On the Application of Multi-frequency Ground-Penetrating Radar Method for Mapping Underground Pipe

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Abstract. Ground penetrating radar (GPR) method is commonly used to map underground pipe network due to its ability to map objects on shallow area and its minimum effect to surrounding area, although the resolution and depth of interest of mapping really depend on the antenna’s frequency. To improve the resolution of object that is going to be detected, more than one antenna frequencies are used in a measurement in the same line and multiple-frequency compositing is performed to combine those radargrams to simplify the analysis. This research will use and compare three compositing methods ability, i.e. simple summation, comparison of average radargram amplitude spectrum of each radargram, and least-square weighting according to Berlage wavelet analysis - called also Optimal Spectral Whitening (OSW), to map a big pipe with metal casing that surrounded with some metal cables from 200 MHz and 400 MHz radargram datasets. Comparisons of those three methods mentioned above were performed through the analysis of each radargram and sample trace analysis on some positions to show the ability of each method in separating boundary of each medium. The analysis showed that multiple-frequency compositing was able to improve resolution for showing underground condition, with OSW method had better ability compared to other methods.

1. Introduction

The mapping of subsurface infrastructure networks with shallow depths, such as mapping subsurface pipelines, is one of the problems in the geotechnical field. Ground penetrating radar (GPR) are commonly used because of their non-destructive nature and do not interfere with activities in the research area. This method is also effective in providing information about the existence, location, and depth of an object below the surface.

Although the GPR method is effective for mapping shallow areas, this method has a disadvantage regarding the depth and resolution range that is highly dependent on the frequency content of the antenna used. The frequency of GPR antennas used in a survey determines the range of depth and spatial and temporal resolution [1]. If the object to be mapped has varying sizes with different depths, it is commonly used various GPR antennas with various frequencies to map general conditions in the measurement area on the same measurement path. To obtain a more comprehensive subsurface view, the radargram as the result of GPR data acquisition at different frequencies but taken on the same path is combined into one radargram. The process of combining the radargram is also called multiple-frequency radargram compositing [2].

This research will explain the application of multiple-frequency radargram compositing to improve the quality of mapping the condition of a subsurface pipe and cables surrounding the pipe. There are
three methods of multiple-frequency radargram that are going to be used; simple summation, comparison of average radargram amplitude spectrum of each radargram, and least-square weighting according to Berlage wavelet analysis or Optimal Spectral Whitening (OSW). The results from those methods are then compared to determine the best method for combining radargram in this case.

2. Synthetic analysis of multiple-frequency compositing
The concept of multiple-frequency compositing was first introduced to solve the problem of radargram resolution at deep depth since the basic principle of this method is to sum up the measurement radargram with the various working frequencies measured on the same path [3]. The main purpose of the multiple-frequency compositing technique is to increase the radargram resolution at deep depth at a working frequency reference. In short, multiple-frequency compositing can be stated as

\[
[A] = w_1[A_1] + w_2[A_2] + \cdots + w_N[A_N]
\]

with A states the composite radargram matrix, \(A_N\) states the component radargrams that have been rubber-banded, and \(w\) states the weight of each component radargrams. These radargram’s weight is then determined using various techniques to make good resolution on composite radargram.

There are various approaches in the multiple-frequency compositing technique. In this research we use simple summation; comparison of average radargram amplitude spectrum of each radargram, known as dominant frequency amplitude equalization (DFAE); and the amplitude ratio based on the Berlage wavelet analysis as the weight in the radargram compositing [4] known as optimal spectral whitening (OSW). Those three methods then compared to get the best result in this case.

2.1. Berlage wavelet analysis
Berlage wavelet equation (Aldridge, 1990) is stated as

\[
w(t) = A t^n e^{-\alpha t} \cos(2\pi f_0 t + \phi_0) H(t)
\]

with \(w(t)\) states the wavelet value; \(A\) states the amplitude coefficient; \(t\) states the time; \(n\) states the time exponent; \(\alpha\) states the decay factor that equals with \(1/f_0\); \(f_0\) states the dominant frequency; \(\phi_0\) states phase angle in radians; and \(H(t)\) states Heaviside step function, with \(H(t)=0\) at \(t<0\) and \(H(t)=1\) at \(t>0\). The reasons of using Berlage wavelet as the reference of data compositing are its similarity with GPR antenna source wavelet, the wavelet character that is flexible for modeling a wide range of waveforms [5] and easy-to-create wavelet with specific properties [5]. Figure 1 shows comparisons between Berlage wavelet and other wavelets.

Figure 1. Comparison between Blackman-Harris, Berlage, and Ricker wavelet.
Based on figure 1, it is showed that Berlage wavelet has wider period if compared with other wavelets on same length of time. From that result, Berlage wavelet will be used as reference for determining the radargram weighting during radargram compositing process.

3. Data processing
The research was performed on an underground pipe model with some metal cables on its surroundings. The pipe diameter was 150 cm and it has metal casing with 10 cm thickness of the casing. Detail of the model is shown on figure 2. In this research, the frequencies of antenna used to detect underground condition were 200 MHz and 400 MHz.

![Figure 2. Reference model used in this research.](image)

There are two-steps of data processing performed in this research. First, each component radargram is pre-processed to remove noises occurred during measurements. Pre-processing steps in this research are following GPR processing steps like dewow, static correction, gain, background removal, and bandpass filter [6]. For gain steps, the manual gain was used due to the complexity of the radargram.

After the pre-processing steps finished; the multiple composite radargram steps were performed to join those radargram. First step were equalizing the components like total traveling time, sampling time, and sampling distance of each pre-processed radargrams based on the components of the biggest frequency radargram, in this case, the 400 MHz radargram, which known as rubber-banding. The radargrams then amplitude-normalised, multiplied by each weightings, then summed to make the composite radargram. For simple summation, weightings used for each radargram were 1, the weightings used for comparison of average radargram amplitude spectrum method were 1.00 and 1.71 for 200 MHz and 400 MHz radargrams, and the weightings of OSW method varies according to the travel time from 0.6 until 1.8, with the graph of the weightings is shown on figure 3. For the OSW method, Berlage wavelet analysis was performed using 200 MHz frequency and 7 ns period.
4. Results
Both radargrams obtained from 200 MHz and 400 MHz GPR measurements are pre-processed separately using steps described on the previous part to remove the noises. The results of preprocessing steps are shown and analysed on figure 4 and figure 5.

Figure 3. Graph of OSW weighting factor.

Figure 4. Analysis of 200 MHz radargram.
Figure 5. Analysis of 400 MHz radargram.

From 200 MHz and 400 MHz radargram, the big pipe at the center of area is shown clearly, although some small objects like metal objects around big pipe cannot be seen from 200 MHz radargram alone and the type of small objects at the top of big pipe cannot be determined from 400 MHz radargram alone. Also, from the 200 MHz radargram alone, the contact between big pipe casing can be seen clearly but from the 400 MHz radargram alone that contact is missing. Due to this problem, radargram compositing is performed to analyse the underground condition better.

After being pre-processed, the radargrams are combined using three multiple-compositing methods mentioned on Section 3 before. The results of each combined radargram, known as the composite radargram, are shown on Figure 6, 7, and 8 below.

Figure 6. Composite radargram from simple summation method.
Compared to the radargram sources of composite radargram, the combined radargram has better quality to show the position and the depth of the underground pipes. For example, the contact between metal casing and filling medium of the big pipe can be seen clearly using simple summation and OSW method, with OSW method can show the thickness of the casing better than using simple summation method. All of the compositing method also can show the availability and amount of metal objects at the top and bottom of the big pipe, with DFAE method can determine the availability and amount of metal objects better if compared with other method. The composite radargram also can map the contact between concrete and soil layer better if compared with the radargram sources, with OSW method shows the best results. From the amount of anomaly types that can be improved using
multiple-frequency method, OSW method can improve the radargram better if compared with other method.

Not only from the visual interpretation of each radargram, the analysis was also performed on some sample trace for determining the ability of each method to differentiate contact between two different medium based on its amplitude pattern. The samples were taken on trace 16 for checking the ability to detect the metal object on the bottom; and on trace 45 for detecting the contact between concrete and soil together with contact of metal pipe casing and pipe filling. The trace analysis is shown in figure 9 and figure 10.

![Figure 9. Trace sampling comparison on trace 16.](image1)

![Figure 10. Trace sampling comparison on trace 45.](image2)

From trace analysis on figure 9 and figure 10, can be concluded that OSW method can differentiate most of the object better than other method in this area of research. These are shown by the amplitude change pattern that showed clearly when passing the different medium contact if referred with the
reference model and compared with another method. For example, only OSW method that can differentiate the pipe casing thickness and show the concrete-sediment layer contact better through its anomaly contrast.

5. Conclusion
All of the GPR multiple-compositing method used in this research are proven effective to increase the radargram resolution and reduce the noise on the radargram if compared with the component radargrams. This is shown from the results of trace analysis that shows the ability of multiple-compositing method to scale the amplitude between the medium boundaries so the medium difference and the boundary can be seen clearly, such as the boundary between pipe casing and pipe filling-medium and the amount of metal objects around big pipe.

From the model analysed in this research, OSW method has better resolution if compared with other multiple-frequency method used in this research due to its ability to show most contact between different medium. The proofs of this method ability can be checked through radargram analysis and trace analysis.

References
[1] Davis, J.L., Annan, A.P., [1989] Ground-penetrating radar for high-resolution mapping of soil and rock stratigraphy, Geophys. Prosp. 37, pp 531-551
[2] Endres, A.L., Booth, A.D., Murray, T., [2004]. Multi-frequency compositing of spatially coincident GPR datasets. Proceedings of the 10th International Conference on Ground Penetrating Radar, pp 271–274
[3] Dougherty, M.E., Michaels, P., Pelton, J.R., Liberty, L.M., [1994] Enhancement of ground penetrating radar data through signal processing, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, EEGS.
[4] Booth, A.D., Endres, A.L., Murray, T. [2009] Spectral bandwidth enhancement of GPR profiling data using multiple-frequency compositing, Journal of Applied Geophysics, 67(2009), pp 88–97
[5] Aldridge, D.F. [1990] The Berlage wavelet, Geophysics, 55(11), pp 1508-1511
[6] Sandmeier, K.J. [2006] “ReflexW,” Version 4.0, Sandmeier Scientific Software, Karlsruhe