Applicability of phased array antenna to ground penetrating radar

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Ground Penetrating Radar (GPR) has been widely used to detect objects in shallow subsurface. Although a bow-tie antenna, which is the major antenna in practice, provides clear cross sections in the shallow subsurface especially under survey line, the resolution in the direction of cross-line depends strongly on the spatial interval between neighboring survey lines. Moreover, no subsurface image could be obtained for subsurface beneath complex artificial structures on the surface since no survey line may be drawn above the structures. These are the two major problems in the current practice of GPR surveys. We would like to propose a method to overcome these two problems with the use of phased array antenna as a radar source. We conducted some numerical simulations using a 3D-FDTD method and examined the performance of the antenna in terms of signal-to-noise ratio of the generated electromagnetic (EM) wavefield and the response to slanted EM wavefield input. Our numerical results indicate that the application of the phased array system to GPR could enhance the signal-to-noise ratio for reflectors located lateral to the survey line, and has a potential to be used as an angular scanner imaging tool that has not been attempted in the conventional GPR system. The latter may also indicate that the number of survey lines could be reduced to lower the cost of GPR surveys.

1. INTRODUCTION

GPR is commonly used for detecting objects in shallow subsurface, such as buried pipes, land mines or tree roots (Hirano *et al.*, 2009). We measure electro-magnetic (EM) waves scattered by anomalies in the subsurface in response to an input EM plane wave generated on the earth surface. The measured scattered waves can estimate the location of scatterers in a non-destructive way. For the generation of the input EM wave, a bow-tie antenna, which has mostly been used as conventional GPR antennas, has the limitation in the cross-line resolution in the prospecting. It leads to an increase of the time for surveys to achieve required spatial resolution. Also, artificial structures on the surface could limit the extent of the survey areas. The resolution in the cross-line direction and the imaging of subsurface structure beneath artificial structures are the major two problems.

In this study, we propose the use of a phased array system (Lutz and Perroud, 2006) to solve this problem. This system is commonly used for air radar technology (Hansen *et al.*, 2009). However, underground structure is normally inhomogeneous which causes complex wave phenomena such as scattering. Therefore, it is difficult to propagate EM waves in desired directions (Das *et al.*, 2003). This means that understanding the behavior of phase shifted EM waves in inhomogeneous subsurface is essential to utilize the phased array system for GPR.

In this study, we conducted some numerical simulations using a 3-D FDTD method to understand the radiation pattern of the phase shifted EM waves. Firstly, we describe the theory of numerical method and our strategy of generating EM waves. Then we apply these theories to GPR. The way of Phase shifting is mentioned here. Finally, we conduct some simulations. Comparing a dipole antenna and phased array antenna, we confirm the applicability of the phased array to GPR.

2. THEORY

(1) Maxwell's Equation

EM fields in a linear, isotropic medium are described from Maxwell's equations

$$\text{rot}\mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t} \quad (1)$$

$$\text{rot}\mathbf{H} = \varepsilon \frac{\partial \mathbf{E}}{\partial t} + \sigma \mathbf{E} \quad (2)$$

$$\text{div}\mathbf{E} = 0 \quad (3)$$

$$\text{div}\mathbf{H} = 0 \quad (4)$$

where $\mathbf{E}$ and $\mathbf{H}$ are electric and magnetic vector fields, respectively, and ε , μ and σ are the electric permittivity, the magnetic permeability and electric conductivity of the medium, respectively.

Table 1 shows the electric and magnetic parameters that we used in our numerical simulations. Parameters in free space are

$$\begin{aligned}\epsilon_0 &= 8.854e - 12 \\ \mu_0 &= 4.0\pi e - 7 \\ \sigma_0 &= 0.000\end{aligned}$$

Table 1. Electric and Magnetic Parameters

	$\epsilon_r(-)$	$\mu_r(-)$	$\sigma(\text{S/m})$
Dry soil	3.000	1.000	0.0001000
Water	81.000	1.000	0.01000

We adopt Yee's (1996) staggered grid to calculate the $\mathbf{E}$ and $\mathbf{H}$ fields so as to simulate how EM fields propagate in the medium using a 3D-FDTD method. C-PML absorbing condition (Roden *et al.*, 2000) is applied in this simulations to avoid artificial reflections from model edges.

Figure 1. 2-D Phased Array Antenna

(2) Array Antenna Theory

The array theory is described in Pascale Lutz *et al* (2006). Consider an array antenna composed of N single units positioned along the x-axis with a regular spacing d (Figure 1). The electrical field radiated by the array antenna at the observation point P is

$$\begin{aligned}\mathbf{E}(R, \theta, \phi) \\ = \mathbf{f}(\theta, \phi) \left(\frac{\exp(-ikR)}{R} \right) F(\theta, \phi)\end{aligned}\quad (5)$$

where (R, θ, ϕ) is the spherical coordinates of the observation point P, with respect to the origin at the center of the array. We assume that the point P is far enough from the antenna. Finally, $k = 2\pi/\lambda$ is

the wavenumber and λ is the wavelength.

$\mathbf{f}(\theta, \phi)$ is the vector radiation pattern of each antenna and $F(\theta, \phi)$ is called the array factor,

$$F(\theta, \phi) = \sum_{n=-(N-1)/2}^{(N-1)/2} \exp(in\psi) \quad (6)$$

$$\psi = \beta + kd\sin\theta\cos\phi \quad (7)$$

where β represents the phase current excitation. The array factor $F(\theta, \phi)$ can be expressed as

$$F(\theta, \phi) = \frac{\sin(\frac{N\psi}{2})}{\sin(\frac{\psi}{2})} \quad (8)$$

3. METHOD

(1) Dipole Antenna and Phased Array Antenna

We compare two different kinds of antenna, a dipole antenna and a phased array antenna. The phased array antenna has an 8×8 sending units and one receiving unit at the center of the radar (Figure 2). Both antennas have the length of about 0.5 meters. The electrical current source is the first derivative of a Gaussian pulse (Figure 3).

Figure 2. A dipole antenna and a phased array antenna

Figure 3. Electrical Current Source (1st derivative of a Gaussian pulse)

(2) Phase Shifting

To direct the energy towards a desired direction, we have to control ψ . Let us suppose the 8 antennas in the same y -coordinate (smallest y) are y_1 gather. Naming every 8 sets of antennas, $y_2, y_3, \dots, y_8$ are allocated (Figure 4).

Figure 4. Allocation of 8 sets of antennas

Since we assume that our phased array antenna would conduct a scanning probe along the survey lines, equation (9) still holds. It means that we change the electrical direction only across the survey lines. Equation (10) represents that every single antenna excite the same form of electrical current source. where ϕ_n is the azimuth angle relative to x -axis of y_n and β_n is the phase current excitation of y_n .

For distance far from the antenna, we assume $\theta_n = \theta$ and the following far-field approximation can be made

$$\phi_n = 0 \quad (9)$$

$$\beta_n = \beta \quad (10)$$

$$f_n(\theta_n, \phi_n) = f(\theta, 0) \quad (11)$$

Thus, in the frequency domain, adjusting ψ_n as Equation (12), we can control the direction of the EM fields.

$$\psi_n = (n - 1)k \sin \theta \quad (n = 1, 2, \dots, 8) \quad (12)$$

where ψ_n represents the phase delay for y_n .

In the time domain, the time delay we give to y_n is described as

$$\Delta t_n = d(n - 1) \sin \theta / v \quad (n = 1, 2, \dots, 8) \quad (13)$$

where v is the velocity of the EM waves in the ground and θ is the deviation from the vertical direction.

Figure 5 is the visualization of the electric field radiated towards the desired direction.

Figure 5. Visualization of Electric Field Radiated by the Phased Array Antenna ($\theta = 0.50 \text{ rad}$)

4. MODEL SETUP

(1) The Ground model with a PEC surrounded by water

To confirm the applicability of the phased array antenna, we conducted some numerical simulations using a 3-D model, which includes water bodies and a single small perfect conductor (PEC) with cubic shape as scatterers (Figure 6). The background medium is assumed to dry sand. Both antennas are fixed and the phased array antenna radiates the energy towards the PEC.

Figure 6. Ground model with a PEC

(2) Forward Modeling of the practical survey

Second, two more cubes of PEC are positioned (Figure 7). Then, we moved two kinds of antenna along the survey line and conducted numerical simulations at 32 source positions. Two ways of numerical simulations are conducted, using a dipole antenna and a directional phased array antenna ($\theta = 0.50\text{rad}$).

Figure 7. Ground Model with three PECs

5. RESULTS and DISCUSSIONS

Figure 8 shows the scattered wave observed in the first ground model (Figure 6). Red and blue lines show the waveforms obtained by the dipole and phased array antennas, respectively. In this experiment, we concluded that the phased array antenna has an advantage in enhancing the noise-to-signal ratio. It also shows that the phased array antenna enhanced the amplitude of a scattered wave from the PEC located out of the survey line. The enhancement of noise-to-signal ratio results from the random overlaps of 64 signals of each antenna of the array. Since the array is constructed planarly, each signal of the phased array is more

random than the dipole.

Figure 8. Comparison of scattered waves from a PEC

Figure 9 and Figure 10 represent the 32 trace gathers observed in the second model (Figure 7). Strong amplitude can be observed in the blue circle in Figure 9 while small amplitude can be observed in corresponding part in Figure 10. These events are generated by two PEC under the survey line. This results from the radiation pattern of the dipole antenna. On the other hand, the blue circle in Figure 10 represents the greater effect from the PEC out of the survey line. Since the desired direction of the phased array antenna corresponds to the position of off-center PEC, we conclude that we successfully enhance the amplitude of the scattered wave from the desired position.

Figure 9. Trace of Dipole Antenna

Figure 10. Trace of Directional Phased Array Antenna ($\theta = 0.50\text{rad}$)

5. CONCLUSION

In this study, we conclude that the application of the phased array system to GPR has a potential to survey with wider angle than the conventional GPR system. Furthermore, this system could be able to reduce the number of survey lines. This leads to a reduction of the time of a survey. Also, this system would let us probe the unconventional sites, such as the place under a structure or under trees.

In the present study, we used very simple model. However, the true ground model is more complex and has more complex shaped objects. To examine how precisely we could survey near surface, more of the fundamental simulations are planned to be conducted.

6. REFERENCES

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