I048

Experimentally Achieving Borehole Radar Antenna Directivity in the Time Domain in the Presence of Strong Mutual Coupling (Best of SAGA)

D. Vogt* (CSIR) & T. Nyareli (CSIR)

SUMMARY

It is difficult to achieve significant directivity in the radial direction of a borehole radar antenna, because the spacing of antenna elements is typically constrained by the borehole diameter to be considerably less than a wavelength. Previously published borehole radar antennas have achieved directivity by post processing data received in the frequency domain, or by constructing an aperture antenna, where borehole dimensions allowed this.

In this paper, a time-domain technique is investigated for determining the radial direction of reflectors detected in borehole radar images. The antenna itself is an array of four elements and the delay in arrival of the signal between elements is used to determine its direction.

We show here that a relativity slow sampling rate is adequate to resolve the small time intervals between signals received on different antenna elements. Mutual coupling between the antenna elements does affect the relative timing, but does not prevent the extraction of usable directional data. Experimental data from a test tank confirms that estimates of reflector direction can be made within about +15°/-5° of the true direction for antenna elements 20mm apart in water, excited with a pulse that has a centre frequency of 250 MHz.

Experimentally achieving borehole radar antenna directivity in the time domain in the presence of strong mutual coupling

Declan Vogt[1], Teboho Nyareli[2]

1. CSIR, South Africa, dvogt@csir.co.za
2. CSIR, South Africa, tnyareli@csir.co.za

ABSTRACT

It is difficult to achieve significant directivity in the radial direction of a borehole radar antenna, because the spacing of antenna elements is typically constrained by the borehole diameter to be considerably less than a wavelength. Previously published borehole radar antennas have achieved directivity by post processing data received in the frequency domain, or by constructing an aperture antenna, where borehole dimensions allowed this.

In this paper, a time-domain technique is investigated for determining the radial direction of reflectors detected in borehole radar images. The antenna itself is an array of four elements and the delay in arrival of the signal between elements is used to determine its direction.

We show here that a relatively slow sampling rate is adequate to resolve the small time intervals between signals received on different antenna elements. Mutual coupling between the antenna elements does affect the relative timing, but does not prevent the extraction of usable directional data. Experimental data from a test tank confirms that estimates of reflector direction can be made to within about +15°/-5° of the true direction for antenna elements 20 mm apart in water, excited with a pulse that has a centre frequency of 250 MHz.

Key words: borehole radar, directional antennas, time domain, scale model, physical model.

INTRODUCTION

Borehole radar has become a useful technique for mineral exploration, particularly in the tabular orebodies of the South African Witwatersrand Basin gold fields, and the platinum mines of the Bushveld Complex (Van Schoor et al, 2006). In typical reef delineation, centre frequencies of less than 100 MHz are used, to reflect from targets hosted in anorthosite or quartzite at distances of 30 m to 50 m. At these centre frequencies, the wavelength is typically 1 m to 2.5 m. Typical boreholes that are used are 48 mm in diameter.

In the radial direction, there is therefore very little space to construct the antenna elements required for an effective directional antenna. High directivity is usually achieved through the use of large antenna aperture in terms of wavelength. For example, in seismic reflection, another wave based technique, a wide spread of geophones is used to achieve good angular detail (Dobrin and Savit, 1988, 99-103).

It is possible to achieve directivity with small apertures, at some cost in gain: the system is no more sensitive than a single antenna but is able to discriminate the direction of incoming signals. Such direction-finding techniques are often applied in tracking antennas, such as those used for vehicle tracking.

In previously published borehole radar antenna designs, directivity has been achieved in a number of ways. The antenna described by Siever (2000) uses two loop antennas to achieve a measure of directivity. A loop antenna has zero gain normal to its loop plane, and full gain tangential to its loop plane. Interpretation is conducted by recording data on both antennas, then synthesizing a view in a particular direction in order to see which reflectors are highlighted in that direction, and which are not.

Another relatively low frequency (100 MHz) borehole antenna (Van Dongen et al, 2002) uses a mechanical reflector system, similar to that used in air surveillance radars, to scan the ground around the antenna. The tool is 160 mm in diameter, significantly larger than a typical exploration borehole.

(Ebihara and Sato, 2002) built a borehole array with seven antennas that fed electro-optical transceivers.

They analysed the performance of the array analytically, but did not present results that showed the direction of the incoming radiation. In addition, the gain of the electro-optical elements resulted in poor overall performance (Pers. comm., Ebihara).

METHOD AND RESULTS

System description
In this paper, a directional antenna that is being developed for a 250 MHz borehole radar system is described. The receive antenna is an array of four resistively loaded dipoles arranged at the corners of a square, within the dielectric material of the antenna structure (Figure 1). The antenna elements are resistively loaded with a Wu-King profile (Wu and King, 1965, see also Nyareli and Vogt, 2007) implemented using five discrete resistors.
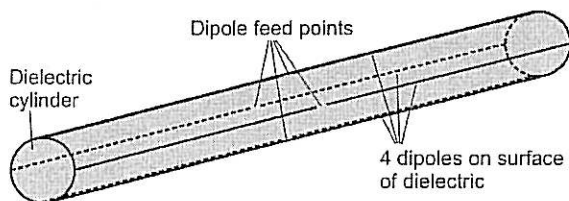

Figure 1. The directional receive antenna, consisting of four dipoles embedded in dielectric.

The transmit antenna is omnidirectional in the radial direction, and consists of a single element otherwise identical to the four used in the receive antenna. The pulse generated in the transmitter has a bandwidth from 125 MHz to 500 MHz, centred on 250 MHz. The bandwidth of the pulse actually transmitted depends on the transmit antenna bandwidth.

The radar system consists of a pulse transmitter and a high-speed receiver. A multiplexer connects each of the four antenna elements to the receiver in turn when making up the final received waveform. A sampling rate of 2.56 GHz is used, for a sample time of 391 ps.

Test bed description
In the final radar, antenna elements are expected to be placed in a dielectric with a permittivity of about four, spaced approximately 20 mm apart. At that distance and permittivity, they are about 1/60th of a wavelength apart for a 250 MHz signal.

Theory suggests that the mutual coupling between antenna elements as close as 1/60th of a wavelength is likely to be very high (Balanis, 1982). This strong mutual coupling implies that any signal received on one element will quickly be coupled onto the other elements, regardless of what the other elements might receive independently. Fortunately, the coupling occurs quickly, but not instantaneously, so it is possible to

measure time delays between the four arms of the antenna (Nyareli and Vogt, 2007). However, the time delays are likely to be smaller than the sampling time of the radar receiver.

To determine whether it is practically feasible to resolve angle of incidence from relative arrival time, a test system was constructed in a water tank (Figure 2). For simplicity, the system uses monopole antennas above a ground plane, which are electrically equivalent to dipole antennas. A transmission system has been constructed, rather than a reflection system, because in a small tank it is easier to remove spurious reflections: the first arrival at the receive antenna array must be the direct wave from the transmit antenna.
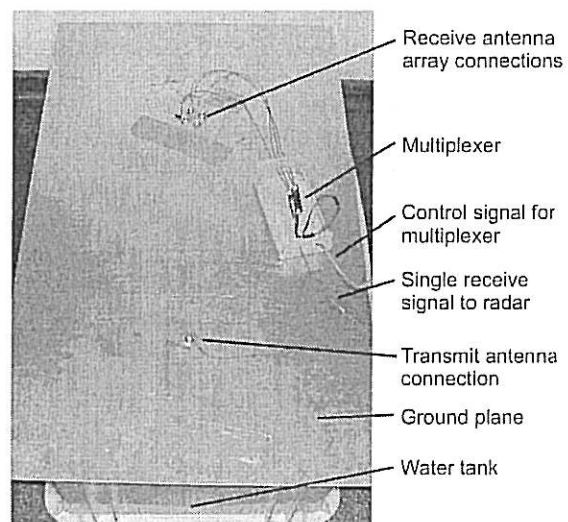

Figure 2. Water test tank showing the ground plane. Antennas are constructed downwards from the ground plane into the water below.

The transmit antenna is a single monopole. The receive antenna is an array of four monopoles, as in the proposed borehole system. For practical reasons, the antennas are placed at the corners of a square of size 20 mm. In the final antenna, the antennas will also be spaced 20 mm apart, but in a medium that is expected to have a relative permittivity of about 4. In this scale experiment, the antennas are embedded directly in the water with a relative permittivity of 81, so are considerably further apart electrically than they will be in the final system. The expected delay between two antenna elements 20 mm apart in the absence of mutual coupling would be 600 ps, or about 1.5 sample periods.

A series of measurements was made with the receive antenna array geometry defined as in Figure 3, relative to the transmit antenna. Approximately 200 – 300 traces were acquired on each of the four antenna elements with the receive antenna orientated at 0° to the transmit antenna, then a further 200 – 300 traces were acquired at each of 13 angles from 0° to 270° in steps of 22.5°.
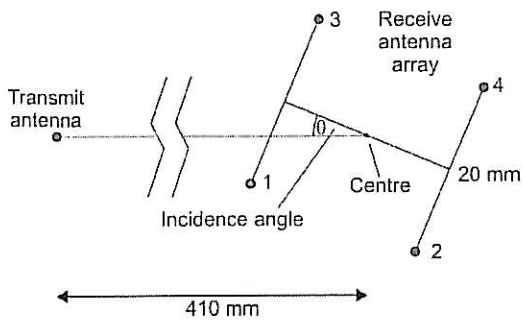
Figure 3. A plan view of the test system showing the receive antenna geometry definition. The angle of incidence in this case is 22.5°.

Results

From each set of traces, 100 on each antenna were taken to represent the signal in each direction. If the traces from a single antenna element are merged to form a radargram, they appear as in Figure 4. Small changes in arrival time of the waveforms are visible at each angle, and shifts are also visible during a single angle. These changes are largely due to static timing changes in the test system that are temperature related.
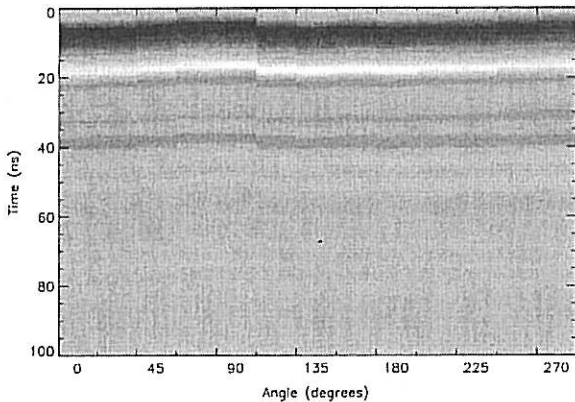

Figure 4. A composite radargram of 100 traces in each of 13 directions.

Static time shifts are not present between traces acquired from the four antennas in the array: the hardware receiver system interleaves reception from each antenna so that any drift elsewhere in the radar will be applied to all antenna elements equally during a single measurement.

In Figure 5, the received signal is plotted for the antenna at two different angles, 0° and 270° degrees to the transmitter. The data presented is raw measured data from a single trace, unfiltered in any way, but is presented in a very short time window. In Figure 5a, elements 1 and 3 are at equal distances to the transmit antenna, as are elements 2 and 4. It is apparent that the signals received on the antennas show the same time relationship at the onset of reception of the incoming pulse up to 5 ns. Later in the pulse the mutual coupling

between the antennas obscures the delay between the two pulses.

In Figure 5b, elements 1 and 2 are now at the same distance and time from the transmitter, while elements 3 and 4 are at a greater distance and time. Again, the shift in first arrival times is apparent.

a) Antenna at 0° to incoming signal
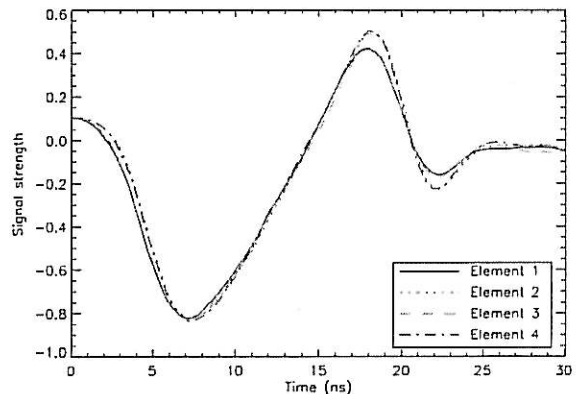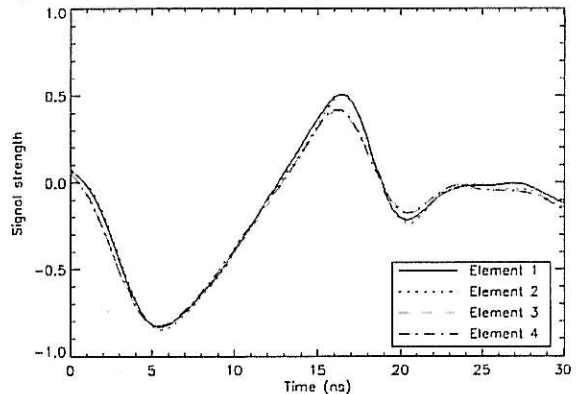

b) Antenna at 270° to incoming signal

Figure 5. Results for receive antenna at two angles of incidence.

Because of the mutual coupling, the time shifts between the signals are not as great as the geometry would suggest. In attempting to estimate the direction from the data, it is assumed that the time shift is unknown, but proportional to the distance between the antenna elements. The time shift between antenna elements is then measured by cross-correlating the signals at different lags, and determining where the correlation is a maximum. Because the expected delay is of the order of the sample time, all the waveforms were interpolated 64 × before cross-correlation.

For simplicity, while determining the transform from lag to direction, the 100 traces on each antenna in each direction were stacked into a single trace in each direction. The lags between elements are smaller than those predicted by no mutual coupling (Figure 6). The

numerical modelling results in Nyareli and Vogt (2007) showed lags that were greater than predicted.
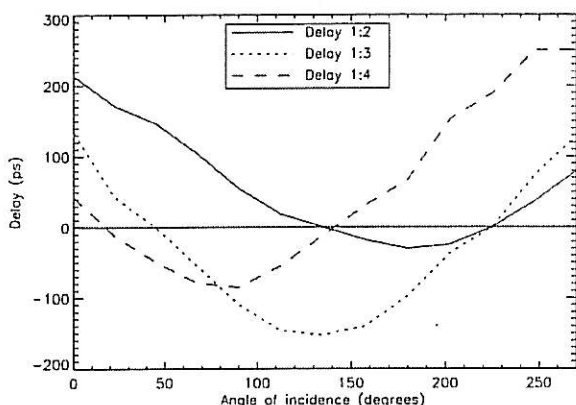

Figure 6. Lag between antenna elements for each of 13 angles of incidence.

The predicted lag between each element for different incident directions can be predicted from geometry:

$$L_{12} = l\cos(\theta) \tag{1}$$
$$L_{13} = -l\sin(\theta) \tag{2}$$
$$L_{14} = \sqrt{2}l\cos(45° + \theta) \tag{3}$$

where L_{xy} is the lag between elements x and y, l is the time between adjacent antenna elements, proportional to the distance between them, and θ is the angle of incidence. The theoretical value for l is 600 ps.

The predicted lag for the 13 angles of incidence (Figure 7) compares well in form to that measured in Figure 6 but there are some differences in offset and scaling.
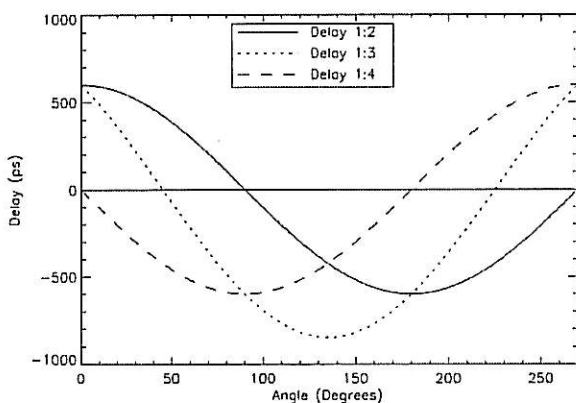

Figure 7. Calculated lag between two antennas for angles of incidence up to 270°.

Variations in offset are likely to be caused by small variations in the cable length between each of the antenna elements and the multiplexer. Variations in scaling between measured and predicted lag are expected to be smaller and are caused by the antenna geometry not being exactly orthogonal.

The measured lags illustrated in Figure 6 are fitted to the model, as follows:

$$L_{fit} = a + bL_{measure} \tag{4}$$

where a is the offset in lag, and b is the scaling in lag. The two coefficients a and b are determined by a least squares fit between data and model and the results of the fit are given in Table 1.

Table 1. Calculated correction coefficients

	a	B
L12	-401	5.33
L13	-280	3.43
L14	-41.4	5.22

From Equations 1 to 3, it is possible to determine the direction of incidence of signals received by the directional antenna by taking ratios of lags between two elements. Two independent measurements of direction are available based on the three lags L_{12} to L_{14}:

$$\theta_{23} = -\tan^{-1}\frac{L_{13}}{L_{12}} \tag{5}$$
$$\theta_{24} = \tan^{-1}\frac{L_{12} - L_{14}}{L_{14}} \tag{6}$$

It is now possible to estimate the direction for each set of four traces plotted in Figure 4, and the result is plotted in Figure 8. If the correct angles are subtracted, the error is plotted in Figure 9. Almost all the estimates lie within +15°/-5° of the correct angle.
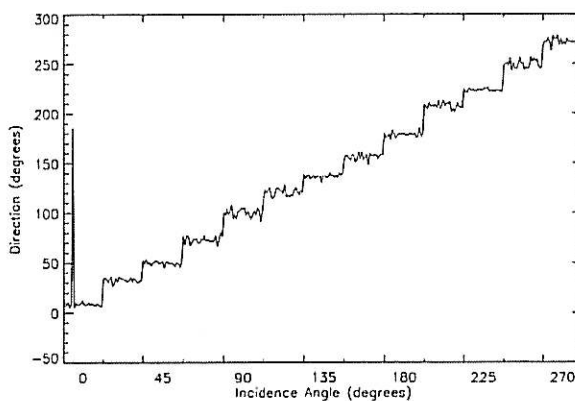

Figure 8. Direction of incoming wave estimated for 25 traces in each of 13 directions.

- The antenna performance has been characterised with near perfect signals. The effect of noise needs to be investigated, and further work is required on whether suitable filtering can reduce the effect of noise on the direction finding technique.
- The lag determination technique used here it was applied to the whole trace. In practice it will have to be applied only to the wavelet associated with a single reflector.

There is also opportunity to apply more sophisticated analysis techniques to determine the direction of incoming waves given the response of four antennas. As an example, the traces in Figure 5 show that the amplitude response of the four elements is also affected by the direction of incoming waves.

ACKNOWLEDGEMENTS

We thank the PlatMine research collaborative for funding this work and for permission to publish the results presented here.

REFERENCES

Balanis, C. A., 1982, Antenna Theory, Analysis and Design, John Wiley and Sons, New York.

Dobrin, M. B., and Savit, C. H., 1988, Introduction to Geophysical Prospecting, Fourth Edition, McGraw Hill, New York.

Ebihara, S., and Sato, M., 2002, 3-D estimation of target positions with borehole radar using E-field sensor array: Ninth International Conference on Ground Penetrating Radar, Koppenjan, S. J., and Lee, H. L., editors, Volume 4758, SPIE, 551-557.

Nyareli, T., and Vogt, D., 2007, Small directional borehole radar antennas; numerical modelling method: this volume.

Siever, K. (2000), Three dimensional borehole radar measurements – a standard logging method? Eighth International Conference on Ground Penetrating Radar, Volume 4084 of SPIE, 114-120.

Van Dongen, K. W. A., Van den Berg, P. M., and Fokkema, J. T., 2002, A directional borehole radar for three-dimensional imaging: Ninth International Conference on Ground Penetrating Radar, Koppenjan, S. J., and Lee, H. L., editors, Volume 4758, SPIE, 25-30.

Van Schoor, M., Du Pisani, P., and Vogt, D., 2006, High-resolution, short-range, in-mine geophysical techniques for the delineation of South African orebodies: South African Journal of Science 102, 355-360.

Wu, T. T., and King, R. W. P., 1965, The cylindrical antenna with non-reflecting resistive loading: IEEE Transactions on Antennas and Propagation 13, 369-373 and 998.

CONCLUSIONS

The results show that it is possible to measure delays between nominally identical traces that are smaller than a single sampling period. In this case, delays of less than 100 ps are being accurately measured in the absence of noise although the sampling interval is 400 ps.

While mutual coupling changes the lag between received signals on different antenna elements from that predicted in the absence of mutual coupling, the geometry of the antenna means that as long as the coupling effect is constant, it disappears when ratios of lags are taken. By following a simple calibration procedure it is possible to determine the direction of incoming waves to within a few degrees.

A number of questions remain to be investigated:

- The elements of the antenna in the scale model are not as electrically close as those likely to be used in the final antenna. The sampling rate of the system may have to be increased to provide adequate resolution of the lag.
- The physical model measured here is not identical to the numerical model tested in Nyareli and Vogt (2007), so modelling differences may explain why the measured lags are smaller than expected. Further work is necessary to understand this problem, particularly considering the smaller lags expected in the final system.
- The dielectric support between the antenna elements of the proposed antenna needs to be investigated to determine the optimal tradeoff between mutual coupling and delay.

The result presented in Figure 9 is from experimental data of good quality. If 1 % additional noise is introduced to the recorded traces, good results are still achieved. If 10 % noise is added, without filtering it is not possible to determine the direction of the radiation striking the receiver.

Figure 9. Error in measured direction compared to actual direction.
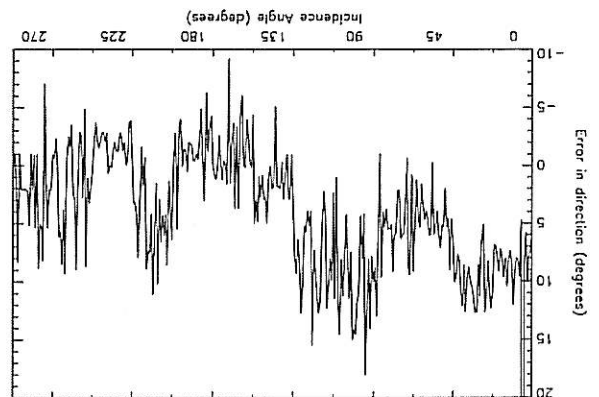
Dr D. Vogt
CSIR
PO Box 91230
Auckland Park, Johannesburg 2006
South Africa

5 March 2008

Subject: 70th EAGE Conference & Exhibition incorporating SPE EUROPEC 2008

Dear Dr Vogt,

It is our pleasure to inform you that the technical programme committee has accepted your extended abstract "Experimentally Achieving Borehole Radar Antenna Directivity in the Time Domain in the Presence of Strong Mutual Coupling (Best of SAGA)" by *D. Vogt* (CSIR) & T. Nyareli (CSIR)* for a(n) oral presentation at Rome 2008.

The presentation is scheduled in the "Rock Physics II + Wellbore Acquisition (EAGE)" session on Thursday 12 June, at 17.45hrs in the Lecture room I.
A preparatory meeting, which you must attend, will be held on Wednesday 11 June, 14.15 - 14.30 in the same room as your presentation.

Your extended abstract has been registered under abstract number I048 and will be included on the CD-Rom.

Please find enclosed the speakers' recommendations. This information includes useful presentation guidelines; therefore you are kindly requested to read this carefully.

As a Best of SAGA speaker, you will receive a complimentary full registration for Rome 2008, you will find the registration confirmation letter enclosed.

Should you be unable to give your presentation, please notify us by email (rome2008@eage.org) before **20 April 2008**. Please note that failure to do so will be considered a no-show and will disqualify you from presenting papers at all EAGE conferences for the next 3 years.

Speakers, who have a limited budget, may apply for PACE support via the Rome 2008 website.

We look forward to meeting you in Rome.

Yours sincerely,

Sandra Hermus
Event Coordinator

System requirements:

Pentium processor
Windows 95/98/2000/NT4.0 or higher
CD-Rom drive
ODBC Microsoft access 97
32 MB Ram
Screen resolution 800x600, or better
16 bit colour or higher
Adobe Acrobat Reader

This CD-ROM will start automatically after insertion. If not, double-click the file 'start.exe' on the CD-ROM.

This CD-ROM was produced by
Co Productions, Houten, The Netherlands

Extended Abstracts & Exhibitors' Catalogue

EAGE
EUROPEAN ASSOCIATION OF GEOSCIENTISTS & ENGINEERS

ROME 2008

ISBN 978-90-73781-53-5
© EAGE 2008