A 3-D Migration Imaging Algorithm Suitable for Expressway Detection

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Abstract. The imaging technology is an important part of the ground penetrating radar (GPR) technology research. Traditional ground penetrating radar imaging technology mostly stays in two-dimensional (2-D) imaging. However, when the line of the 2-D section is inclined obliquely to the underground target, the 2-D section will be inconsistent with the actual underground structure, which makes the 2-D imaging technology have inherent defects. Therefore, the research of the 3-D imaging technology has become a hot and difficult problem in current research. In this paper, a 3-D prestack time migration imaging algorithm for expressway detection is proposed. In order to better realize the 3-D migration imaging display, it is necessary to do some preliminary processing on the 3-D ground penetrating radar reflected echo data, including data preprocessing and data processing. Then the 3-D prestack migration imaging technique is applied to the process of the 3-D ground penetrating radar reflected echo data after pre-processing. By rearranging the amplitude of the collected reflected echo signals, the reflected echo energy can be homing to the real position of the space where the initial reflection point is located, thereby the horizontal resolution of the detection area is improved and finally the true outline of the measured target can be reconstructed. The simulation results verify the effectiveness and superiority of the proposed algorithm.

Keywords: GPR · Data processing · 3-D prestack time migration imaging

1 Introduction

In the traditional expressway roadbed detection, it is generally to use the punch coring excavating the sample to obtain the sample first, and then pass the soil test. This method not only has low efficiency, low accuracy, but also damages the roadbed and increases the cost of roadbed quality inspection. The advanced ground penetrating radar solution has the advantages of fast detection, no damage to the roadbed and high detection accuracy. As early as the late 1980s, Europe and the United States began to apply advanced ground penetrating radar technology, and it was not introduced to China until the 1990s. In recent years, the community has become more and more concerned about road maintenance, and the ground penetrating radar with non-destructive detection features has become one of the dark horses.

Ground penetrating radar provides a non-destructive detection solution for underground target detection, which is used more and more widely in engineering. For the

M. Jia et al. (Eds.): WiSATS 2019, LNICST 281, pp. 47–55, 2019.
https://doi.org/10.1007/978-3-030-19156-6_5

research of ground penetrating radar imaging methods, it is generally concentrated on 2-D imaging. Commercial ground penetrating radar products generally do not have 3-D imaging functions. However, for the 2-D image of ground penetrating radar, when the line of the 2-D section is inclined obliquely to the underground target, the reflected signal from the target interface directly below the line is not within the section, but for the reflection point not in the section can be recorded, causing the 2-D section to be inconsistent with the actual underground structure. On the one hand, the use of 3-D imaging of ground penetrating radar can solve the above-mentioned shortcomings of 2-D imaging section. On the other hand, 3-D image facilitates a more detailed understanding of the distribution of underground targets, so 3-D imaging technology has been extensively studied [1].

In the research of 3-D imaging technology, imaging migration can improve the resolution of target detection and restore the original shape of the target. Therefore, to some extent, the development level of imaging migration technology indicates the development level of detection technology. Imaging migration techniques can be divided into two categories: one is the polarization method based on the Huygens principle, and the method is based on the geometric principle of electromagnetic waves propagating in the medium. The other type is based on physical optics, starting from the solution of the wave equation, which is collectively referred to as the wave equation migration method. The common wave equation migration method mainly includes: Kichhoff integral migration method, finite difference migration method, F-K migration method, finite element migration method [2], etc.

In 1972, Claerbout introduced a finite difference migration method based on the parabolic equation [3]. In 1978, Stolt and Gazdag first performed the F-K transformation on the data, then solved the wave equation and extrapolated the electromagnetic wave field in reverse. This method is called the F-K migration method [4]. In 1978, Schneider used the Kichhoff integral equation solved by the wave equation to perform the migration imaging process [5]. In 1996, Grasmuck used the phase shift method to migration the common migration data [6]. In 1987, Lee et al. used the one-way acoustic equation to implement the finite difference method [7]. In 1992, Fisher et al. applied a split Fourier migration method to transform data for single migration data. In the same year, Fisher applied the inverse time migration method for migration processing for multi-migration data post-profiles [8]. In 1993, Deng et al. researched the Kichhoff integral migration method in depth [9]. In 2003, Chen et al. applied the hybrid domain one-way wave propagation operator to the migration imaging technique [10]. In 2011, Qu et al. applied compressive sensing theory to frequency stepped ground penetrating radar migration imaging [11]. In 2013, Huang conducted a study on the least squares migration imaging method for carbonate fractured reservoirs [12]. In 2015, Zheng et al. proposed a data autocorrelation multiple-wave migration imaging technique [13]. In 2016, Lu Yuting gave an analysis of the migration imaging method based on regularization of multi-source mixed mining data [14]. In 2017, He et al. carried out research on high-order generalized screen migration imaging based on particle swarm optimization algorithm [5].

In recent years, migration imaging technology has become a key technology in the development of ground penetrating radar technology. The use of migration imaging technology can improve the horizontal resolution of the system at the data processing level and analyze the distribution of underground media more accurately.

In this paper, the proposed 3-D prestack migration imaging algorithm combines the advantages of prestack migration imaging technology and time migration imaging technology. The prestack migration imaging technique performs the migration processing on the common midpoint (CMP) gather of ground penetrating radar. Then the algorithm extracts signal gather, which has the same reflection point. Finally, it stacks the common reflection point (CRP) gathers [15]. This algorithm has high precision and can improve the signal to noise ratio. The time migration imaging algorithm is implemented based on the summation of the diffraction curves, and the result is placed at the apex of the diffraction curve [16]. This algorithm is simple, the calculation speed is fast, the efficiency is high, and the actual engineering is widely used. The 3-D prestack migration imaging technique is applied to the echo data processing of the ground penetrating radar system. By rearranging the amplitude of the collected reflected echo signals, the reflected echo energy can be homing to the real position of the space where the initial reflection point is located, and finally the true outline of the measured target can be reconstructed [17].

At the same time, in order to better realize the 3-D migration imaging display, it is necessary to do some preliminary processing on the three-dimensional ground penetrating radar reflected echo data, including data preprocessing and data processing [18]. The preprocessing algorithm includes processing for removing bad sectors, zero correction, gain control, and the data processing algorithm includes background elimination, band pass filtering, and wavelet domain filtering [19].

2 3D Ground Penetrating Radar Data Processing Scheme

When studying the 3-D migration imaging technology, in order to obtain a better migration imaging effect, it is necessary to do some preliminary processing on the three-dimensional ground penetrating radar reflected echo data, including data preprocessing and data processing, and the 3-D data processing can be converted into multiple 2-D data processing. In the data processing part of this paper, the 2-D data preprocessing algorithm is given first, including the processing of removing bad track, zero correction, gain control and so on. The algorithm of removing bad track is used to estimate the effective echo data corresponding to the bad track and replace it, so as to reduce the influence of the bad track on the subsequent data processing; use the algorithm of zero correction to adjust the same axis to the same horizontal line, and reduce the effect of the up and down jitter on the detection in the actual detection in ground penetrating radar system; the gain control algorithm is used to amplify the echo signal data generated by the deep target, thereby making the deep target easier to be identified1. Then a 2-D data processing algorithm is provided, including background elimination, band pass filtering, wavelet domain filtering. The algorithm of background elimination is used to reduce the influence of standing wave interference, and highlight the detection target located at the standing wave position; the algorithm of band-pass filtering is used to improve the signal-to-noise ratio of the reflected echo signal, and reduce the interference of high-frequency clutter on the target detection; the algorithm of wavelet domain filtering is performed aimed at the non-stationary characteristics of the reflecting echo, achieving a better filtering effect. Finally, using the migration imaging algorithm, the 2-D prestack time migration imaging algorithm and the 3-D prestack time migration algorithm proposed in this paper are used respectively. By rearranging the amplitude of the collected reflected echo signals, the reflected echo energy can be homing to the real position of the space where the initial reflection point is located, finally the true outline of the measured target can be reconstructed. The entire data processing flow chart is shown in Fig. 1.

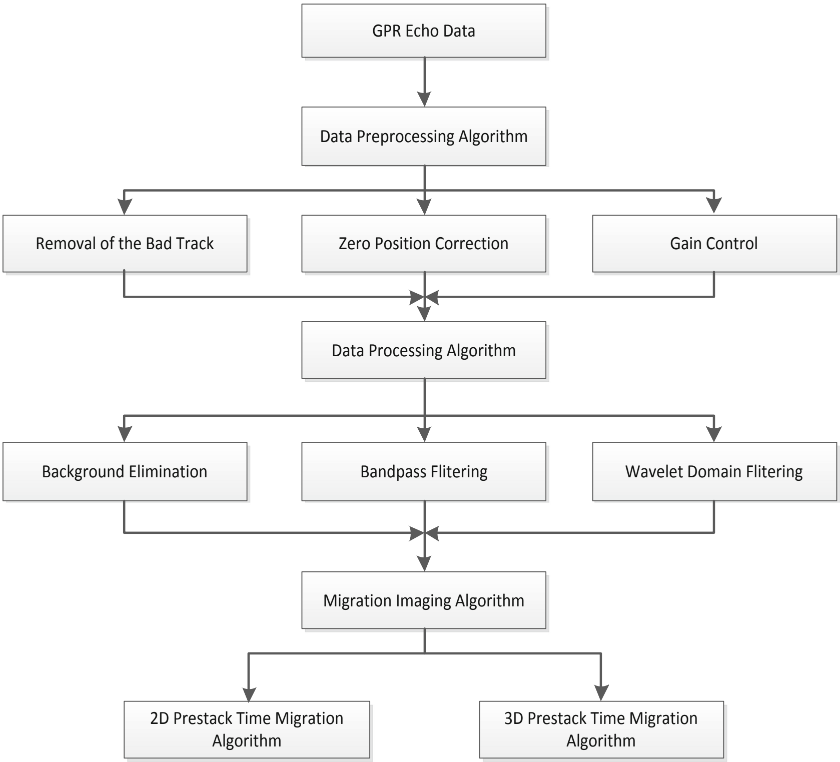

Fig. 1. Flowchart of the data processing

3 The Principle of 3-D Prestack Time Migration Imaging Algorithm

First the following assumptions are given: a coordinate system is given for the measured area, assuming that the z-axis is vertically downward, and the ground penetrating radar moves in the positive direction of the x-axis, where the positive direction of the y-axis conforms to the left-handed criterion. Also assume that the velocity of electromagnetic waves propagating in a lossy medium is constant, $u(x, y, z, 0)$ represents the true restoring section after using the migration algorithm, and $u(x, y, 0, t)$ is the superimposed section before using migration algorithm. By using half speed instead of the average propagation velocity of electromagnetic waves in a lossy medium, then the scalar wave equation in 3-D space can be expressed as

$$\frac{\partial^2 u}{\partial t^2} - \frac{v^2}{4}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) = 0 \tag{1}$$

First, the basic Fourier transform pairs used is given as follows:

$$\left.\begin{array}{l} u(x,y,z,t) \Leftrightarrow \tilde{u}\left(k_x,k_y,k_z,\omega\right) \\ \frac{\partial^2 u}{\partial t^2} \Leftrightarrow -\omega^2\tilde{u} \\ \frac{\partial^2 u}{\partial y^2} \Leftrightarrow -k_y^2\tilde{u} \\ \frac{\partial^2 u}{\partial x^2} \Leftrightarrow -k_x^2\tilde{u} \\ \frac{\partial^2 u}{\partial z^2} \Leftrightarrow -k_z^2\tilde{u} \end{array}\right\} \tag{2}$$

The Stolt-migration method is used for derivation. Let $\tilde{u}\left(k_x,k_y,k_z,t\right)$ is the 3-D - FT of $u(x,y,z,t)$, 3-D - FT is performed on the Eq. (1), and substituting the (2) into the above (1), Then we can obtain:

$$\begin{cases} \omega^2\tilde{u} - \frac{v^2}{4}\left(k_x^2 + k_y^2 + k_z^2\right)\tilde{u} = 0 \\ \frac{\partial^2 \tilde{u}}{\partial t^2} + \frac{v^2}{4}\left(k_x^2 + k_y^2 + k_z^2\right)\tilde{u} = 0 \end{cases} \tag{3}$$

Hence:

$$\frac{\partial^2 \tilde{u}}{\partial t^2} + \omega^2\tilde{u} = 0 \tag{4}$$

Solve the differential equation and take the up-going wave to get the positive value:

$$\tilde{u}\left(k_x,k_y,k_z,t\right) = A\left(k_x,k_y,k_z\right)e^{i\omega t} \tag{5}$$

We can see that $A\left(k_x,k_y,k_z\right)$ is unrelated to t. Assume that $t = 0$ in Eq. (5). Hence:

$$\tilde{u}\left(k_x,k_y,k_z,0\right) = A\left(k_x,k_y,k_z\right) \tag{6}$$

It is easy to see that $A\left(k_x,k_y,k_z\right)$ is the FT of the migration section $u(x,y,z,0)$ to be sought.

Next, we will discuss how to use the horizontal stacking section $u(x,y,0,t)$ to solve $A\left(k_x,k_y,k_z\right)$. Inverse FT is performed on $\tilde{u}\left(k_x,k_y,k_z,t\right)$. Hence:

$$u(x,y,z,t) = \frac{1}{8\pi^3}\int_{-\infty}^{\infty} dk_x \int_{-\infty}^{\infty} dk_y \int_{-\infty}^{\infty} A\left(k_x,k_y,k_z\right)e^{i\omega t} \cdot e^{-i\left(k_x x + k_y y + k_z z\right)} dk_z \tag{7}$$

Assume that $z = 0$. Equation (7) can be written as

$$u(x, y, 0, t) = \frac{1}{8\pi^3} \int_{-\infty}^{\infty} dk_x \int_{-\infty}^{\infty} dk_y \int_{-\infty}^{\infty} A\left(k_x, k_y, k_z\right) e^{i\left(\omega t - k_x x - k_y y\right)} dk_z \tag{8}$$

Assume that $B\left(k_x, k_y, \omega\right)$ is the 3-D - FT of the horizontal stacking section $u(x, y, 0, t)$. Then:

$$B\left(k_x, k_y, \omega\right) = \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy \int_{-\infty}^{\infty} u(x, y, 0, t) e^{-i\left(\omega t - k_x x - k_y y\right)} dt \tag{9}$$

Inverse transform is performed on Eq. (9). Then:

$$u(x, y, 0, t) = \frac{1}{8\pi^3} \int_{-\infty}^{\infty} dk_x \int_{-\infty}^{\infty} dk_y \int_{-\infty}^{\infty} B\left(k_x, k_y, \omega\right) e^{i\left(\omega t - k_x x - k_y y\right)} d\omega \tag{10}$$

Compare Eq. (8) with Eq. (10), implies

$$A\left(k_x, k_y, k_z\right) dk_z = B\left(k_x, k_y, \omega\right) d\omega \tag{11}$$

Hence:

$$A\left(k_x, k_y, k_z\right) = B\left(k_x, k_y, \omega\right) \frac{d\omega}{dk_z} \tag{12}$$

Solve by the up-going wave, where ω takes a positive sign and differentiate k_z, then we can get

$$\begin{aligned} A\left(k_x, k_y, k_z\right) = B&\left(k_x, k_y, \frac{v}{2} k_z \cdot \sqrt{1 + k_x^2/k_z^2 + k_y^2/k_z^2}\right) \\ &\cdot \frac{v}{2 \cdot \sqrt{1 + k_x^2/k_z^2 + k_y^2/k_z^2}} \end{aligned} \tag{13}$$

Inverse 3-D - FT is performed on the $A\left(k_x, k_y, k_z\right)$, hence

$$u(x, y, z, 0) = \frac{1}{8\pi^3} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} A\left(k_x, k_y, k_z\right) e^{-i\left(k_x x + k_y y + k_z z\right)} dk_x dk_y dk_z \tag{14}$$

Where $u(x, y, z, 0)$ is the solution of the migration section.

In summary, the flowchart of the 3D prestack time migration imaging algorithm is shown in Fig. 2.

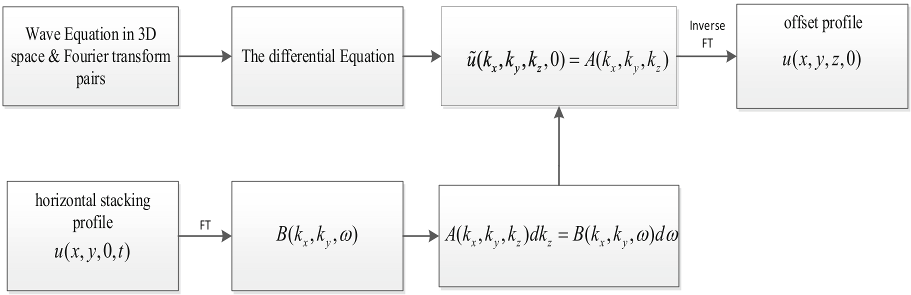

Fig. 2. Flowchart of the 3D prestack time migration imaging algorithm

4 Simulation Results

Figure 3 shows the 2-D image of the ground penetrating radar after the migration. Figure 4(a) shows the 3-D image of the ground penetrating radar before migration, Fig. 4(b) shows the 3-D image of the ground penetrating radar after migration. It can be seen that the diffraction wave in the form of a hyperbola after the Stolt migration is homing, which improves the lateral resolution, and proves the superiority of the algorithm.

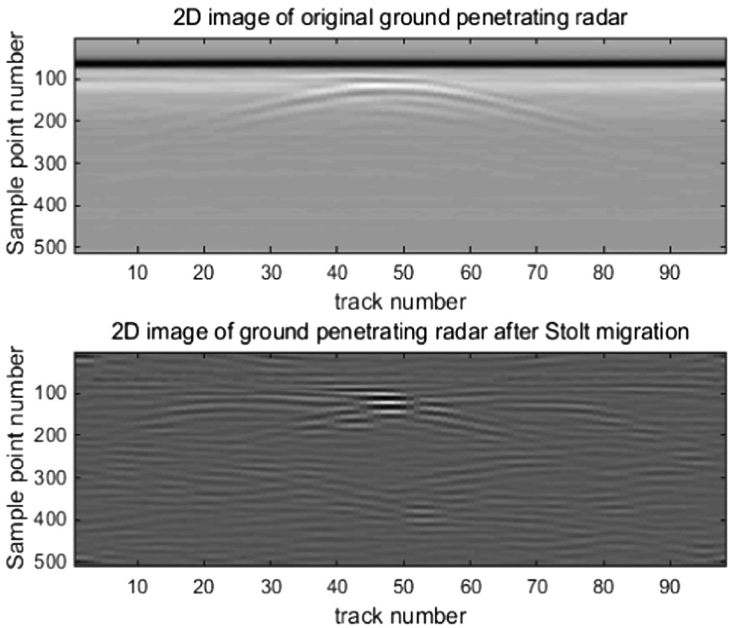

Fig. 3. The 2D prestack time migration imaging result

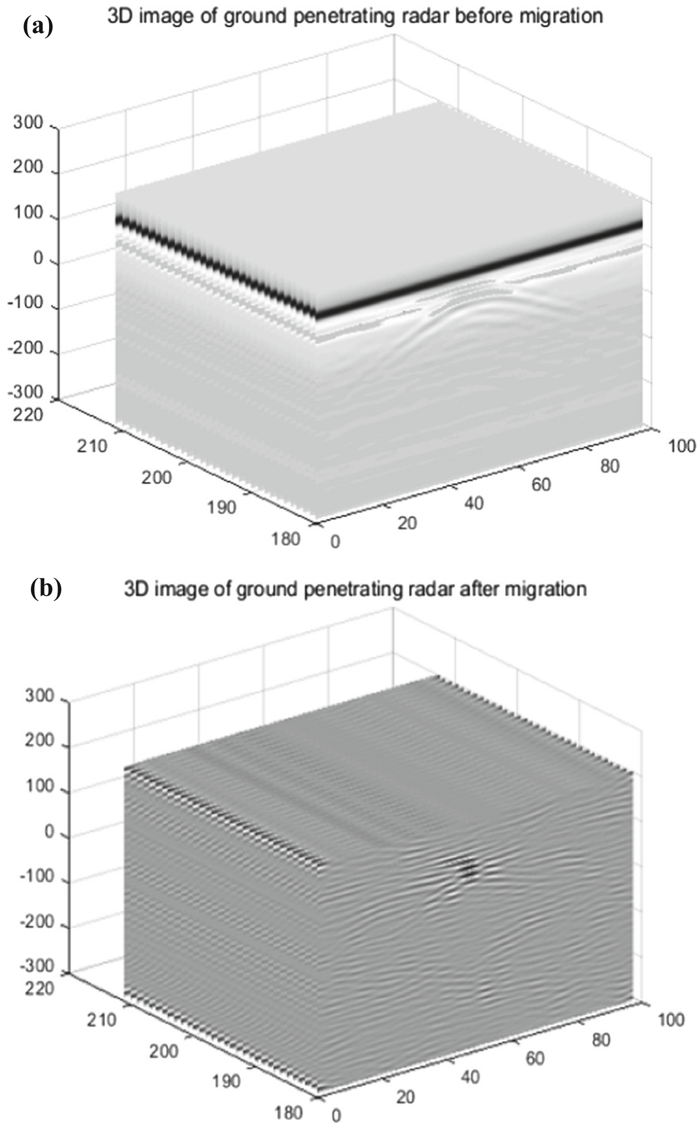

Fig. 4. (a) The 3-D image of the ground penetrating radar before migration. (b) The 3-D image of the ground penetrating radar after migration

5 Conclusion

A 3-D prestack time migration imaging algorithm is proposed. Then the 3-D prestack migration imaging technique is applied to the process of the 3-D ground penetrating radar reflected echo data after pre-processing. By rearranging the amplitude of the collected reflected echo signals, the reflected echo energy can be homing to the real position of the space where the initial reflection point is located, thereby the horizontal resolution of the detection area is improved and finally the true outline of the measured target can be reconstructed Simulation results verify the effectiveness and superiority of the proposed algorithm.

Acknowledgement. This work was supported in part by the National Key R&D Program of China under grant No. 2017YFC1500601.

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