Signal Processing for Extraction of Target Response from Distorted GPR Data

Masahiko Nishimoto *and* Daisuke Yoshida

Graduate School of Science and Technology, Kumamoto University
2-39-1 Kurokami, Kumamoto 860-8555, Japan
nisimoto@cs.kumamoto-u.ac.jp

Abstract— **Two kinds of signal processing techniques for ground penetrating radar (GPR) are applied to measured GPR data in order to improve performance of target identification. One is the method for removing strong ground clutter that covers a weak target response in time domain, and the other is the calibration procedure of GPR response for removing undesirable waveform distortion that is caused by frequency characteristics of antennas. Application result demonstrates that the signal processing techniques employed here give good performance and are effective for extraction of target response from measured GPR data.**

I. Introduction

Ultra-wideband ground penetrating radar (GPR) system is one of the major tools for detection and localization of buried objects [1]. Especially, the localization of buried anti-personnel landmines is one of the well-known applications of GPR system. Compared with conventional metal detectors, GPR has the advantage of detecting plastic or low-metal-content landmines. However, reliability of GPR is still insufficient when it is applied to locating shallowly buried landmines, because a strong ground clutter covers a weak target response in time domain. Therefore, signal processing for removing the ground clutter without damaging the target response is needed. Another cause that reduces reliability of GPR is waveform distortion that is caused by frequency characteristics of antennas. For accurate target identification using GPR system, feature extraction from a target response is the most important part because quality of features extracted from the target response directly affects the identification performance. For feature extraction in time domain, a monocycle incident pulse with sharp peaks and narrow width is convenient. In actual situation, however, the pulse waveform is distorted by frequency characteristics of antennas. In order to obtain a pulse response with no distortion, waveform calibration that can reconstruct the pulse waveform is needed.

In our previous study, we proposed two kinds of signal processing techniques for GPR data in order to improve target detection and identification performance [2],[3]. One is the method for removing ground clutter that covers a target response [2], and the other is the calibration procedure of GPR response for removing undesirable waveform distortion that is caused by antenna characteristics and mutual coupling between the antennas and the ground surface [3]. The purpose of this study is to apply these signal processing techniques to actual measured GPR data and to demonstrate its effectiveness. Application result shows that the signal processing techniques used here have good performance and are significant and essential for target response extraction from measured GPR data.

II. Signal Processing for GPR Data

The GPR measurement system considered in this study is shown in Fig. 1. Since we assume that the location of the buried object is already specified by a preliminary search, we focus on a problem of target identification using the GPR response. For convenience, we shall explain again the signal processing methods proposed in our previous studies [2], [3]. The following descriptions are from [2] and [3].

A. Matching Pursuit for Ground Clutter Reduction [2]

For ground clutter removal, we introduce the Mating Pursuit algorism that is first proposed by Mallat and Zhang [4]. The Matching Pursuit iteratively decomposes any signal $f(t)$ into a linear expansion of non-orthogonal waveforms that are selected from a redundant dictionary of functions expressed by: $D=\{g_\gamma(t):\gamma\in\Gamma\}$, where γ denotes a general index from the set Γ. This algorithm projects a given waveform onto each element in D and selects the element that gives largest projection. The selected component is subtracted from the signal, and this procedure is then repeated on the remaining waveform until the residual energy of the remaining waveform is below some threshold or until some other halting criterion is met. In the first step of the iterative procedure, the function $g_{\gamma 0}$ is chosen which gives the largest projection with the given signal $f(t)$ as follows:

$$\begin{aligned} f(t) &= < f,\ g_{\gamma 0} > g_{\gamma 0}(t) + R^1 f(t). \\ |< f,\ g_{\gamma 0} >| &\geq |< f,\ g_\gamma >| \quad \forall g_\gamma \in D \end{aligned} \tag{1}$$

where $< f, g >$ is the continuous inner product of functions $f(t)$ and $g(t)$. Then the residual vector $R^1 f$ obtained after approximating f in the direction g is decomposed in the similar way. The iterative procedure is repeated and the following Matching Pursuit decomposition is obtained after M iterations,

$$f(t) = \sum_{n=0}^{M} < R^n f, g_{\gamma n} > g_{\gamma n}(t) + R^{M+1} f(t). \qquad (2)$$
$$R^0 f = f(t)$$

It is noted that this decomposition procedure is independent of the dictionary that is employed. If the dictionary of function is properly chosen, then the linear combination of the first M terms gives a good approximation of the signal $f(t)$, and this means that selection of the dictionary function is important for efficient extraction of desired signal. As an atom that is a fundamental element of the dictionary, we here employ an incident pulse or a reflected wave from a flat ground surface. Taking account of scattering mechanisms of electromagnetic waves by various targets, we introduce a wave-based dictionary [5] whose elements are distorted atoms given by

$$g_\gamma(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} X(\omega)\cdot(j\omega)^\beta \exp[j\phi]\cdot\exp[j\omega(t-\tau)]d\omega$$
$$\gamma = [\tau, \beta, \phi] \qquad (3)$$

where $X(\omega)$ represents spectrum of the atom, τ, β, and ϕ are shift, derivative, and phase parameters, respectively. By using this dictionary, we can effectively extract the ground surface reflection from the GPR data.

B. Waveform Calibration Using an Inverse Filter [3]

As shown in Fig. 1, the target response from the buried object in shallow depth is measured together with the ground clutter and the direct wave between the transmitting and the receiving antennas. A signal flow graph of the measurement can be expressed in terms of transfer functions as illustrated in Fig. 2. Thus, the received signal can be expressed as:

$$\begin{aligned} G(\omega) = & H_{Rx}(\omega) H_{ptf}(\omega) H_{targ}(\omega) H_{ptb}(\omega) H_{Tx}(\omega) F(\omega) \\ & + H_{Rx}(\omega) H_{psf}(\omega) H_{surf}(\omega) H_{psb}(\omega) H_{Tx}(\omega) F(\omega) \\ & + H_{Rx}(\omega) H_{crs}(\omega) H_{Tx}(\omega) F(\omega) \end{aligned} \qquad (4)$$

where H_{Tx} and H_{Rx} are transfer functions of transmitting and receiving antennas, H_{targ} and H_{surf} are transfer functions of scattering by the target and the ground surface, H_{ptf}, H_{ptb}, H_{psf}, and H_{psb} are transfer functions of forward and backward propagation between the antennas and the target or the ground surface. The transfer function H_{crs} represents antenna coupling, and F and G are spectra of incident and received pulses, respectively. The first term on the right-hand side of Eq. (4) is the target response, the second is the ground clutter, and the third is the direct wave travelling from the transmitting antenna to the receiving antenna.

Since an S parameter measured by a vector network analyzer corresponds to the transfer function of the entire scattering system, we can express the entire transfer function S_{targ} of this measurement as follows:

$$\begin{aligned} S_{targ} = & H_{ANT}(\omega) H_{ptt}(\omega) H_{targ}(\omega) \\ & + H_{ANT}(\omega) H_{pst}(\omega) H_{surf}(\omega) + H_{ANT}(\omega) H_{crs}(\omega) \end{aligned} \qquad (5)$$

where the functions $H_{ptt}(\equiv H_{ptf} H_{ptb})$, $H_{pst}(\equiv H_{psf} H_{psb})$, and $H_{ANT}(\equiv H_{Tx} H_{Rx})$ are introduced in order to make the expression simple. Since the third term of Eq. (5) is a direct wave travelling from the transmitting antenna to the receiving antennas, it can be easily determined from the response S_{free} that is the S parameter measured in free space (without any targets) expressed as:

$$S_{free} = H_{ANT}(\omega) H_{crs}(\omega) \qquad (6)$$

After subtracting the direct wave from Eq. (5), we have the following expression:

$$\begin{aligned} S_{targ} - S_{free} = & H_{ANT}(\omega) H_{ptt}(\omega) H_{targ}(\omega) \\ & + H_{ANT}(\omega) H_{pst}(\omega) H_{surf}(\omega) \end{aligned} \qquad (7)$$

In order to remove the effect of the antenna characteristics H_{ANT} that causes undesirable waveform distortion, we design an inverse filter that can eliminate the antenna characteristics. As a reference data for calibration, we employ an S parameter $\overline{S}_{surf}$ that corresponds to a reflection from a flat ground surface. This can be obtained from a simple additional measurement and is expressed as follows:

$$\overline{S}_{surf} = H_{ANT}(\omega) \overline{H}_{pst}(\omega) \overline{H}_{surf}(\omega) + H_{ANT}(\omega) H_{crs}(\omega) \quad (8)$$

where $\overline{H}_{surf}$ is a complex scattering amplitude of the response

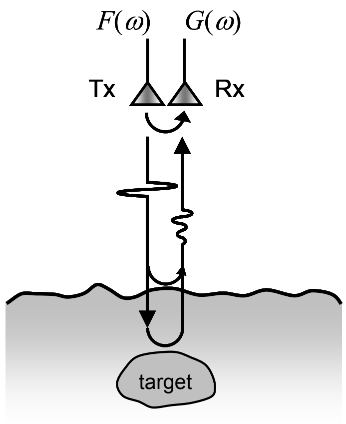


Fig. 1. Measurement of GPR signals from a shallowly buried object.

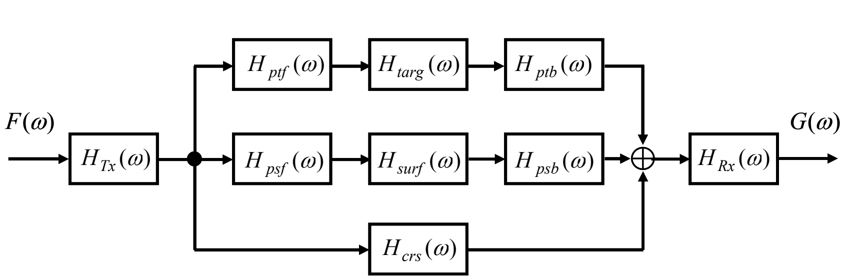


Fig. 2. Signal flow graph of the measurement expressed in terms of the transfer functions.

from the flat ground surface, and $\overline{H}_{pst}$ is a transfer function which corresponds to round-trip propagation between two antennas and the ground surface. After subtracting the direct wave S_{free} from Eq. (9), we can obtain the following inverse filter expressed as:

$$H_{ANT}^{-1}(\omega) = \frac{1}{\overline{S}_{surf} - S_{free}} \overline{H}_{pst}(\omega)\overline{H}_{surf}(\omega) \qquad (9)$$

The scattering amplitude $\overline{H}_{surf}$ corresponds to the Fresnel reflection coefficient, and if we assume that it is constant in our operation frequency band, then the following expression can be obtained:

$$H_{ANT}^{-1}(\omega) = \frac{-A}{\overline{S}_{surf} - S_{free}} e^{-j\omega t_0} \qquad (10)$$

where A is a positive constant and t_0 corresponds to the delay time needed for the pulse to travel back and forth between the antenna set and the ground surface. The inverse filter of Eq. (10) can eliminate the waveform distortion that is caused by the antenna characteristics. By applying Eq. (10) to Eq. (7), we can obtain the result of calibration as follows:

$$\begin{aligned} &H_{ptt}(\omega)H_{targ}(\omega) + H_{pts}(\omega)H_{surf}(\omega) \\ &= -\left(\frac{S_{targ} - S_{free}}{\overline{S}_{surf} - S_{free}}\right)\exp(-j\omega t_0) \end{aligned} \qquad (11)$$

where we set to A = 1 because the coefficient A is related only to the amplitude of the target response. The parameter t_0 is a linear phase constant that corresponds to a delay time of the pulse, and that can be estimated using the least squares estimation [4]. The first and the second terms in the left-hand side of Eq. (11) correspond to the scattering transfer function of the target response and the ground clutter, respectively. Therefore, by using Eq. (11), we can obtain time-domain responses for arbitrary incident waveforms. The target response $g(t)$ from the buried object can be calculated by the inverse Fourier transformation as follows:

$$\begin{aligned} g(t) &= g_{targ}(t) + g_{surf}(t) \\ &= \frac{1}{2\pi}\int_{-\infty}^{\infty} H_{ptt}(\omega)H_{targ}(\omega)F(\omega)\exp(j\omega t)d\omega \\ &\quad + \frac{1}{2\pi}\int_{-\infty}^{\infty} H_{pst}(\omega)H_{surf}\,F(\omega)\exp(j\omega t)d\omega \qquad (12) \\ &= -\frac{1}{2\pi}\int_{-\infty}^{\infty}\left(S_{targ} - S_{free}\right)/\left(\overline{S}_{surfl} - S_{free}\right)F(\omega) \\ &\qquad \cdot \exp[j\omega\,(t - t_0)]d\omega \end{aligned}$$

By applying this calibration procedure to measured GPR data, we can reconstruct a monocycle pulse response with no waveform distortion that is caused by antenna characteristics. The calibrated response $g(t)$ still includes the unknown ground clutter $g_{surf}(t)$. However, since the calibration suppresses late-time antenna ringing, it becomes easy to extract the target response $g_{targ}(t)$ from $g(t)$ by applying the MP algorithm mentioned before.

III. Application Result

To evaluate the performance of the signal processing methods, we apply them to measured GPR data obtained by a laboratory experiment. The GPR measurement system is made up of a vector network analyser and a UWB-GPR antenna set [6]. The antenna set has identically shaped transmitting and receiving Vivaldi antennas and they are covered with a metal box (shield case) that has one open end as the antenna aperture. The frequency characteristic of the antenna set is shown in [6]. Figure 3 is a schematic drawing of the measurement. As the target, we use a plastic dummy of a Type-72 AP landmine with a rubber cap. The depth the target and the height of the antenna are set to 3 cm and 10 cm, respectively. As the incident pulse with simple waveform, we use a monocycle pulse given by differentiation of a Gaussian pulse. The waveform of the incident pulse is shown in Fig. 4. The width of the pulse is about 1 ns, and most of the energy of the pulse exists below 6GHz.

Figure 5 shows measured GPR data and a calibrated pulse response obtained by using Eq. (12). We can see from this result that the measured GPR response in Fig. 5(a) exhibits a significant level of late-time ringing and it completely covers a desired target response. However, after the calibration, the late-time ringing is suppressed and the target response appears in Fig. 5(b). The target is buried in shallow depth, and thus the crest of the pulse is still covered with ground clutter. However, we can clearly recognize the target response in the calibrated GPR waveform. This means that the calibration is significant for accurate extraction of the target response. Next, we show the result for ground clutter reduction by using the MP decomposition in Fig 6. As the atom of the dictionary elements, we employ a reflected wave from a flat ground surface. The result shows that the removal of the ground clutter can be achieved by using the MP decomposition and target response in the GPR data is successfully extracted.

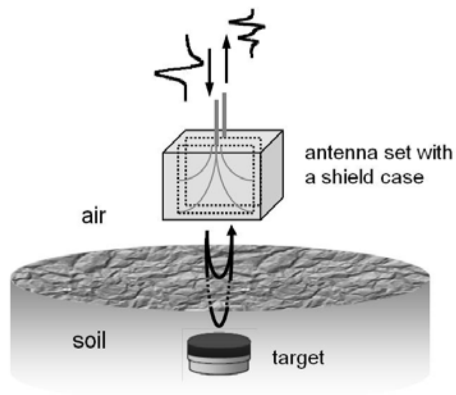


Fig. 3. Schematic drawing of the experiments. The depth of the target is 3 cm, and the height of the antenna set is 10 cm.

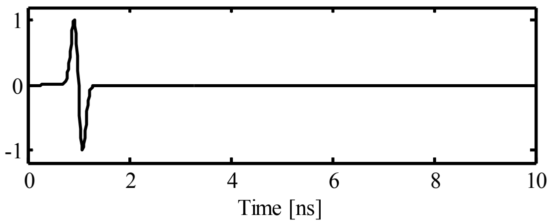
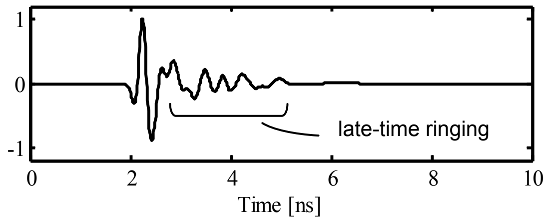
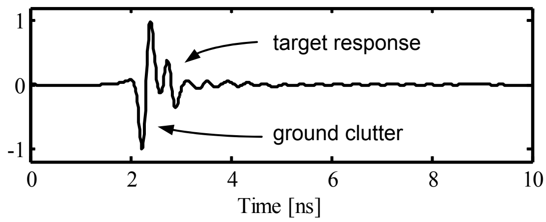


Fig. 4. Monocycle incident pulse used for experiments. (Once-differentiated Gaussian pulse)



(a) Measured pulse response (raw data)



(b) Calibrated waveform by using the inverse filter.

Fig. 5. Pulse response from the plastic dummy of the Type-72 landmine in the ground. (target depth: 3 cm, antenna height: 10 cm.)

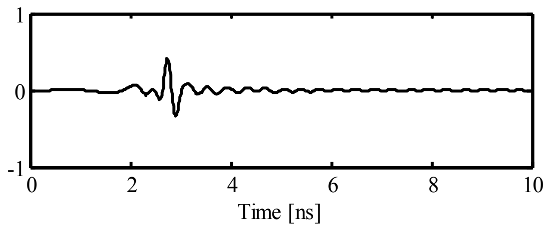


Fig. 6. Target response extracted from GPR data using the Matching Pursuit decomposition.

IV. Conclusion

In order to improve performance of target identification using GPR, two kinds of signal processing techniques for extraction of target response from distorted GPR data have been introduced. One is the method for removing strong ground clutter that covers a weak target response in time domain, and the other is the calibration procedure of GPR responses for removing undesirable waveform distortion that is caused by frequency characteristics of GPR antennas. Application result demonstrate that the signal processing techniques employed here give good performance and are significant and effective for extraction of the target response from measured GPR data.

References

[1] [1] D. J. Daniels (Ed.), “*Ground Penetrating Radar (2nd Edition)*,” Institution of Engineering and Technology (IET) Radar, Sonar, Navigation and Avionics Series 15, IET, 2004.

[2] M. Nishimoto and V. Jandier, “Ground clutter reduction from GPR data for identification of shallowly buried landmines”, *IEICE Trans. Electron*., Vol. E93-C, No. 1, pp.85-88, 2010.

[3] M. Nishimoto, D. Yoshida, K. Ogata, M. Tanabe, “Extraction of a Target Response from GPR data for Identification of Buried Objects”, *IEICE Trans. Electron*., Vol. E96-C, No.1, Jan. 2013 (*in press*).

[4] S. G. Mallat and Z. Zhang, “Matching Pursuits with Time-Frequency Dictionaries”, *IEEE Trans. Signal Processing*, Vol. 41, No.12, pp.3397-3415, 1993.

[5] M. R. McClure and L. Carin, “Matchig pursuits with wave-based dictionary,” *IEEE Trans. Signal Processing*, Vol. 45, No.12, pp. 46-55, Dec. 1997..

[6] M. Nishimoto, K. Tomura, and K. Ogata, “Waveform calibration of ground penetrating radars for identification of buried objects”, *IEICE Trans. Electron.*, Vol. E95-C, No. 1, pp.105-109, 2012.