Ray Tracing of CMP Antenna Array GPR System

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Abstract—There is much interest in vehicle mounted array GPR systems for landmine detection and work is being carried out on various national, because high speed array GPR systems can sweep a large area in a relatively short time to improve performance and efficiency. We developed the vehicle mounted stepped-frequency (SF) CMP antenna array GPR system. The system has three pairs of Vivaldi antennas that configure a symmetrical CMP antenna array. Based on this configuration, multi-offset CMP data gather can be acquired at every measurement position. Migration is an important signal processing method that can improve signal-clutter ratio and reconstruct subsurface image. Diffraction stacking migration and Kirchhoff migration sum amplitudes along the migration trajectory that generally is hyperbolic. But when the ground surface varies acutely, we have to modify the migration trajectory by the technique of ray tracing. We compute the travel time between transmitter, receiver and each subsurface scattering point, and search the propagation ray depending on the Fermat’s principle. The method is tested by an experiment data acquired by the SF CMP antenna array GPR system. The target is a metal ball that is buried under a sand mound. A nice result of ray tracing is shown in the case.

1. INTRODUCTION

Accidents caused by antipersonnel (AP) landmines remaining from past conflicts have received considerable public exposure in the last several years. The global land mine crisis is creating immense social and economic problems worldwide [1]. Because ground-penetrating radar (GPR) is sensitive to changes in all three electromagnetic characteristics of a medium, electric permittivity, electric conductivity, and magnetic permeability, GPR is one of a number of technologies that has been extensively researched as a means of improving mine detection efficiency. In this case, the GPR antenna(s) must be elevated above the ground [2, 3]. This requirement results in heavy surface clutter, especially when the ground is rough [4, 5].

A GPR array is usually employed to sweep a large area in a relatively short time to improve performance and efficiency [6]. We proposed a robust GPR common midpoint (CMP) array technique, including CMP antenna array and CMP processing technique, to enhance signal-to-clutter ratio (SCR). The CMP multi-fold coverage technique, which is widely applied in seismic exploration as a method of enhancing useful signals, was employed into the configuration of antenna array for collecting CMP GPR data over the region to be probed. Then, the CMP processing techniques, including velocity spectrum and multi-fold stacking, were combined to increase the SCR [7]. Based on the velocity, the migration technique can be used to reconstruct subsurface imaging and dramatically enhance the SCR by summing the diffraction wave [8]. The migration technique [9] is now commonly used to process GPR data, and has been in use for almost five decades in seismic reflection surveys.

Generally the diffraction stacking migration or Kirchhoff migration need compute the travel time. But the travel time surface generally is smooth spherical surface in the case of zero-offset data and smooth ellipsoidal surface in the case of nonzero-offset data whose curvature is governed by the velocity function. When the height of ground surface varies largely in the very rough ground area, for example mound, the travel time surface will be affected by the ground surface. In this paper we will consider the effect of the ground surface into the travel time for the CMP Antenna Array GPR System. We will compute the ray path of the electromagnetic wave among the transmitters and diffraction points and receivers and get the diffraction travel time surface.

2. RAY TRACING AND TRAVEL TIME

The basic idea is to find the first-arrival traveltimes by using Fermat’s principles in a velocity model. According to Fermat’s principle, the path with the smallest traveltime is the one best
approximating the ray trajectory. It is possible to determine the traveltime between two arbitrary points. Fig. 1 shows a 2D velocity model. The velocity is $C$ in the air layer and $V$ in the subsurface layer. $B$ is the arbitrary subsurface scattering point and $A$ is the arbitrary transmitter or receiver. The ray path between $A$ and $B$ is $AR_iB$. $R_i$ is the arbitrary point in the ground surface. So if the distance between $A$ and $R_i$ is $d_{i1}$ and the distance between $R_i$ and $B$ is $d_{i2}$, the travel time between $A$ and $B$ is:

$$T_i = \frac{d_{i1}}{C} + \frac{d_{i2}}{V}, \quad i = 1, \ldots, n$$ (1)

![Figure 1: Sketch figure of ray path.](image)

Then we can define the $T_j$ in the ground surface, depending on the Fermat’s principle,

$$T_j = \min(T_i)$$ (2)

So, the ray path between $A$ and $B$ is $AR_jB$ and the first-arrival travel time is $T_j$. For the 3D case, we just need to extend the $R_i$ from line to surface. Using the approach, we calculate the ray path for the experiment data of mound case.

3. CMP ANTENNA ARRAY GPR SYSTEM

The GPR system is a stepped frequency radar system with an operational frequency range of 30 KHz to 6 GHz. A vector network analyzer was chosen for its flexibility in selection of frequencies. To employ CMP technique, we developed an antenna array, shown in Fig. 2, which is constructed of 6 antipodal Vivaldi antennas. These antennas are used to form 3 pairs of transmitting-receiving antennas. In each pair of antennas, one is used to transmit the signal while the other receives. Separation between the antennas is 6 cm. Depending on the antenna array configuration of GPR system, we can acquire CMP multi-offset data directly. The antipodal Vivaldi antenna was chosen because it is a wide frequency range antenna and can easily be used to construct an antenna array due to its flat shape. A coaxial switch is used to connect the vector network analyzer to the transmitting-receiving antenna array, because while the antenna array has five transmitter and receiver antennas, the vector network analyzer has only one transmitting port and one receiving port. A position controller is used to move the antenna array in two dimensions (the $X$ and $Y$ direction) with precision. Based on the vector network analyzer, position controller, coaxial switch and transmitting-receiving antenna array, we developed the stepped-frequency continuous-wave array antenna system, shown in Fig. 3.

![Figure 2: Antenna array.](image)

![Figure 3: SAR-GPR system.](image)
4. EXPERIMENT

We buried a small metal ball whose radius is about 6 cm in the homogenous soil and the ground surface is mound, shown in Fig. 4, in laboratory. Then we measured it in C-scan model using GPR. The operational frequency range is from 300 MHz to 6 GHz. The number of frequency points is 401. The distance between two antennas is 6 cm. The height of antenna is 8 cm and the depth of metal ball is 10 cm. The x interval and y interval are 1 cm.

![Metal ball](image)

**Figure 4**: Metal ball.

![Ray path in the mound](image)

(a) side view  
(b) top view

**Figure 5**: The ray path in the mound.

![Profile through metal ball and travel time trajectory](image)

**Figure 6**: A profile through metal ball buried in the mound and travel time trajectory.
Using the ray tracing, we calculate the ray path for the experiment data. Fig. 5 shows the ray path among one subsurface scattering point and all antenna position in C-scan model. From the figure, we can find the ray path distributed irregularly. Fig. 6 shows one vertical profile of the survey line above the metal ball and the travel time trajectory. From the figure, we can find the travel time trajectory and the diffraction signal from the metal ball correspond each other very well. So in the situation, summing amplitudes along the travel time trajectory in stead of hyperbolic trajectory, migration can improve signal-clutter ratio and reconstruct subsurface image.

5. CONCLUSIONS

The height of ground surface varies largely in the very rough ground area, for example mound, the hyperbolic trajectory can not correspond with the diffraction signal very well. In the case, the ray tracing can offer a accurate travel time trajectory.

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REFERENCES