency information may provide additional insightful perspective. For example, the analysis of the newly proposed GPR-RFID system [4] is mainly in the frequency domain.

For the comprehensive analysis of the collected data, Joint Time-frequency Analysis (JTFA) methods are conducted to transfer the data from time domain to time-frequency domain. Previous studied have developed many JTFA methods, such as short-time Fourier transform (STFT) [5], wavelet transform [6] and S transform [7]. However, these widely employed methods suffer low time-frequency resolution which largely limits their practical implementation for GPR applications. So, in this study, we choose the variational mode decomposition [8] (VMD)-based JTFA method in particular, which shows intrinsic advantages in higher time-frequency resolution than the traditional ones. The VMD method is a newly developed method for adaptive and quasi-orthogonal signal decomposition. Combining with the instantaneous frequency, a sparser time-frequency spectrum with high resolution can be obtained.

Further technologies can be applied on the data after transferring, such as the constant-frequency slicing and peak frequency slicing. The peak frequency slice refers to a 2D dataset which shows the main frequency distribution of the corresponding B-scan. By aligning the slices, we can obtain a sparse 3D dataset. Combining with the data interpolation method, the frequency 3D slice image visualization (frequency C-scan) can be obtained, then we can figure out the frequency distribution over a surface at certain depth by segmenting the slices at particular radar depth.
In this paper, we propose a method to construct a 3D dataset which represents the distribution of the main frequency components of the scanning area. The experiment setups are first introduced. Then, a signal processing flow is designed to improve the signal-to-noise ratio (SNR), transfer the data to time-frequency domain and reconstruct the frequency C-scan. Finally, combining with the collected GPR data, we give our interpretation of the frequency distribution of the scanning subsurface.

2. Experiment Setups
The field experiments are conducted in our 2.0×1.5×0.75 m wooden tank filled with dry sand, of which the relative permittivity is 3, as shown in Figure 1. The GEOTECH OKO-3 pulsed GPR with 1200 MHz antenna is chosen to collect the data. A 75 mm external diameter and 72 mm internal diameter PVC pipe is buried in the sandbox which is positioned horizontally 20 cm away from the sand surface. The photo and schematic of the setup are shown in Figure 1 and 2a, respectively.

Figure 1. The sandbox with the buried pipe at the top (front). The GPR survey area is represented by the arrow.

Data collections of the experiments are performed in an orthogonal grid overlaid on the sand surface, which is shown in Figure 2b. The grid is designed to match the center point of the buried pipe for the easy recognition of the pipe. 1D A-scan data are laterally compiled to build 2D B-scan radar images where the JTFA method is applied on. There are 7 GPR traverses (X1-X7) parallel to the x-axis and another 5 traverses parallel to the y-axis (Y1-Y5) of the designed grid. All collected GPR data are post-processed by the following proposed signal processing flow for radargram display and frequency C-scan construction.
3. **Signal processing**

The proposed signal processing flow is mainly divided into three parts, which is displayed in Figure 3. The first is basic signal processing part which is consist of three steps, DC offset removal, time-zero correction and background removal [9]. This part is focus on improving the low signal-to-noise ratio (SNR). The second is JTFA and the peak frequency slices acquisition. After transferring the data into time-frequency domain by JTFA method, we can pick the frequency corresponding to the peak amplitude point at each sampled time step in every A-scan, then align and combine them to construct a 2D dataset, which is also known as the peak frequency slices. The last is frequency C-scan reconstruction. By aligning every obtained slice corresponding to each B-scan data, we can construct the initial 3D dataset. As for frequency information at the points not covered by radar traverses, Scattered Data Interpolation with Multilevel B-Splines [10] method is implemented to interpolate. Then the frequency C-scan can be obtained.

![Figure 3. The proposed signal processing flow.](image)

Figure 4a shows the B-scan data of traverse X4 after basic processing, as we can see, the direct waves are largely removed and the visuality of the object is greatly enhanced. It shall be noted that though the background removal method removes most of the background, the residual still exists, especially those reflected from the tank walls. Figure 4b is the peak frequency slice of traverse X4, as can be seen, it...
shows the distribution of the main frequency components. At time-zero position, which refers to the ground position, the frequency response is scattered and higher than the center working frequency of the GPR. It can be explained by the background residual. The frequency response at 2.5 ns can be seen as the response of the pipe at around 1300 MHz which is a little higher than the GPR center working frequency, 1200 MHz. The frequency response of the tank wall can also be recognized at 9 ns, which is at around 1000 MHz and does not affect the main object response.

**Figure 4.** (a) The B-scan image of traverse X4 after basic signal processing. (b) The peak frequency slice of traverse X4.

### 4. Results

After collecting the peak frequency slices of each B-scan data and the data interpolation, we can obtain the frequency 3D slice image visualization. Then, slices are segmented at particular radar time to represent the frequency distributions, which are displayed in figure 5.

**Figure 5.** Slice scans in frequency C-scan at (a) 0 ns, (b) 2.5 ns and (c) 6 ns.

As can be observed in Figure 5a, the frequency distribution at 0 ns is notably scattered and it is caused by the remaining background noise. And most of the frequency response is at around 1100 MHz. In Figure 5b, a rectangular frequency distribution can be seen obviously, which is indicated by the black rectangle. This area is believed to be the response of the PVC pipe at 2.5 ns and 21 cm deep. The frequency response is at 1300 MHz, which is a little higher than the center working frequency of the GPR. Besides, scattered noises can be found in other area. And in the slice scan at 6 ns, no main frequency distribution can be observed expect several scattered noises, in fact, there is no change of material property at that depth in the sandbox.

### 5. Conclusions

In this work, we propose a signal processing flow for frequency 3D slice image visualization construction for GPR applications. This frequency C-scan allows for analysis of the frequency distribution over a surface at particular radar time/depth. Combining with VMD method, time-frequency
spectra with high resolution can be obtained. The slice scans show potential to obtain the spatial and identification information of the buried objects in frequency domain at certain depth, which is recommended for GPR applications, such as GPR-RFID system.

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