

# Design of a slimline directional borehole radar antenna using FDTD

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**Abstract** – It is difficult to build directional antennas for borehole radar due to the limited space available in the borehole. Recently published results show, however, that it is possible to obtain directional information even from electrically small antennas. In this paper, we use Finite-Difference Time-Domain (FDTD) modelling to optimise the design of a four-element directional antenna array, so that it provides optimal directional discrimination for a 250 MHz radar system. Modelling is used to investigate the use of different filler materials inside the antenna array and the effect of mutual coupling on the directional antenna array. The effect of the borehole material (i.e. air or water) on the directionality of the antennas is also explored. Lastly, the effect of unevenly distributed borehole material around a borehole radar system, with a diameter that is much smaller than the diameter of the borehole, is discussed. A filler material that matches the permittivity of the surrounding rock offers a good compromise between the permittivity of air and that of water. The borehole contents do not affect the ability of an antenna array to determine direction, but the antenna must be placed centrally in the borehole, so the use of centralizers is recommended.

**Keywords** – borehole radar system, directional antennas, mutual coupling, FDTD, monopole antennas, dielectric.

## I. INTRODUCTION

Borehole radar is the application of Ground Penetrating Radar (GPR) within a borehole [11]. GPR is a technique used to delineate structures and features of a subsurface. The borehole radar technique has been used successfully to delineate geological features, especially orebody geometry in the gold and platinum mines of South Africa [10].

Most of the borehole radar systems already used in mines can determine the distance between the borehole and the target reflector but the systems do not allow one to determine the direction of the target reflector. (as shown in Figure 1).

Radio direction finding techniques and directional antennas have been in use almost since radio was invented. Most of the techniques are based on the Watson-Watt technique and employ the Adcock direction-finding antennas [1].

Considerable work has been done to refine direction-finding antennas [4], but all such systems rely on antenna elements that are at least of the order of a quarter of a wavelength apart. The typical diameter of an exploration borehole in the South African mining environment is 48 mm. In borehole radar systems, the 48 mm diameter constraint means that elements are much closer together than a quarter of a wavelength, and are therefore strongly affected by mutual coupling [3].

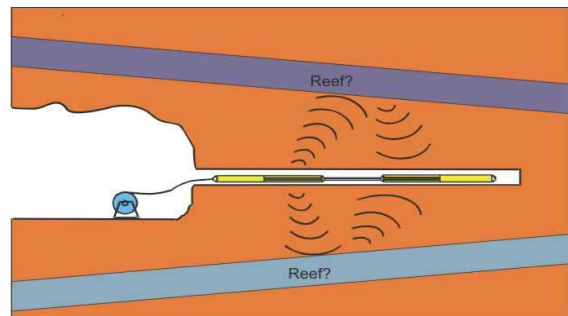


Figure 1. Geometry of a borehole survey

A number of directional techniques have been applied to the antennas of a borehole radar system. Van Dongen et al [8] designed a directional borehole radar system using a dipole antenna shielded by a reflector. The reflector modifies the omnidirectional radiation pattern of the dipole. The system operates at 100 MHz and has a diameter of 160mm, too large for the South African application.

Sato and Takayama [7] developed a directional borehole radar system using an array antenna connected to passive optical electric field sensors. Their system could estimate the reflected wave azimuth angle to within 30°. Mutual coupling distorts phase information at certain frequencies.

In this paper, we investigate the factors that affect the directionality of a borehole radar system that uses a four element dipole receive antenna array. The investigation is undertaken using numerical modelling.

## II. NUMERICAL MODELLING

There are a variety of ways of designing a GPR or borehole radar system. In this paper we consider a design based on a time domain system implementation. A numerical modelling tool called GprMax3D is used to simulate the transmission of electromagnetic waves between the transmit and receive antennas of a borehole radar system. GprMax3D is an electromagnetic wave simulator for GPR modelling based on the Finite-Difference Time-Domain (FDTD) numerical method [5].

A borehole radar system measures the time of flight of an electromagnetic signal travelling from the transmit antenna to the receive antenna. Directional antennas have the capability of determining the direction of the received signal by measuring the difference in time of flight of the signal at each element of an array of receive antennas. GprMax3D has been used to show that directional information can be determined from an array of receive antennas even in the presence of strong mutual coupling [6].

In this paper, GprMax3D is used to investigate the effect of the following factors on the directional performance of the antenna array:

- The filler material supporting the array of antennas;
- The effect of the borehole material, air or water; and
- The position of the borehole radar within a larger diameter borehole.

A directional borehole radar system is being designed for the South African mines [9]. The numerical model discussed here takes into consideration the actual size and type of antennas used in borehole radar design.

Transmit and receive antenna probes of a borehole radar system are usually inline, as shown in Figure 1. To simplify the modelling, transmit and receive antennas are placed parallel to each other and only the direct signal from transmitter to receiver is considered. The setup of the antenna model is as shown in Figure 2. To reduce the computational time, the dipole antennas are represented by monopole antennas above a ground plane as shown in the Figure.

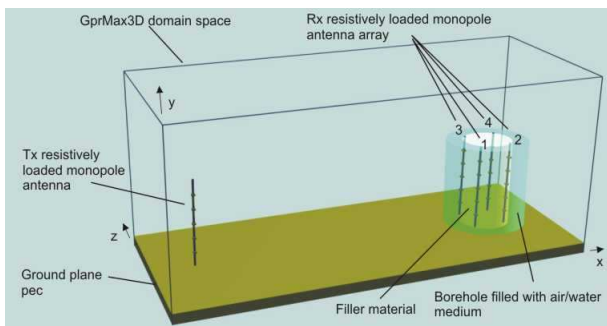


Figure 2. GprMax3D model space

The size of the modelling space is 1500 mm x 400 mm x 200 mm. The medium of propagation of the EM wave is assumed to have a relative permittivity  $\epsilon_r = 9.0$ , conductiv-

ity  $\sigma = 0.001$  (S/m), relative permeability  $\mu_r = 1.0$  and complex conductivity  $\sigma^* = 0.0$ . The maximum operating frequency is 500 MHz. The FDTD model's cell size is 2 mm (i.e.  $\Delta x = \Delta y = \Delta z = 2$  mm). The absorbing boundary condition implemented is the Perfect Matched Layer [2]. The inner cylinder that supports the four element antenna array is modelled using a filler material that holds the antenna array in an actual borehole radar system, and has a diameter of 28 mm. The outer cylinder represents the borehole with a diameter that is larger than the borehole radar system. The medium within the borehole is either air or water.

The antenna elements are resistively loaded with a Wu-King profile [12], implemented as five discrete resistors. The resistor values along the length of the antenna are given by:

$$R_n = \frac{R_0}{1 - \left(\frac{n \times l}{h}\right)} \quad (1)$$

where  $R_0$  is the antenna impedance taken here as 50  $\Omega$ ,  $l$  is the spacing between the resistors,  $n$  is the resistor number, and  $h$  is the length of the antenna arm. In this case  $h = 300$  mm and  $l = 50$  mm. Therefore,  $R_1 = 60$   $\Omega$ ,  $R_2 = 75$   $\Omega$ ,  $R_3 = 100$   $\Omega$ ,  $R_4 = 150$   $\Omega$  and  $R_5 = 300$   $\Omega$ .

GprMax3D cannot model resistors directly. Therefore, the resistors along the length of the monopole antennas are represented by conductive Yee cells placed adjacent to the wires as shown in Figure 3. To model a resistor in the  $y$  direction, four Yee cells are used. The conductivity of a Yee cell as a function of resistance is:

$$\sigma_n = \frac{\Delta y}{R_n \cdot \Delta x \cdot \Delta z} \quad (2)$$

where  $\Delta x$ ,  $\Delta y$  and  $\Delta z$  are the cell sizes along the  $x$ ,  $y$  and  $z$  coordinates. Figure 3 shows four cells with equal conductance. To model resistors  $R_1$ ,  $R_2$ ,  $R_3$ ,  $R_4$  and  $R_5$  conductivities need to be  $\sigma_1 = 8.33$  S/m,  $\sigma_2 = 6.67$  S/m,  $\sigma_3 = 5.00$  S/m,  $\sigma_4 = 3.33$  S/m and  $\sigma_5 = 1.67$  S/m respectively.

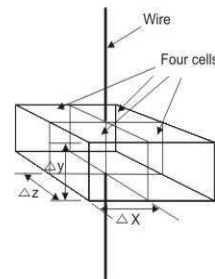


Figure 3. FDTD model of a resistor using four conductive Yee cells

In a borehole radar survey, the electromagnetic wave (EM) travels from the transmit antenna and gets reflected by a

target to the receive antenna (as shown in Figure 1). The receive antennas are arranged as a four element array that forms a square (as shown in Figure 4). Elements are spaced 20 mm apart. In the geometry shown in Figure 4, an EM wave from the transmit antenna will be captured first by receive antennas 1 and 3. The EM wave is then delayed by:

$$t = \frac{s\sqrt{\epsilon_r}}{c} \quad (3)$$

where  $c$  is the velocity of light in free space,  $3 \times 10^8$  m/s,  $\epsilon_r$  is relative permittivity of the filler material and  $s$  is distance between antennas. The EM wave is captured  $t$  seconds later by receive antenna 2 and 4.

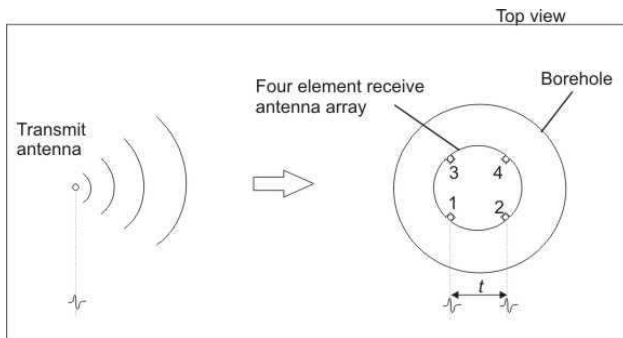


Figure 4. Top view of model space

To determine direction, the time-delay between the antenna elements is measured. From the timing relationship, the direction of the incoming EM wave can be determined [6].

### III. FILLER MATERIAL INSIDE ANTENNA ARRAY

Ideally, there is no material between the antenna body and the rock surrounding it. In that case, the filler material would be matched to the dielectric of the surrounding rock. In a real situation, the borehole will always be slightly or much larger than the borehole radar system. The borehole will either contain air or water. Therefore, any signal captured by the antenna array travels through either of these media.

In order to reduce the effects the different media in the surrounding rock, the borehole and the antenna, the filler material should be carefully chosen. GprMax3D is used to explore the use of different filler materials inside the antenna array on the relative timing of signals at different antenna elements. All the models here are run with a borehole diameter of 76 mm.

First, the situation of matching the filler to the borehole is considered. In the first case, the borehole is filled with air and the dielectric of the filler material is matched to it,  $\epsilon_r = 1.0$ . The signal is preserved (as shown in Figure 5), but the difference in time-of-arrival of the signal at different antenna elements is small.

In the second case, the borehole is filled with water, and the dielectric of the filler material is matched to the dielectric

of water,  $\epsilon_r = 81.0$ . The signal received now includes some ringing (as shown in Figure 6), but the difference in time-of-arrival of the signal at the antenna array is large.

Based only on matching the borehole media, the higher permittivity filler material, matched to a water filled borehole, would be preferred as it gives longer delays that are easier to measure between antenna elements.

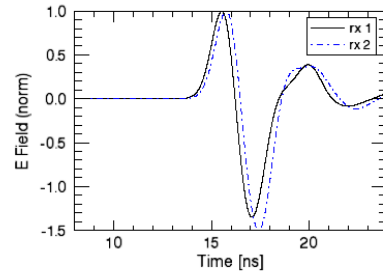


Figure 5. Filler material matched to dielectric of air. Borehole filled with air.

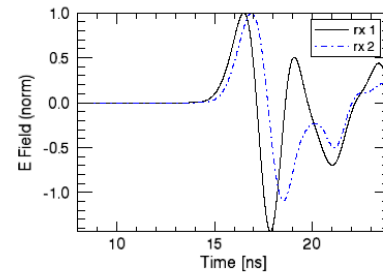
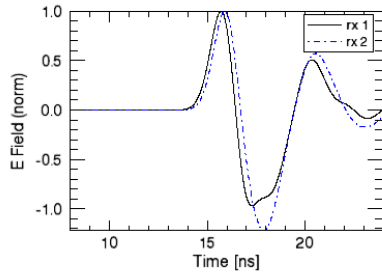


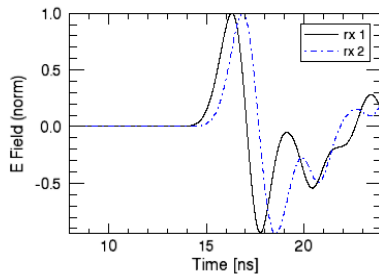
Figure 6. Filler material matched to dielectric of water. Borehole filled with water.

However, in general it is not possible to dictate that a borehole be air or water filled. The next two cases consider the mismatch between filler and borehole when the antenna ends up in the 'wrong' borehole. When the filler material is matched to the dielectric of water and the borehole is filled with air, the signal captured by antenna 1 is distorted (as shown in Figure 7 at about 17ns). In this case, the signal travels faster in the borehole material than in the filler material. When the filler material is matched to the dielectric of air and the borehole is filled with water, the captured signal is distorted (as shown in Figure 8).

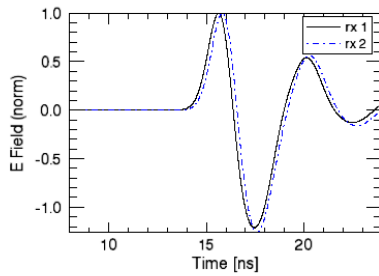
There is a trade off: a high dielectric filler makes system design easier, by slowing the transmission between antenna elements, but it distorts the received signal in an air-filled borehole. One option would be to use a filler material with a dielectric that is between that of air and water. The dielectric of rock is assumed to be  $\epsilon_r = 9.0$  and between that of air and water. It is also readily achievable in modern polymer materials. If the filler is switched to  $\epsilon_r = 9.0$ , good results are obtained both for delay and for quality of signal, as shown in Figure 9 and Figure 10.



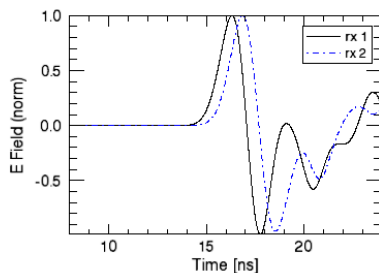
**Figure 7. Filler material matched to dielectric of water. Borehole filled with air**



**Figure 8. Filler material matched to dielectric of air. Borehole filled with water**



**Figure 9. Filler material matched to dielectric of rock. Borehole filled with air**

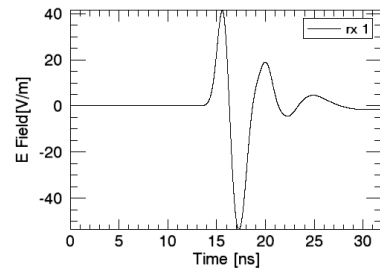


**Figure 10. Filler material matched to dielectric of rock. Borehole filled with water.**

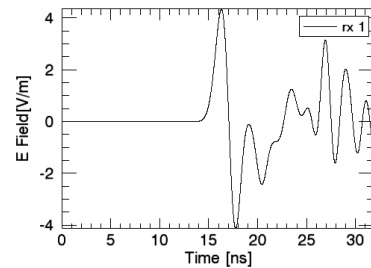
#### IV. BOREHOLE MATERIAL

The diameter of the filler material is always less than the diameter of the borehole. Here models are run where the diameter of the filler material is 28 mm and that of the borehole is assumed to be 76mm. Therefore, it is important to consider how the borehole medium affects the signal captured by the antenna array. The borehole medium will either be water or air. Figure 11 and Figure 12 compare the effect of the borehole material on the captured signal. A signal that passes through a water filled borehole rings more than in an air filled borehole. A water filled borehole also attenuates the amplitude of the signal more than an air filled borehole.

Apart from the influence of the borehole on the received signal, the results in Figure 11 and Figure 12 and models run at other diameters of 100 mm and 150 mm showed that the borehole medium does not influence the ability of the antenna array to determine direction, if it is centrally positioned in the borehole.



**Figure 11. Signal captured at receive antenna 1 after travelling through an air filled borehole.**



**Figure 12. Signal captured at receive antenna 1 after travelling through a water filled borehole.**

#### V. LOCATION IN A BOREHOLE

However, the assumption that the antenna is centrally positioned is not valid. During a survey, the borehole radar system may be situated on one side of a borehole and result in the medium within the borehole not being distributed evenly around the antenna array. Modelling is used to determine how this affects the signal received by the antenna array. The models here contain a four element antenna array in a filler material of diameter 28 mm. The antenna array is located within a borehole of diameter 76 mm.

Two scenarios are investigated to determine the effect of the borehole medium on the signal captured by the antenna array. Firstly, the borehole radar system is situated on the west side of the borehole (as shown in Figure 13). A signal from the transmit antenna travels within the borehole medium for a very short period before being captured by the four element antenna array. In this case, the signal is first captured by receive antenna 1 and 3. The signal is then captured by antenna 2 and 4 a fraction of a second later. The situation is the same for both air and water filled borehole (as shown in Figure 14 and Figure 15).

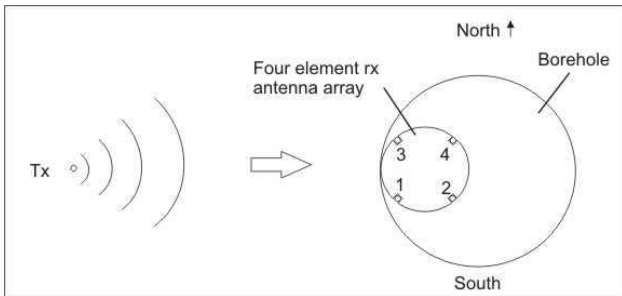


Figure 13. Receive antenna probe mounted against the west side of the borehole

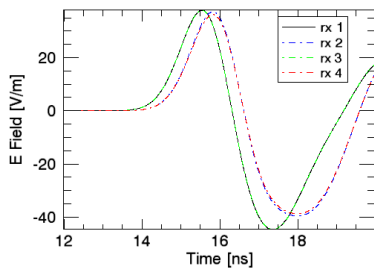


Figure 14. Signal captured by antenna 1, 2, 3 and 4. Borehole is filled with air and the receive antenna is mounted on the west side of the borehole.

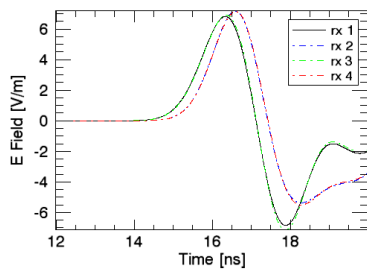


Figure 15. Signal captured by antenna 1, 2, 3 and 4. Borehole is filled with water and the receive antenna is mounted on the west side of the borehole.

In the second scenario, the antenna array is located on the south side of the borehole (as shown in Figure 16). A signal from the transmit antenna travels through the borehole medium before being captured by the antenna array. When the medium within the borehole is air, the signal is first cap-

tured by antenna 1 and 3, and then later by 2 and 4 (as shown in Figure 17). This result is similar to the results obtained when the borehole radar was located on the west side of the borehole. When the medium within the borehole is water, the signal is captured first by antenna 1, and then 3 (as shown in Figure 18). Later, the signal is captured by antenna 2 and then antenna 4. The different time delays at the four antenna elements are due to the effect of the water which is unevenly distributed around the borehole radar system.

The results obtained from the two scenarios imply that the location of a borehole radar system within a borehole affects the signal captured by the four element antenna array. Without significant processing it will not be possible to remove this effect. Therefore, it is recommended that a directional borehole radar system always employ centralizers to improve its directional accuracy.

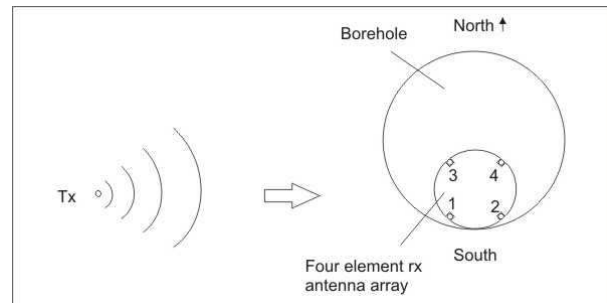


Figure 16. Borehole radar system mounted against the south side of the borehole

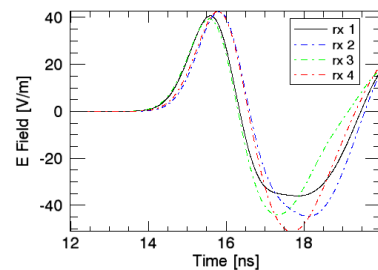


Figure 17. Signal captured by antenna 1, 2, 3 and 4. Borehole filled with air and the receive antenna is mounted on the south side of the borehole.

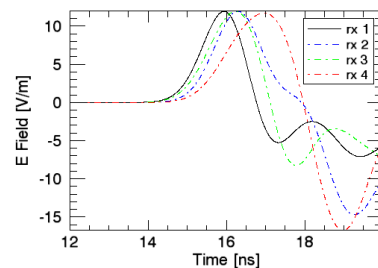


Figure 18. Signal captured by antenna 1, 2 and 3. Borehole filled with water and the receive antenna is mounted on the west side of the borehole.

## VI. CONCLUSIONS

Modelling has shown that the measured time delay between the antenna elements depends on the filler material, and that a material with a permittivity close to that of the surrounding rock offers a good compromise between better directional performance and increased distortion.

Modelling has already shown that time delay information can still be obtained in the presence of mutual coupling for a four elements antenna array spaced 20 mm apart and operating at a maximum frequency of 500 MHz. Here, it is further shown that the material in the borehole does not affect the directional properties of the antenna, as long as it is centrally positioned.

It is important to mount the antennas of a borehole radar system at the centre of the borehole in the case where the diameter of the borehole is much larger than that of the borehole radar system. This ensures that the borehole material is evenly distributed around the borehole radar system.

## ACKNOWLEDGMENTS

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## REFERENCES

- [1] Adcock, F. "Radio direction finding in three dimensions" Proceedings of Inst. Radio Eng., 1959, Volume 20, pp 7-11.
- [2] Berenger, J. P., "A perfectly matched layer for the absorption of electromagnetic waves", Journal of Computational Physics, 1994, Volume 114, pp 185-200.
- [3] Balanis, C. A., "Antenna theory, analysis and design", John Wiley and Sons, New York (1982).
- [4] Friedlander, B. and Weiss A. J., "Direction finding in the presence of mutual coupling", IEEE Transactions on Antennas and Propagation, Volume 39, Issue 3, pp 273-284.
- [5] Giannopoulos, A., "Modelling ground penetrating radar by GprMax", Construction and Building Materials, 2005, Volume 19, Issue 10, pp 723-772.
- [6] Nyareli, T. and Vogt D., "Small directional borehole radar antennas; numerical modelling method", 10<sup>th</sup> Biennial Technical Meeting and Exhibition Wild Coast 24 – 26 October 2007, pp 171-175.
- [7] Sato, M. and Takayama, T., "A novel directional borehole radar system using optical electric field sensors", IEEE transactions on geoscience and remote sensing, 2007, Volume 45, No. 8, pp 2529-2535.
- [8] Van Dongen, K. W. A., Van den Berg, P. M., and Fokkema, J. T., "A directional borehole radar for three-dimensional imaging", Ninth International Conference on Ground Penetrating Radar, 2002, Koppenjan, S. J. and Lee, H. L., editors, Volume 4758, SPIE, 25-30
- [9] Vogt, D., and Nyareli, T., "Experimentally achieving borehole antenna directivity in the time domain in the presence of strong mutual coupling", 10<sup>th</sup> Biennial Technical Meeting and Exhibition Wild Coast October 24 – 27. pp 166-170.
- [10] Vogt, D. R., "A slimline borehole radar for in-mine use", Ninth International Conference on Ground Penetrating Radar, Steven K. Koppenjan, Hua Lee, Editors, Proceedings of SPIE, 2002, Volume 4758, pp 31 - 36.
- [11] Vogt, D., "A borehole radar system for South African gold and platinum mines", South African Journal of Geology, 2006, Volume 109, pp 521-528.
- [12] Wu, T. and King, R. W. P., "The cylindrical antenna with non-reflecting resistive loading", IEEE Transactions on Antenna and Propagation, 1965, Volume AP-13, No. 3, pp 369-373.