SIGNAL PROCESSING TO IMPROVE TARGET DETECTION USING GROUND PENETRATING RADAR

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ABSTRACT

This paper focuses on some important GPR pre-processing tasks. These tasks are necessary to improve formal target detection and estimation stages. Evaluations performed using a conventional matched filter on real GPR data demonstrate the benefits of pre-processing. This effort is conducted with the ultimate goal of realising a reliable GPR-based coal-thickness sensor.

1 INTRODUCTION

Ground penetrating radar (GPR) is a non-intrusive technique used to obtain information about media below the surface of the earth. The technique relies upon the transmission of electromagnetic energy into the earth, and subsequent reflection of that energy at interfaces of differing dielectric permittivity. There are a wide range of fields that have used GPR such as archaeology, geology, civil engineering, and military applications. Current applications of GPR include but are not limited to the detection of buried landmines, road layer thickness measurement, depth of underground pipes, and detection of chemical spills [1].

One GPR application of particular interest is the estimation of coal seam thickness. Not only is this useful information for geophysical engineers and mine personnel, it can also provide key sensor input for an automatic horizon control system. The research in this area will contribute to the automation of mining machines, which will improve both safety and quality control of the extracted product.

However, a significant limitation of GPR in this application is that it can be very difficult for a non-expert user to extract information about the sub-surface from the raw data returned. In order for GPR to be useful in a practical context, new processing methods need to be devised. The key to the success of these methods lies in proper pre-processing of GPR data, which is a very important step before formal data analysis can begin.

This paper overviews the hardware components associated with a typical impulse GPR system currently in use. A signal model that represents the returned radar data is described, along with several important signal pre-processing issues. The benefits of signal pre-processing are demonstrated by comparisons with real GPR data using a conventional matched filter detector.

2 THE GPR SYSTEM

An impulse GPR system has been developed by the CSIRO specifically for sub-surface applications in mining applications. The data from this unit is currently being used in the development of a robust and reliable coal thickness estimation algorithm. Impulse GPR offers better performance in the reduction of clutter over frequency modulated continuous wave GPR in the application of interest [2].

The GPR system consists of five main components: transmitter/receiver radar electronics, transmitter and receiver antenna assembly, timing module, analogue sampling circuitry, and data acquisition. A block diagram of the GPR system is shown in Figure 1.

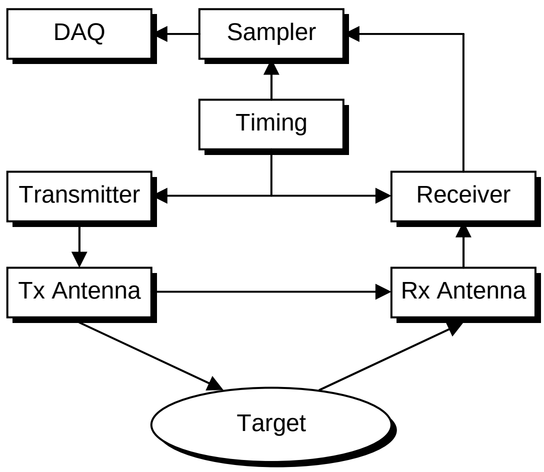

Figure 1. Block diagram of the GPR system.

2.1 Antenna Hardware and Operation

The GPR transmitter electronics produces a 1-2ns pulse, which is transmitted and received via a pair of shielded bi-static bow-tie antennas. The centre frequency of the pulse, as determined by the dimensions of the antenna, is 800 MHz with a bandwidth suitable for propagating through coal [3].

2.2 Equivalent Time Sampling

An equivalent time sampling technique is employed which uses analogue electronics to acquire the received signal at a rate significantly lower than direct sampling. The pulse repetition frequency of the system is 28.8 kHz, where one sample of the received waveform is obtained from each pulse. A complete waveform of the received signal is comprised of 512 samples. An entire waveform of the received signal has an equivalent time duration of 17.8 msec. An equivalent sampling frequency is necessary so that the distance to a target can be estimated. The equivalent sampling frequency is 111.3 GHz in free space, as determined using the following equation:

$$f_{es} = \frac{Nc}{2d\sqrt{\varepsilon_r}}$$

where N is the number of samples in a waveform, c is the speed of light in a vacuum, d is the range of the GPR system, and ε_r is the relative permittivity of the medium.

2.3 Data Acquisition

The GPR data has been digitised and logged using a PCMIA 12-bit data acquisition card connected to a laptop computer. A graphical user interface enables the user to change the parameters of the data acquisition card such as sampling rate, number of samples per realisation, and the number of realisations per ensemble. A falling edge synchronisation pulse is generated by the analogue sampling electronics at the start of a new received waveform. The synchronisation pulse is used by the acquisition software to form consecutive data realisations. The data can then be ported into other signal processing packages for further processing and analysis as necessary.

3 SIGNAL MODEL

A useful GPR received signal model has been suggested in [3], which is given by:

$$Z_k(t) = W_O(t) + \sum_{m=-M}^{M-1} W(m) R_k(t-m) + N_k(t)$$

This model comprises of the summation of three components. They are the direct pulse from transmitting to receiving antennas, $W_O(t)$; reflections from interfaces as the convolution of the radar wavelet impulse response with the reflection coefficients; sensor timing jitter and background noise, $N_k(t)$. The reflection coefficients are given by:

$$R_k(t) = \sum_{n=0}^{p_k-1} a_k(n)\delta(t - \tau_k(n))$$

where $a_k(n)$ is the echo magnitude, and $\tau_k(n)$ is the pulse echo time delay for each layer. A typical received signal is shown in Figure 2.

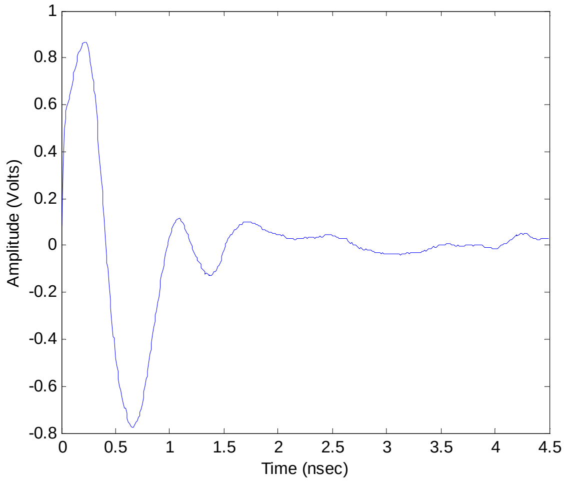

Figure 2. Typical received GPR signal.

The received signal is processed to detect the distance to each layer by estimating the pulse echo time delay $\tau_k(n)$ where k is the layer number. Section 4 describes the signal processing techniques employed.

4 DATA PRE-PROCESSING

Several pre-processing techniques are now described. These are important to simplify the interpretation of GPR data. These include jitter correction, averaging (also referred to as stacking), background signal removal, and time varying gain. Figure 3 shows the stages of pre-processing steps involved.

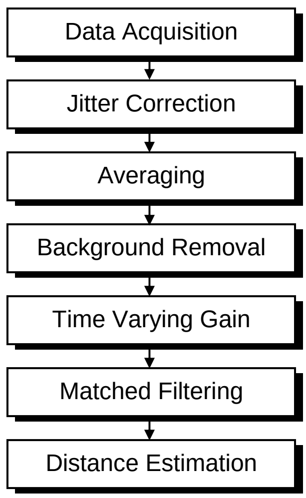

Figure 3. Signal processing stages of GPR data.

4.1 Jitter Correction

As a result of the GPR hardware electronics and the equivalent timing system, timing jitter exists in the received data and has a smoothing effect [4]. Jitter correction needs to be implemented to align both the received and background signals.

The index of the waveform peak (from the direct path signal) can be determined via a conventional search algorithm.

4.2 Averaging

Short time ensemble averaging, or stacking, is a technique used to reduce the noise bandwidth of the received signal [5]. The stacking number is the number of realisations of the received signal used in determining the average.

In the current investigation, the antennas are stationary during the acquisition of an entire ensemble. Therefore the stacking number used was the total number of realisations of the process, which is the expectation of the process.

4.3 Background Removal

The background signal can be considered as a calibration signal, which is always observed even when the target is not present. This signal consists of the direct pulse from transmitting to receiving antennas, ringing from the antennas, and clutter from other objects that reflect the electromagnetic energy within the antenna beamwidth but not considered a target.

The background is subtracted from the received signal, resulting in a wavelet shape signal with a time delay proportional to the distance of the target.

4.4 Time Varying Gain

Electromagnetic energy is attenuated by the earth and disperses radially as it propagates away from its source. The received power is inversely proportional to distance to the 4^{th} power[6]. This has the effect of reducing the amplitude of pulse echoes due to targets further away from the antennas. This effect can be compensated for by applying a non-linear gain to the received waveform.

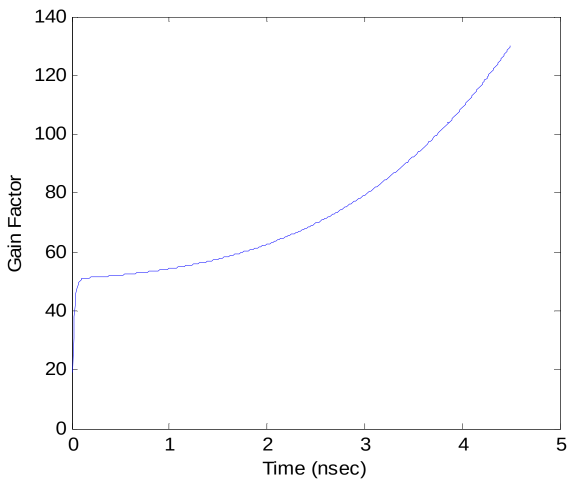

Figure 4. Time varying gain function.

To achieve the best results for the experiment performed, the time varying gain function required the addition of two components, an exponential and a 4^{th} power. The exponential component is designed to maintain the close range signal, whilst the other is to amplify the attenuated signal at distances furthest from the antennas. The function is shown in Figure 4. The processed received signal is shown in Figure 5 where the target was 55cm from the antennas resulting in the wavelet shape at 3.5ns.

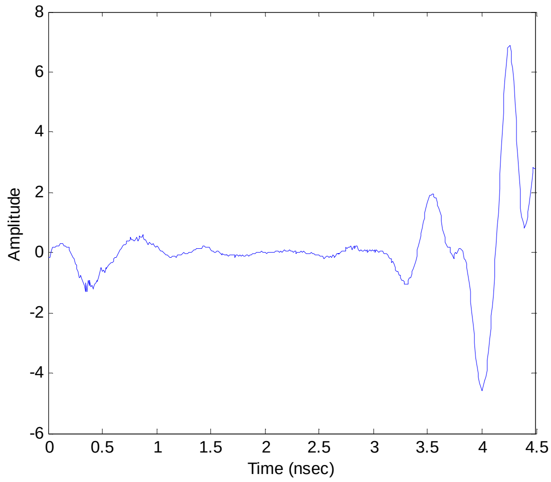

Figure 5. Pre-processed received signal.

4.5 Matched Filter Based Detector

The main objective of matched filtering is to recognise the presence of a pulse signal in the presence of additive noise and clutter [7]. The filter detects when the signal component of the received waveform is highly correlated with a reversed time shifted version of the transmitted signal. The point with the greatest correlation is taken to be the reflection from the target.

4.6 Transmitted Pulse Identification

In the case of GPR, it is often difficult to measure the actual transmitted signal, therefore it must be estimated. Two different methods are considered in the following section.

5 COMPARISON AND RESULTS

5.1 Direct Coupling Signal

The first pulse of the received signal is propagated directly from the transmitting to receiving antenna. A good first approximation is given by a single period of a sine wave.

Three variations of this direct signal were used for the matched filter. These variations were: one complete period as described above; the first half of the extracted sine wave such that it resembles an impulse; and a mathematically calculated sine wave of frequency and amplitude similar to the extracted version.

5.2 Wavelet Pulse Estimation

Another technique used to estimate the transmitted pulse was to place a large metal plate normal to the antennas at a distance from them such that the received pulse (from the plate) is not within range of the direct coupling pulse, but close enough that it can be identified. The wavelet shaped pulse was isolated from the other signal. The extracted pulse was not perfectly symmetrical, so the first side was mirrored onto the second side, and then used for the matched filtering. The wavelet used for the matched filter is shown in Figure 6.

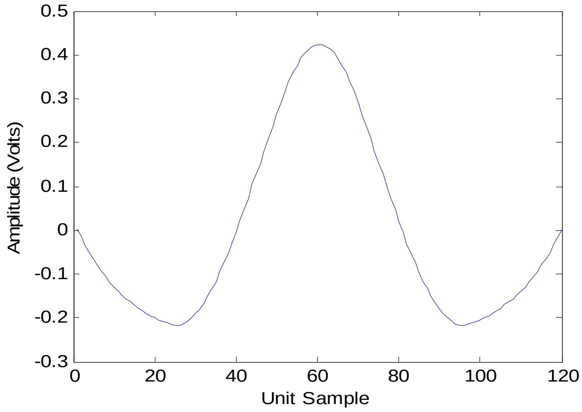

Figure 6. Wavelet pulse used for matched filter.

For the purpose of transmitted pulse identification, experiments were performed where a metal plate was placed normal to the antennas at distances from 2cm to 64cm in 2cm increments. The data was then processed as described in section 4, and the block diagram of Figure 3. The distance to target was also estimated using the raw data and pre-processed data only using background removal. The results of the measured and estimated distances are shown in Figure 7.

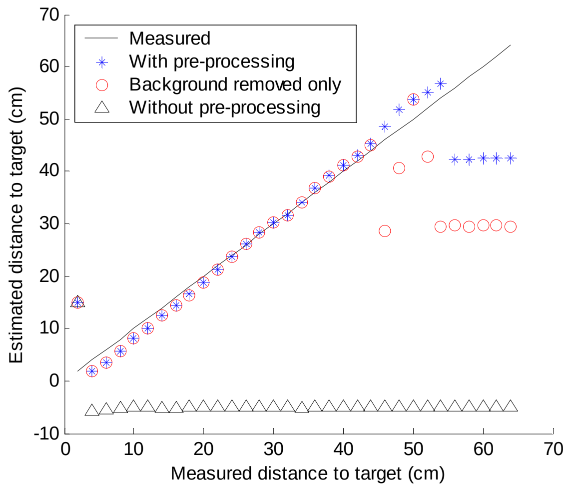

Figure 7. Measured and estimated distance using a matched filter with pre-processing, background removal, and without pre-processing.

Clearly the use of radar pre-processing has lead to an improvement in distance estimation even before formal processing has begun. The most successful combination of data pre-processing steps involved the use of the time varying gain function and the wavelet pulse for the matched filter, as shown in Figures 4 and 6 respectively. These results are sensitive to the form of the time-varying gain. In this experiment, the transmitted power, pulse shape, clutter and target reflection coefficient were constant.

6 CONCLUSION

A GPR system that is currently being used in research to develop a coal seam thickness estimation algorithm has been described, along with a signal model that represents the received GPR data returns. Some techniques used to pre-process GPR data have been shown and implemented successfully. A matched filter using a wavelet extracted from the pulse echo of a metal plate was successful in detecting the distance to a target within an error of approximately 3cm.

The limitation of the conventional matched filtering technique applied here is that only one target can be detected as the point of highest correlation is taken as the reflection from the target. Further research and data collection is required before this can be applied to the underground coal mining application.

ACKNOWLEDGEMENT

The authors would like to kindly thank the members of the CSIRO Mine Automation Group, Queensland, Australia for the use of their facilitates, GPR system, and data.

7 REFERENCES

[1] L. P. Peters Jr., J. J. Daniels, and J. D. Young, "Ground penetrating radar as a subsurface environmental sensing tool," *Proceedings of the IEEE*, vol. 82, pp. 1802-1822, December 1994.

[2] D. J. Daniels, "Short pulse radar for stratified lossy dielectric layer measurement," *IEE Proceedings Pt. F*, vol. 127, pp. 384-388, October 1980.

[3] J. C. Ralston and D. W. Hainsworth, "Application of ground penetrating radar for coal depth measurement," in *IEEE International Conference on Acoustics Speech and Signal Processing (ICASSP99)*, 1999, pp. 2275-2278.

[4] S. Valle, L. Zanzi and G. Lenzi, “2D and 3D focusing of ground penetrating radar data for NDT,” *Proceedings of the Eighth International Conference on Ground Penetrating Radar (GPR 2000)*, pp. 157-162, May 2000.

[5] J. C. Ralston, D. W. Hainsworth, and R. J. McPhee, "Application of ground penetrating radar for coal thickness measurement," in *Proceedings of IEEE TENCON*, 1997, pp. 835-838.

[6] D. M. Pozar, *Microwave Engineering*. John Wiley & Sons, Inc., 1998.

[7] S. Haykin, *An Introduction to Analog & Digital Communications*. John Wiley & Sons, Inc., 1989.