

# SUB-GRIDDING FDTD METHOD FOR BOREHOLE RADAR ANTENNA

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## 1. Introduction

Effective numerical techniques are very useful for designing and understanding radar systems for subsurface sensing. Borehole radar is one form of ground penetrating radar (GPR), which is very effective for geophysical exploration in deep subsurface. A borehole radar system is used in a drilled borehole, and it increases the radar resolution by its accessibility to radar targets. Borehole radar has been successfully used in applications such as ground water detection for final disposal, and geological survey for construction[1][2].

FDTD has widely been accepted in GPR, however, the computational capacity is always problem for detailed modeling. Typically, the size of antennas for GPR is the order of 0.5-1m. However, the water proof housing and the diameter of boreholes is typically smaller than 10cm. On the other hand, the distance to the radar target can be more than 10m. , but the physical dimension of subsurface inhomogeneity is typically smaller than 10cm. Due to the large differences of the physical dimensions, borehole radar was simply modeled by a short dipole antenna in homogeneous material[1] or a simplified analytical theory of stratified cylindrical layers was used[2]. However, we think the stratified material near the dipole antennas has strong influence on the antenna characteristics, and modeling of detailed structure of a dipole antenna in a borehole is important for optimization of antenna design.

In this paper we use the sub-gridding FDTD method[3] for borehole radar antenna analysis and discuss some results of the simulation and compare with experiment.

## 2. FDTD modeling

Sub-gridding technique is effective for modeling a detailed structure, in a large modeling space[3]. In this study, we model the transmitting and receiving antennas of the radar system in a waterproof antenna housing, and the water-filled borehole. The structure around the radar system was modeled by fine grids. The large contrast of the dielectric constant between the water in the borehole and the other material can also be modeled with the fine grids by high accuracy. The normal size grids models the surrounding material. If we need to model geological targets such as subsurface fractures, we can also use the fine grids.

Fig.2(a) shows the shape of the grids for modeling the antenna feeding point and Fig.2(b) shows its cross section. In order to verify our sub-grid based FDTD code, a laboratory measurement was carried out. A monopole antenna, fed from a coaxial line, is placed in an acrylic cylinder, fixed on a ground plane. The cylinder is filled with water. The monopole antenna length and radius are  $h=15$  cm and  $a=3$  mm, respectively. The outer radius, the thickness, and the height of the acrylic cylinder are  $b=30$

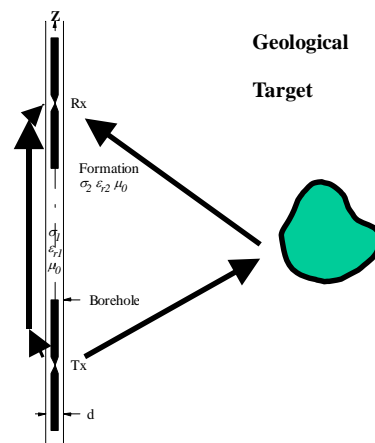


Fig.1 Borehole radar

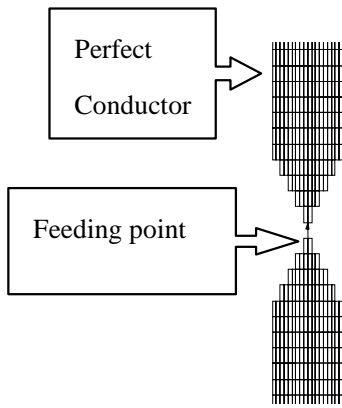


Fig.2(a) Antenna feeding point and grids

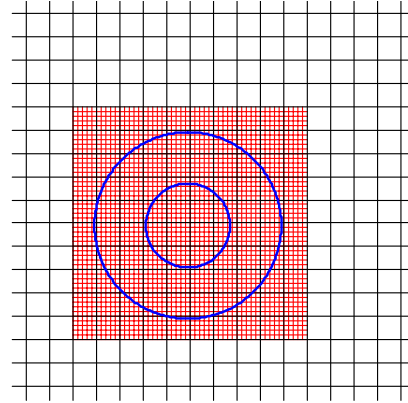


Fig.2(b) Cross section of the antenna

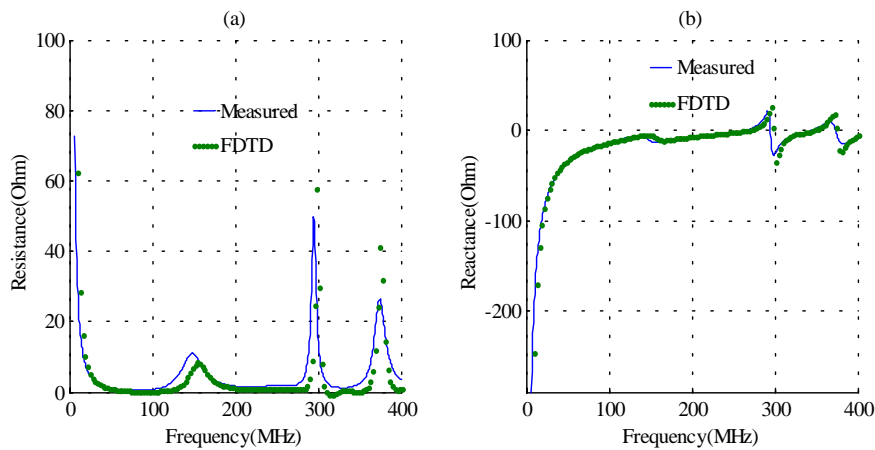


Fig.3 Input impedance of a monopole antenna in a water cylinder.

mm,  $c=3.5$  mm and  $H=0.5$  m, respectively. The conductivity and dielectric constant of the water are  $\sigma_1 = 0.0072$  S/m and  $\epsilon_{r1}=81$ , respectively. Corresponding qualities of the acrylic cylinder are  $\sigma_2=0$  S/m and  $\epsilon_{r2}=2.5$ , respectively. The input impedances of the antenna in the frequency range 0.5 MHz-400MHz were measured by a network analyzer (HP8752A).

In the FDTD, the radiation process continues, for more than 80 ns, until the transient current at the feeding point converges. The input impedance is calculated in the frequency domain by Fourier transforming the current and the voltage waveforms at the feeding point, and then took the ratio. The calculated impedance showed good agreement with measurement, especially at low frequencies, as shown in Fig. 3.

### 3. Radiation from a dipole in a borehole

Fig.4 shows a typical borehole radar signal measured in granite rock. Strong signal, which appears at around 20ns is the direct coupling from the transmitter to the receiver antenna. Following to the directly coupled signal, we can find many reflections from subsurface fractures. Due to its thin structure, isolation of a transmitter and a receiver is difficult in borehole radar.

We can improve the radar performance by reducing the direct coupling, because we can increase the dynamic range by avoiding the receiver saturation. We think that the radiation from a dipole antenna in a water-filled borehole is not the same as that in a homogenous material. In order to understand the radiation mechanism, we use FDTD simulation.

The Cartesian dimensions for this FDTD simulation are 10m x 10m x 10m. A dipole antenna, having length  $2h=80$  cm and radius  $a=2.25$  cm, is located in a borehole of radius  $b=5$  cm. The dimensions of the antenna are the same as those used in actual borehole radar measurements. The top and the bottom of the borehole are connected to a PML layer. Under these conditions, the borehole can be considered infinitely long.

Fig.5 shows the snap shots of transient radiation from a dipole antenna in a water-filled borehole. The conductivity and the dielectric constant of the water in the borehole are  $\sigma_1=0.0072$  S/m and  $\epsilon_{r1}=81$ , respectively, and the surroundings is homogeneous rock with conductivity,  $\sigma_2=0.001$  S/m, and dielectric constant,  $\epsilon_{r2}=5.8$ . The  $z$ -component of the electric fields at 6 ns, 11 ns, 16 ns, 20 ns and 29 ns are shown in Figs. 5(a)-(d), respectively.

#### 4. Discussion

The radiation from a dipole antenna in a water-filled antenna is slightly different from a dipole antenna in homogeneous material [4]. For example, the shapes of  $W_1$  and  $W_2$  in Fig. 5 (c) are unlike their counterparts in the homogeneous case. Wave front  $W_2$  looks like a distorted circle with a narrow tip pointing in the  $z$ -direction. Additionally, the wave fronts  $W_1$ ,  $W_2$ ,  $W_3$ , and  $W_4$  appear later than their counterparts in the homogeneous case. This is due to the fact that the wave velocities inside the borehole for the antenna in a water-filled borehole is different from the homogeneous medium case. The time required for the wave to travel from the feeding point to the tip of the antenna, can be expressed as  $\tau_a = h/v$ , where  $v$  is the velocity of the wave along the antenna if the antenna is located in a homogeneous medium or in an air-filled borehole. The water-filled borehole causes a change in  $\tau_a$  and a change in the shapes of all wave fronts and the superimposed fields. The state of the outward radiating electric field at 29 ns is shown in Fig. 5(e).

It is evident that the electric field  $z$ -component near the borehole is positive, but turns negative a little farther from borehole, as shown in Fig. 5 (b). Since the dielectric constant of the water in the borehole is higher than that of the surrounding rock, the velocity of the electric field inside the borehole is less than that outside the borehole. It results, from the different velocities that the electric field has in the various regions, that the total field  $E_t$  near the borehole points in a different direction from that far from the borehole. This means that the electric field  $z$ -component is opposite in sign for these two regions, as shown in Fig. 5 (b).

Also we can find high frequency components propagate along the borehole. It is a guided wave along a dielectric cylindrical rod. However, propagation loss is large and it vanishes quickly.

#### 5. Conclusion

We showed FDTD simulation of transient radiation from a dipole antenna in a water-filled borehole. The cylindrical stratified structure including a dipole antenna, an insulation layer and an annular water layer in a borehole was modeled by using a sub-gridding FDTD. The measured input impedance showed good agreement with the simulation.

Then, the transient radiation from borehole radar was discussed. Due to the difference of velocity in each layer, the electric field is deformed. The guided wave energy was observed along the water-filled borehole. We think that FDTD simulation can be used for optimizing antennas in complicated surrounding material.

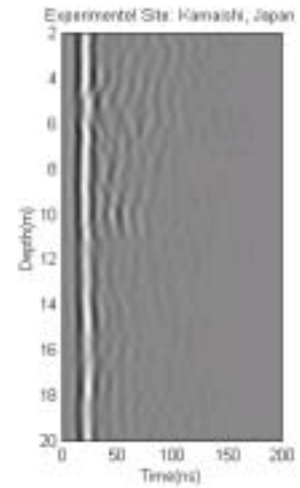


Fig.4 Borehole radar signal

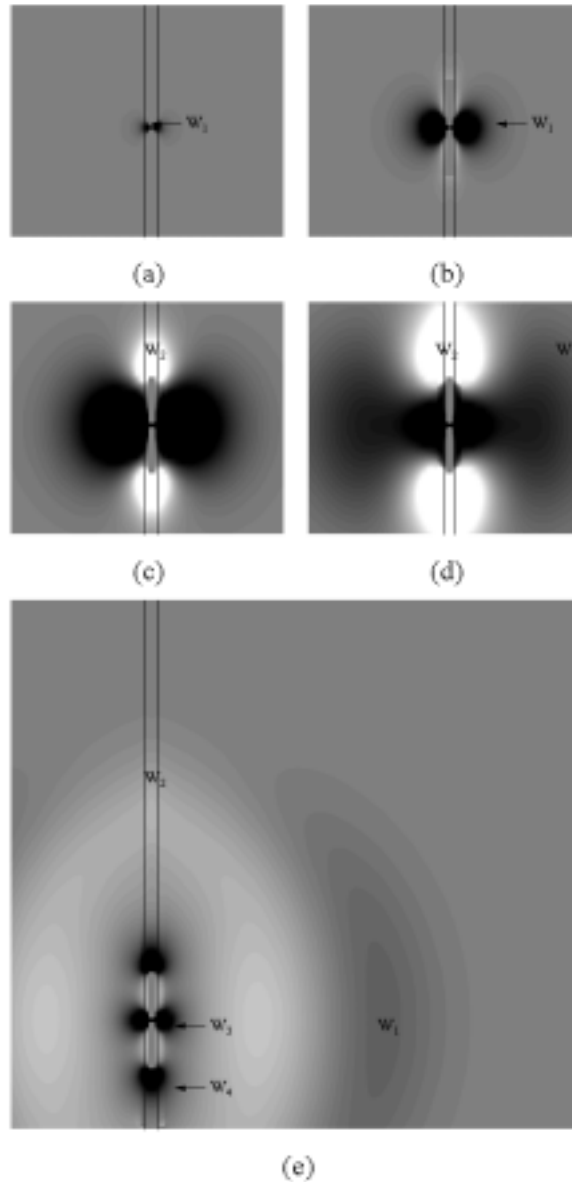


Fig.5 Transient radiation from a dipole antenna in a water-filled borehole  
The  $z$ -component electric field at (a)6 ns, (b)11 ns, (c)16 ns, (d)20 ns and (e)29 ns.

#### References

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