Sensors & Transducers, Vol. 180, Issue 10, October 2014, pp. 51-55

Sensors & Transducers

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Research on Ground Penetrating Radar Migration Imaging Technology

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Received:10 July 2014 /Accepted: 30 September 2014 /Published: 31 October 2014

Abstract: The ability of Ground penetrating radar (GPR) to estimate the shape and position of objects in target area is depends on the imaging technology. Migration image method was popular used in seismic wave detection technology, and now it is used in GPR electromagnetic wave detection technology. In this paper, three migration image methods: Finite Difference Time Domain (FDTD), Frequency Wave number, and Kirchhoff migration method are been discussed separately. By dealing with GPR simulation and experiment data, it shows that the seismic wave migration method used in GPR imaging is effectiveness and stability. At last, compare the imaging results of three migration methods, several useful conclusions are been given. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Ground penetrating radar, Migration imaging, FDTD, Frequency Wave number, Kirchhoff.

1. Introduction

Ground penetrating radar (GPR) is a mature remote sensing technique employed by engineers and scientists to obtain information from subsurface structures. Image technology is an important subject of ground penetrating radar signal processing technology. The images of subsurface objects are different with actual location because the antenna has limited lobe width and bandwidth. There is one of the most important problems that how to extract the information such as the location and shape of subsurface objects from GPR output images. Different methods have been put forward by overseas and domestic scholars. Migration method is been widely used in seismic data processing. This paper chooses Finite Difference Time Domain (FDTD), Frequency Wave-number, and Kirchhoff migration method to deal with GPR imaging. Simulation and experiment results show that the seismic wave migration method used in GPR imaging is effectiveness and stability.

2. Migration Theory

Migration is a tool used in GPR processing to get an accurate picture of underground targets. It involves geometric repositioning of return signals to show an event where it is being hit by the electromagnetic wave rather than where it is picked up.

Migration principle can be explained by Fig. 1. In Fig. 1, GPR detects on the surface of medium. There is a metal point target in the medium. O is the true position of the target. O' is the detected position

from x_i. Assuming $\Delta x_i = |x_i - x_0|$, the travel time from x_i to O' is $\frac{t_i}{2}$, and from x to O' is $\frac{t}{2}$. According to the geometric repositioning, the relationship of travel time from different position can be written as:

$$\left(\frac{t}{2}\right)^2 = \left(\frac{t_i}{2}\right)^2 + \left(\frac{\Delta x_i}{v}\right)^2 \quad (1)$$

Hence:

$$t_i = \left[t^2 - 4(\Delta x_i / v)^2\right]^{1/2} \quad (2)$$

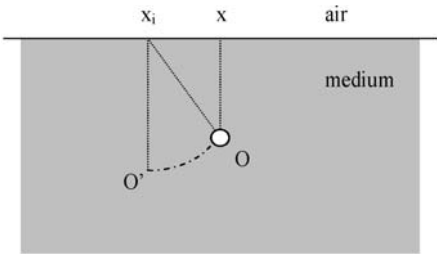


Fig. 1. Migration principle.

Migration process can be summarized as: GPR ground receiving point is considered as the center. Put reflection arrival time of different detect position to the arc, and the radius depth of the arc is $z = \frac{1}{2}vt$. Plus all the value together on the same point, then, the migration section is been built up.

3. FDTD Migration Method

According to explode reflection model (ERM) used in GPR data processing, the propagation path of electromagnetic wave under ground can be considered to be vertical if reflecting angle is less than 30°. Then using 15° finite difference time domain method to solve electromagnetic wave equation can get the satisfied results. 15° FDTD is a recursive method，and it is sensitive with different horizontal velocity and vertical velocity of electromagnetic wave.

Under ground electromagnetic wave $\varphi(x,z,t)$ can satisfied with two-dimensional wave equation:

$$\varphi_{xx} + \varphi_{zz} - \frac{4}{c^2(x,z)}\varphi_{tt} = 0 \quad (3)$$

Assuming $D = \frac{1}{2}ct + z$, $d = z$, the above can be written as:

$$\phi_{xx} + \phi_{dd} + 2\phi_{dD} = 0 \quad (4)$$

By variable substitution, the wave filed $\phi(x,0,D)$ can be transformed to $\phi(x,D,D)$. Migration of the point is been finished. If the incident direction of electromagnetic wave is nearly perpendicular, reflect wave inclination angle is also smaller then 15°, $\phi_{xx} >> \phi_{dd}$, ϕ_{dd} can be neglected, the reflect wave function can be written as

$$\phi_{xx} + 2\phi_{dD} = 0 \quad (5)$$

Discrete variable, assuming $D_j = j\Delta D$ and $d_k = k\Delta d$, note $\phi(x)_j^k \equiv \phi(x, d_k, D_j)$. Symmetry implicit difference grid is been used to do the iterative compute. The difference grid is shown in Fig. 2. Here, horizontal and vertical axes are representation x and d direction, respectively. The calculated direction with d is from top to down. The direction perpendicular to the paper is D, which is extension direction.

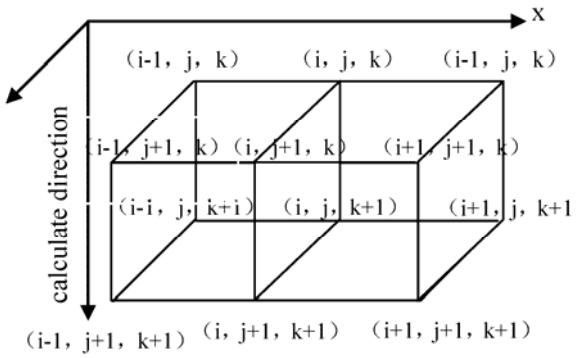


Fig. 2. Finite difference time domain grid.

Differential expression for the wave equation is:

$$(1-T)\phi_j^{k+1} = -(1-T)\phi_{j+1}^k + (1+T)\left(\phi_{j+1}^{k+1} + \phi_j^k\right), \quad (6)$$

where $T = \frac{\Delta D \Delta d}{8}\frac{d^2}{dx^2}$, derive that:

$$\phi_j^{k+1} = -\phi_{j+1}^k + (1+2T)\left(\phi_{j+1}^{k+1} + \phi_j^k\right) \quad (7)$$

Equation (7) is the iterative function of FDTD migration.

4. Frequency Wave-number Migration Theory

The electromagnetic pulse, radiated from GPR transmitting antenna, impinges on the objects and is scattered back towards the received antenna.

According to Huygens' principle, the reflected field, supposed the propagation velocity in the medium is half of the true value, it can be thought originated from the scatters and propagating towards the antenna. The problem is to reconstruct the wavefield existed at $t=0$ from the wavefield observed at $z=0$.

Supposed that the recorded profile is $e(x,z=0,t)$, x and z are horizontal and vertical coordinates respectively, t is time, the migrated profile is $e(x,z,t=0)$, Let $E(k_x,z=0,\omega)$ be the 2-D Fourier transform of $e(x,z=0,t)$

$$E(k_x,z=0,\omega)=\int\int e(x,z=0,t)e^{-j(k_x x+\omega t)}dxdt \quad (8)$$

In the F-K domain, wavefield at the depth of z can be expressed as

$$E(k_x,z,\omega)=E(k_x,z=0,\omega)e^{jk_z z}, \quad (9)$$

where k_x, k_z and ω are constrained by the dispersion relation for scalar waves

$$\frac{\omega^2}{(v/2)^2}=k^2=k_x^2+k_z^2 \quad (10)$$

Let $e(x,z,t)$ be the 2-D inverse Fourier transform of $E(k_x,z,\omega)$ with respect to k_x and ω

$$e(x,z,t)=\frac{1}{(2\pi)^2}\int\int E(k_x,z,\omega)e^{j(k_x x+\omega t)}dk_x d\omega \quad (11)$$

Using (10) and let $t=0$, then

$$e(x,z,t=0)=\frac{1}{(2\pi)^2}\iint E\left(k_x,z=0,\frac{v}{2}\sqrt{k_x^2+k_z^2}\right)\cdot\left(v\Big/\left(2\sqrt{1+k_x^2/k_z^2}\right)\right)e^{jk_x x}e^{jk_z z}dk_x dk_z \quad (12)$$

This is the migrated profile. Let

$$A(k_x,k_z)=E(k_x,z=0,\frac{v}{2}\sqrt{k_x^2+k_z^2})\cdot(v\Big/(2\sqrt{1+k_x^2/k_z^2}))$$

F-K migration can be described as the flowing steps: $e(x,z=0,t)\xrightarrow{FFT}E(k_x,z=0,\omega)\rightarrow A(k_x,k_z)\xrightarrow{IFFT}e(x,z,t=0)$ The F-K migration is the fasted known migration techniques. In the transforms of $E(k_x,z=0,\omega)\rightarrow A(k_x,k_z)$, we need properly choice the interpolation method. The F-K migration is also very sensitive with the variation of velocity in the medium, so it is relatively suitable for the homogeneous medium.

5. Kirchhoff Migration Method

Kirchhoff migration method uses diffraction integral formula to collect different traces energy from the same diffraction point, and forces the hyperbola focus to the reflection point.

Assuming the underground medium is uniformity and isotropy, the scalar quantity electric field equation can be written as:

$$\nabla^2 E(\vec{x},t)=k^2\frac{\partial^2 E(\vec{x},t)}{\partial t^2}, \quad (13)$$

where $k^2=1/v_0^2$, v_0 is the velocity of electromagnetic wave in the medium.

According to Green theorem and point source Green formula, we can get the integral equation:

$$E(\vec{x}_0,t)=\int_{\partial V}\left[\begin{array}{l}\frac{1}{r}\left[\frac{\partial E}{\partial n}\right]_{t+r/v_0}-\frac{1}{v_0 r}\frac{\partial r}{\partial n}\left[\frac{\partial E}{\partial t}\right]_{t+r/v_0}\\+\frac{1}{r^2}\frac{\partial r}{\partial n}[E]_t\end{array}\right]d_{surf}, \quad (14)$$

here v_0 is the velocity, it can be a constant or a matrix. r is the distance from transmition point to the reflection point, $r=\sqrt{(x-x_0)^2+(y-y_0)^2+(z-z_0)^2}$ n is stands for the outside normal direction of integration plane, and the direction of z axis is pointing down, so $\partial_n=-\partial_z$.

The traditional selection of integral surface is to choose infinite ground plane and the lower hemisphere. In practical problems, the observation surface and reflection points cylindrical surface is often used as integral surface. Ignore the boundary effect and the near-field term, the integral equation can be expressed as:

$$E(\vec{x}_0,t)=\int\left[-\frac{1}{r}\left[\frac{\partial E}{\partial z}\right]_{t+r/v_0}+\frac{1}{v_0 r}\frac{\partial r}{\partial z}\left[\frac{\partial E}{\partial t}\right]_{t+r/v_0}\right]dsurf \quad (15)$$

6. Simulation Results

Fig. 3a is a simulation image of GPR by GprMaxV2.0 software. The width and depth of simulation area is 1.21 m and 0.75 m separately. There are three perfect metal pipes 0.45 m up to the bottom. The transmitting and receiving antenna move on the ground, and detect every 1cm distance. The sample interval is 0.001 ns. There are totally 121 traces which contain 2050 samples of each trace. The actual electromagnetic wave velocity is 17.3 cm/ns.

Fig. 3b-3d are FDTD migration, FK migration and Kirchhoff migration results respectively with the same velocity 16.6 cm/ns, which is lower by 4 % with the actual value.

Even through, from the results of three different migration methods, there can be clearly recognized the point targets. The simulation results represent that migration methods to dealing with the GPR image is effective and the error between estimated velocity and actual velocity is acceptable.

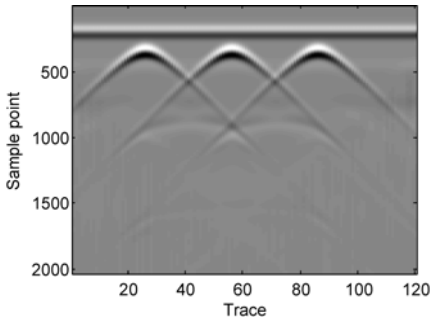


Fig. 3a. Point scatter image.

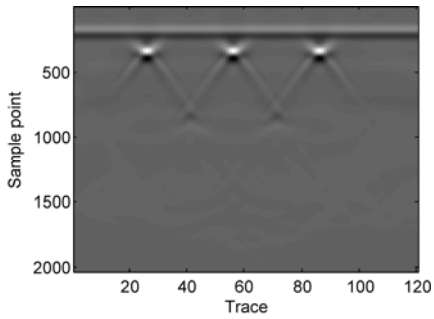


Fig. 3b. FDTD Migration of Fig. 3a.

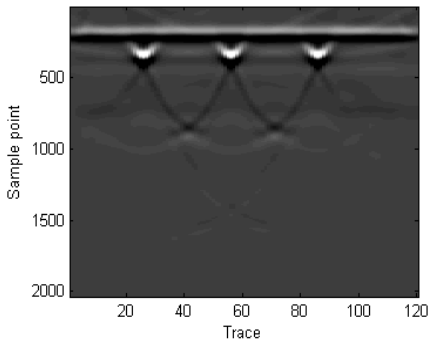


Fig. 3c. FK Migration of Fig. 3a.

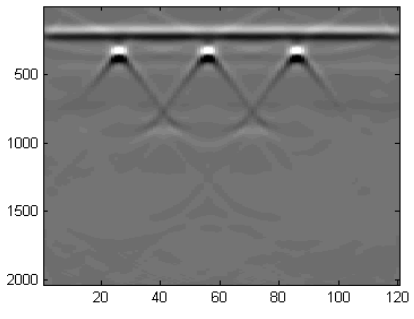


Fig. 3d. Kirchhoff Migration of Fig. 3a.

7. Experiment Results

Fig. 4a is a GPR data profile. The horizontal and vertical coordinates are trace and sample point respectively. Fig. 4b-4d are FDTD migration, FK migration and Kirchhoff migration results respectively with the same velocity 8.1 cm/ns. From the result, we can see that the hyperbola focuses its vertex. And the position and shape of the target can be seen clearly.

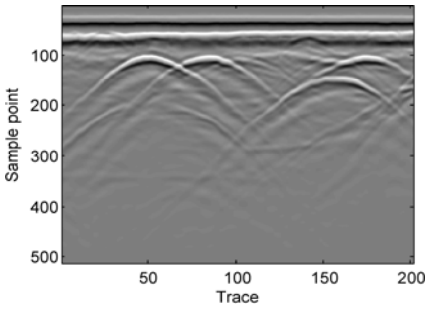


Fig. 4a. Image get from GPR.

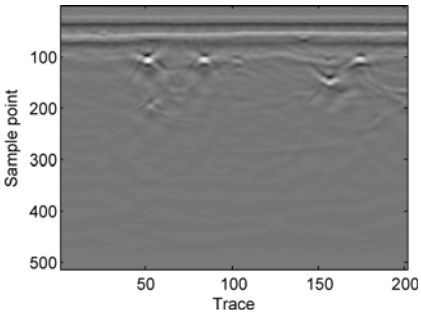


Fig. 4b. FDTD Migration of Fig.4a.

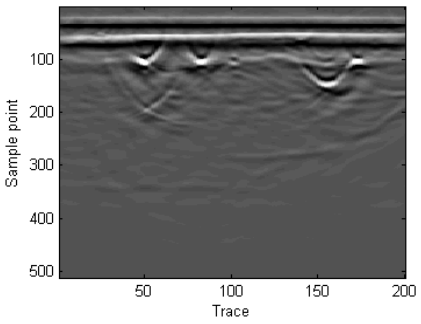


Fig. 4c. FK Migration of Fig.4a.

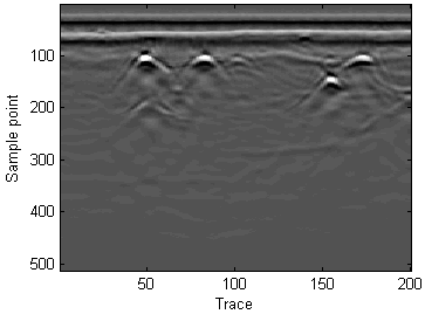


Fig. 4d. Kirchhoff Migration of Fig.4a.

8. Conclusions

The simulation and experiment results show that FDTD, FK and Kirchhoff Migration methods have strong ability to image the multiple objects in GPR output images. But there are some differences between the three methods. FDTD is an iterative method, it saves memory but costs longer time. FK migration method is sensitively by wave velocity. It only can be used in well proportioned medium. Kirchhoff migration method needs some transcendental knowledge of the medium, otherwise it is hard to confirm the migration parameters.

In summary, using migration methods to dealing with the GPR image is effective. The position and the shape of the objects can be easily obtained, and the velocity of electromagnetic wave in the detect medium can be estimated. According to the specifically application situation, we can choose the proper migration method.

Acknowledgements

The authors would like to thank for the support by National Natural Science of China Foundation under Grant 61201389, 61201390, and 11201120. The authors also thank for the support by Science and Technology Research Key Project of Henan Education Department under Grant 12A510006.

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