Signal Processing ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Signal Processing

journal homepage: www.elsevier.com/locate/sigpro

Development of regularization methods on simulated ground-penetrating radar signals to predict thin asphalt overlay thickness

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ARTICLE INFO

Article history:
Received 10 December 2015
Received in revised form
17 May 2016
Accepted 14 June 2016

Keywords:
Ground-penetrating radar
Range resolution
Deconvolution
Thin asphalt overlay
Tikhonov regularization
Total variation
L-curve

ABSTRACT

The range resolution of ground-penetrating radar (GPR) signal is important in thin asphalt overlay thickness estimation. In this paper, regularized deconvolution is utilized to analyze simulated GPR signals to increase their range resolution. Four types of regularization methods, including Tikhonov regularization and total variation, were applied on noisy GPR signals; and their performance was evaluated in terms of accuracy in estimating distance of close impulses. The L-curve method was used to choose the appropriate regularization parameter. The total variation regularization method and zeroth-order Tikhonov regularization outperform first-order and second-order Tikhonov regularization in terms of average asphalt layer thickness estimation error and the standard deviation of the error. An example of the field GPR data is provided to validate the proposed algorithm. The study shows that the algorithm based on regularization is a simple and effective approach to increase the GPR signal range resolution with presence of noise in the case of thin asphalt overlay thickness prediction.

1. Introduction

Ground-penetrating radar (GPR) is a special type of radar that detects the impedance discontinuities in the subsurface. In civil engineering, GPR is mainly used to find rebar and delamination in concrete structures [1]. This technique has been widely applied in transportation infrastructure surveying: It is used to calculate the dielectric constant of the pavement [2] and to estimate the thickness [3,4] and density [5–7] of pavement; it was also used to detect the free water [8] under the asphalt pavement layer.

Estimating the asphalt pavement layer thickness is one of the most successful GPR applications. The typical method to estimate the asphalt layer thickness using GPR has been the two-way travel time method. Assuming asphalt mixture is uniform and isotropic under the GPR signal wavelength, and that the magnetic permeability of the asphalt mixture is the same as that of the free space, the two-way travel method requires the accurate determination of the asphalt concrete dielectric constant, which can be estimated using the surface reflection method [3] or calibration by taking cores. In many GPR applications, the dielectric constant of material may be dependent on frequency of the signal, in which case the velocity of the EM wave within the material becomes the key; however, in this study, the dielectric constant of asphalt pavement is assumed constant because asphalt can be usually considered as nondispersive material. The asphalt pavement is also assumed lossless as it is non-conductive. The common midpoint method is an alternative method to estimate the dielectric constant and layer thickness of the asphalt pavement [9–11]. In either method, the range resolution of the GPR signals is the dominant parameter, compared to the cross-range resolution, or azimuth resolution, because the pavement can be considered as a one-dimensional structure and only the range direction needs to be considered.

The azimuth resolution of GPR signals is determined by the antenna pattern: the larger the directivity of the GPR antenna, the better the azimuth resolution. The range resolution of radar describes a signal's ability to distinguish adjacent pulses and depends on the duration of the transmitted pulse. For example, an electromagnetic (EM) wave with a larger bandwidth has a shorter pulse duration and could therefore distinguish objects with smaller distances. An infinite bandwidth signal is a unit impulse (delta function); in reality, all GPR signals are bandpass signals and have nonzero pulse durations. A signal with larger bandwidth has a greater range resolution.

The Rayleigh resolution criteria, proposed by Lord Rayleigh

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http://dx.doi.org/10.1016/j.sigpro.2016.06.015

Please cite this article as: S. Zhao, I.L. Al-Qadi, Development of regularization methods on simulated ground-penetrating radar signals to predict thin asphalt overlay thickness, Signal Processing (2016), http://dx.doi.org/10.1016/j.sigpro.2016.06.015

[12], is the most common criteria for range resolution. The one-dimensional Rayleigh resolution of a signal is the width of a pulse, defined as the distance between the maximum point of the pulse and the first zero point of the pulse. In GPR applications of measuring asphalt layer thickness, the range resolution of the GPR signal plays an important role. To resolve the thickness of an asphalt layer requires the resolution of the GPR signal to be finer than the asphalt layer thickness; otherwise the pulse reflected from the surface of the layer could be overlapped with the pulse reflected from the bottom of the layer. This criterion cannot always be met because of the restriction of the bandwidth of the GPR antenna. The typical operation frequency of a GPR system is 300 MHz to 3 GHz, which corresponds to 1 m and 0.1 m in predominant wavelength in free space; in concrete pavement, the predominant wavelength is between 0.3 m and 0.03 m if it is assumed the dielectric constant (relative permittivity) of concrete is 9. According to [13], the practical resolution of pulsed signals is about one-quarter of the predominant wavelength. It should be noted that it is assumed that the adjacent pulses have the same amplitude. It also doesn't take into account the error introduced to the pulse distance because of pulse overlapping. In the case of asphalt pavement, the surface layer and the bottom layer usually do not have significant dielectric constant difference; therefore, the second pulse has much smaller amplitude compared to the surface reflection. This suggests that it is much difficult to resolve thin layers in the case of asphalt pavement.

There have been studies to solve the "thin layer problem". Lahour et al. [14] used "match and subtract" method, where strong reflections are detected iteratively by matched filter detector and then substracted from the original signal to reveal the weak reflection. Li [15] applied independent component analysis (ICA) and successfully separated the overlapped GPR signals. Both methods require iteratively finding the layer thicknesses and are computationally expensive. Bastard et al. [16] used a support vector regression method (SVR) to predict pavement layer thickness. Good results were reported for both overlapped and non-overlapped signals. However, the performance of SVR method at low signal to noise ratios was not studied.

The general GPR image reconstruction methods include migration method and inverse filtering method. Migration method was originally used in seismic signal processing, and its principle is to use the transpose of the forward imaging operator as the inverse operator [17]. The inverse filtering technique is inversing the forward imaging operator by regularization method [18]. It was found that migration techniques are fast, while the inverse filtering techniques can reconstruct targets with better accuracy [19]. In the case of one-dimensional target reconstruction such as pavement layer detection, the resolution of the GPR signal becomes the key factor. The migration and inverse filtering method are called matched filtering and deconvolution [20]. The matched-filtering technique is commonly used for chirp signals, i.e., linearly frequency-modulated (FM) signals; however, the matched-filtered signals may not resolve pulsed signals, as shown in Section 4. Another signal-processing technique that can theoretically perfectly resolve the target location is deconvolution [21]. For linear FM signal, it can be demonstrated that the matched-filter gives the same result as the deconvolution method. The forward and inverse system models of one-dimensional radar imaging for matched-filter and deconvolution are illustrated in Fig. 1. In Fig. 1, $h_0(t)$ is the target function, $x(t)$ is the incident signal, $y(t)$ is the received signal and is the convolution of $h_0(t)$; and $x(t)$, $x^*(-t)$ is the complex conjugate of $x(-t)$, $\mathscr{F}^{-1}$ represents the inverse Fourier transform, $X(\omega)$ is the Fourier transform of $x(t)$, and $h(t)$ and $h_0(t)$ are the reconstructed target function by matched-filter and deconvolution, respectively. It should be noted that the way to calculate the inverse filter by inverse Fourier transform of $1/X(\omega)$, as shown in Fig. 1, is usually not applicable in practice because $X(\omega)$ is usually band-limited. Alternatively, the time domain deconvolution can be done by regularization, as illustrated in the following section.

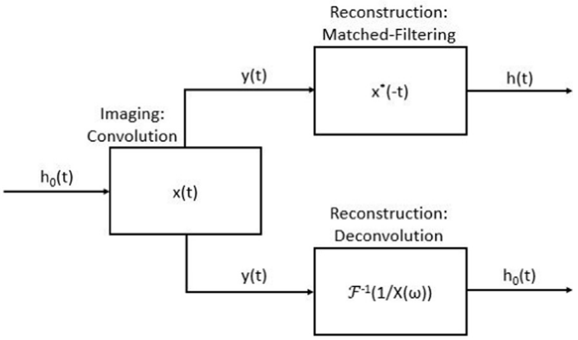

Fig. 1. One-dimensional radar imaging and target reconstruction system models.

The matched-filter technique has been used in GPR applications [22]. To increase the range resolution of GPR signals, Savelyev and Sato [23] reported the success of the deconvolution method in landmine detection. Al-Qadi and Lahouar [3] also reported good results in estimating asphalt pavement layer thickness using the deconvolution method. Economou et al. [24] and Schmelzbach et al. [25] developed several deconvolution algorithm on GPR signals. However, none of these studies concerned the ill-posed nature of the deconvolution. The authors [26] proposed a regularized deconvolution method and applied it on field data, with promising results. Regularization will regularize the deconvolution, and therefore it will be more robust to noise and small amplitude reflections (such as reflection at asphalt pavement layer interfaces). In that study, only zeroth-order Tikhonov regularization was considered, and the influence of noise levels and layer thickness on the performance of the deconvolution algorithm was not discussed.

In this paper, several types of regularized deconvolution methods were applied to simulated noisy GPR signals. Their performance was evaluated in terms of the accuracy in resolving very close objects. The L-curve method was used to choose the appropriate regularization parameter.

2. Regularized deconvolution

2.1. Tikhonov regularization

Many linear systems can be represented by the Fredholm integral equations of the first kind [27]:

$$y(t) = \int_a^b K(t, s)x(s)ds, \tag{1}$$

where $x(s)$ is the input function, $y(t)$ is the output function, and $K(t, s)$ is the Fredholm integral operator. By discretizing $x(t)$, $y(t)$, and $K(t, s)$ using simple collocation, Eq. (1) can be written as:

$$\boldsymbol{y} = \boldsymbol{A}\boldsymbol{x}, \tag{2}$$

where $\boldsymbol{x}$ and $\boldsymbol{y}$ are vectors of $x(t)$, $y(t)$, and $\boldsymbol{A}$ is matrix of $K(t, s)$.

The Fredholm integral equations of the first kind represents systems including but not limited to signal processing [28], computed tomography [29], and astronomy [30]. The inverse problem of finding input x from observed data y and system function A can be solved from Eq. (2) by Moore-Penrose inverse, or pseudo-inverse [31]:

$$\hat{\boldsymbol{x}} = \boldsymbol{A}^{+}\boldsymbol{y}, \tag{3}$$

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