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RECONSTRUCTION OF UNDERGROUND OBJECTS BY IMAGING THE SECONDARY CURRENTS

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I. INTRODUCTION

Various subsurface radars have been investigated and developed for detecting underground objects such as water pipes, power and communication cables, archeological remains and so on[1]. However, the reliability and the resolution of present available subsurface radars are still insufficient for practical uses. One of the reasons for the insufficiency is the over-simplification of the subsurface propagation and scattering mechanism. Usually only delay-time of received pulse is utilized for underground imaging, notwithstanding the complexity of the propagation and the scattering mechanism.

We proposed an exact passive imaging method for line sources buried in a dielectric half-space[2]. Later, this method was extended to the imaging of the perfectly conducting object buried under the ground[3]. Because the physical optics current was assumed on the surface of buried object, this method was found less accurate when the buried object is dielectric, or electrically small-sized objects. In this paper, a two dimensional active imaging method based on the above passive imaging method is proposed. The validity of the method is shown by some numerical simulations.

II. ANALYSIS

The geometry of the problem is illustrated in Fig.1. $z > 0$ is air and $z \leq 0$ is a homogeneous lossless medium. An infinitely long cylindrical object having arbitrary cross section is buried underground parallel to y-axis. $E^{inc}(t)$ is an incident wave propagating from air into the ground. $K(x', z', t)$ is secondary current induced on the surface of the buried object. The scattering field $E(x_1, z_1, t)$ is measured along a line parallel to the ground surface.

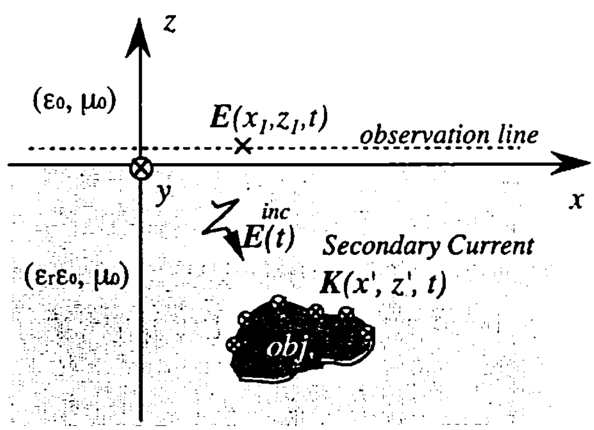

Fig.1 The geometry of the problem

For TM plane wave incidence or the excitation by an infinite y-directed electric current in the air, $E(x_1, z_1, t)$ has only the y-component and its frequency spectrum is given as follows,

$$\tilde{E}_y(x_1, z_1, \omega) = \frac{\omega\mu_0}{2\pi}\iint \tilde{K}_y(x',z',\omega)dx'dz'\int_{-\infty}^{+\infty} \frac{1}{u_1 + u_2}e^{-ju_1z_1 + ju_2z'}e^{-j\xi(x_1 - x')}d\xi \quad (1)$$

where, $\tilde{K}_y(x', z', \omega)$ is the frequency spectrum of the y-component of induced secondary current on the surface of the object, k_1 and k_2 are wave numbers in air and in the ground medium, respectively, and $u_1 = \sqrt{k_1^2 - \xi^2}$, $u_2 = \sqrt{k_2^2 - \xi^2}$.

Fourier-transforming Eq.(1) with respect to the position of observation point x, and the frequency ω, we obtain

$$f(s, \varphi) = \iint K_y(x',z',\frac{\hat{s}\cdot\boldsymbol{r}' - s}{v})dx'dz' \quad (2)$$

$$= \frac{(\gamma + n\cos\varphi)}{\eta_0}\int_{-\infty}^{+\infty} E_y(x_1, z_1, t')dx \quad (3)$$

where, φ is an arbitrary angle and $\hat{s} = (\sin\varphi, \cos\varphi)$, $\boldsymbol{r}' = (x',z')$ is an arbitrary point on the buried object, v is the light velocity under the ground. η_0 is characteristic impedance of free space, $n = k_2 / k_1$ is a refractive index, $t' = [z_1\,\gamma / n + x_1 \sin\varphi - s] / v$, $\gamma = \sqrt{1 - n^2\sin^2\varphi}$.

Eq.(3) is the synthesis of transient scattering fields measured along the ground surface. It is understood from Eq.(2) that the synthesized result corresponds to the projection of the the buried object to $\hat{s}$ direction, if the secondary current satisfies the following two conditions. The first condition is that the excitation is a short pulse, the second is that the secondary current has a maximum value at $t = 0$. However, because we only know the wave form of excitation, the geometric electric delay between an arbitrary point under the ground and the position of the excitation is used to estimate the rising time of secondary current.

Two-dimensional image $g(x,z)$ (where, $\boldsymbol{r} = (x,z)$ is an arbitrary point under the ground) of underground object is given by integrating Eq.(3) with respect to projection angle φ as follows,

$$g(x,z) = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} f(x\sin\varphi + z\cos\varphi + v\,t_d, \varphi)\, d\varphi \quad (4)$$

$$= \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{(\gamma + n\cos\varphi)}{\eta_0}d\varphi\int_{-\infty}^{+\infty} E_y(x_1, z_1, t' + t_d)dx \quad (5)$$

where t_d is geometric electric delay between the excitation and the point (x,z).

For the case of TE plane wave or magnetic current excitation, the similar synthesis equation can be obtained by repeating the above procedure. In this case, the measured y-component of the magnetic field is used.

III. NUMERICAL SIMULATIONS

In the first simulation the buried object is a perfectly conducting circular cylinder as shown in Fig.2. The relative permittivity of the ground is 5.3, and the incident wave is a plane wave propagating with an incident angle ϕ with respect to z axis. The incident wave is a Gaussian pause as follows:

$$E(t) = E_0 e^{-(\frac{t}{\tau})^2} \quad (6)$$

where $\tau = 0.269$ns. The scattering fields are calculated by using FDTD method.

The reconstructed image of buried conducting cylinder are shown in Fig.3 and Fig.4. Fig.3 shows the imaging results of several single plane wave illumination. It is illustrated that the illuminating regions are well reconstructed. The synthesized image obtained by summing up these images is shown in Fig.4. It is seen that the upside contour of the cylinder is well reconstructed. However the downside contour is not well reconstructed because the current on the shadow region is very small.

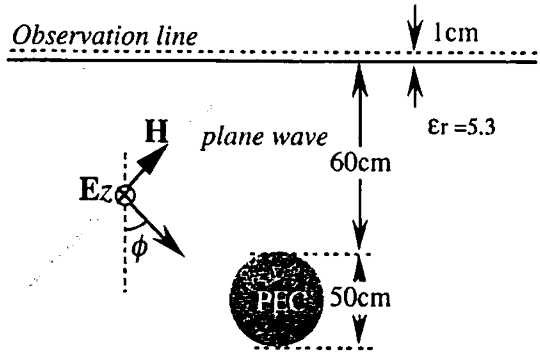

Fig.2 The Geometry of numerical simulation

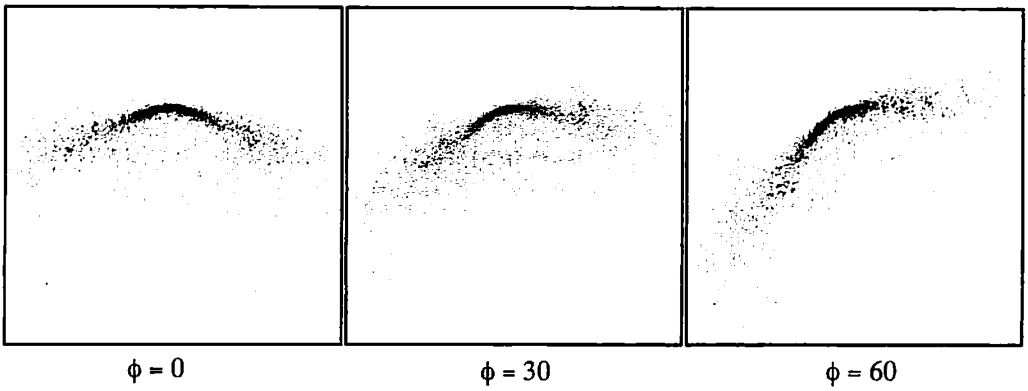

Fig.3 Reconstructed images of a buried cylinder by using single plane wave illumination.

In the second simulation the buried objects are a dielectric cylinder and a rectangular air cavern as shown in Fig.5. The relative permittivity of the dielectric cylinder is 10. The reconstructed image of the buried objects are shown in Fig.6. The cavern and the upside contour of the dielectric cylinder are well reconstructed. The shape of the downside contour is also reconstructed very well except that its radius is greater than the real size. This is primarily due to the reason that the induced polarization current on the downside of the dielectric cylinder is due to the electromagnetic wave that propagates inside the cylinder, thus the error in the estimation

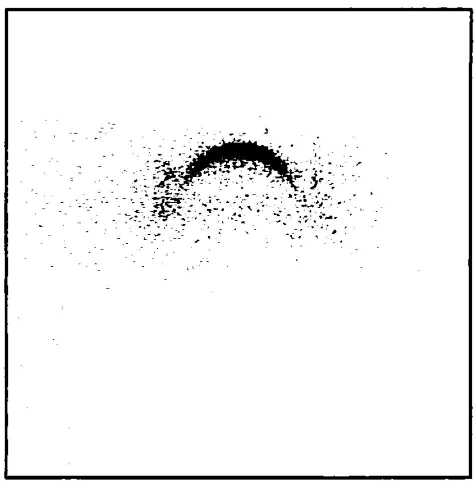

Fig.4 Reconstructed image of a buried cylinder by using multiple plane wave illuminations.

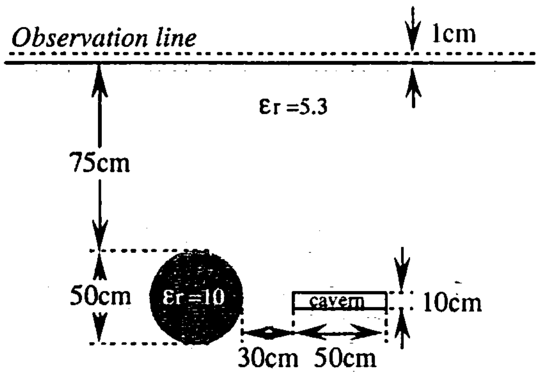

Fig.5 The Geometry of numerical simulation

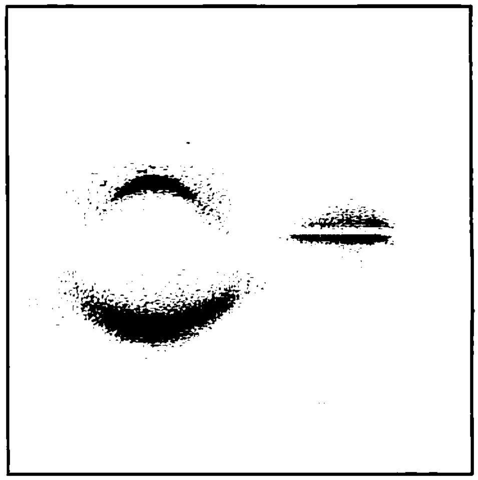
Fig.6 Reconstructed image of buried dielectric objects by using multiple plane wave illuminations.

of the rising time of the secondary current makes the radius unrealistic and the image blear.

Although the plane wave is used as an incident wave in the above simulations, a cylindrical wave such as a wave excited by a line current placed on the ground surface can be also used with some modification.

IV. CONCLUSIONS

A new two-dimensional quasi-exact active image reconstruction method has been proposed. The numerical simulations have proved that the method is valid for both conducting and dielectric objects buried in the ground. It has been found that upside contours of buried objects can be well reconstructed, and downside contour can also be reconstructed even if a buried object is dielectric material.

REFERENCES

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