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Borehole Radar Directionality in the Time Domain in Small Aperture Antennas

Declan Vogt, Teboho Nyareli
CSIR Natural Resources and the Environment
Johannesburg, South Africa
email: dvogt@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. In this paper, a time-domain technique is used to demonstrate that the direction of incoming radiation can be determined by calculating the time delay between antenna elements.**

It is proposed to construct a system with a sampling rate of 2.56 GSa/s, and a bandwidth of 500 MHz. The antenna array will consist of four resistively loaded dipoles, just 20 mm apart, embedded in a material with a relative permittivity of 4. The expected delay between elements is then 133 ps, while sampling would occurs every 391 ps. We show that it is possible to resolve the small time intervals between signals received on different antenna elements by interpolation.

Initial tests show that 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.

The technique is moderately tolerant of noise, and some directional information can be recovered in signal to noise ratios of 10 dB.

***Keywords* - borehole radar, directional antennas, time domain, scale model, physical model, interpolation.**

I. 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 [11]. 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.

Directional data is not essential in many environments, where the relative position of targets can be determined from other information. However, for some applications, directionality is very useful. For example, before sinking a new mine shaft, a borehole is drilled in the location where the shaft is proposed to be sited. The borehole is then surveyed with a number of tools to determine the geotechnical properties of the surrounding rock. If borehole radar is applied, it can determine the presence of structures near the shaft pillar, [2] and has been used in the past to confirm other geotechnical assessments, resulting in the relocation of a shaft. However, if the operator decides that a structure should be investigated further, its direction relative to the shaft borehole has to be known. It can be found by kinematics if another borehole is available [5] or estimated from knowledge of existing structures, but a direct measurement of direction will always be first prize.

At VHF frequencies (30 – 300 MHz), there is very little space available in a 48 mm borehole to separate antenna elements in the radial direction. High directivity is usually achieved through the use of large antenna aperture in terms of wavelength.

In previously published borehole radar antenna designs, directivity has been achieved in a number of ways:

- The antenna described by Siever [8] 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.
- A relatively low frequency (100 MHz) commercial borehole antenna [10] 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 South African exploration borehole.
- Sato and Takayama reported a borehole array with four antennas that fed electro-optical transceivers [7]. Direc-

tionality was determined by comparing the phase differences at each antenna. They showed that mutual coupling was tolerable. In a related paper [9] they presented an algorithm to recover direction that performed well.

II. 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 [12] implemented using five discrete resistors.

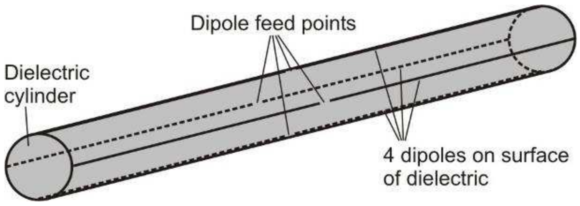

Figure 1. The directional receive antenna, consisting of four resistively loaded dipoles embedded in dielectric.

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, but the bandwidth of the pulse transmitted is influence by the 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.

III. DIRECTION DETERMINATION METHOD

The process proposed here takes the configuration of an Adcock antenna, with four dipole antennas arranged at the corners of a square (Figure 2). However, unlike the Adcock antenna, direction is determined by measuring the time delay between individual elements, for a wavelet in the radargram.

The angle of incidence, θ, is measured between the incoming wave and the array as indicated in Figure 2. The predicted time lag is given by:

$$L_{12} = l\cos(\theta) \quad (1)$$

$$L_{13} = -l\sin(\theta) \quad (2)$$

$$L_{14} = \sqrt{2}l\cos(45° + \theta) \quad (3)$$

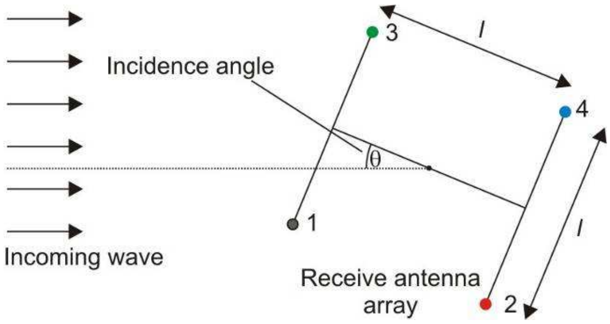

Figure 2. Geometry of direction finding antenna (plan view).

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. From Equations 1 to 3, it is possible to determine the angle of incidence 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}:

$$\theta_{23} = -\tan^{-1}\frac{L_{13}}{L_{12}} \quad (4)$$

$$\theta_{24} = \tan^{-1}\frac{L_{12} - L_{14}}{L_{14}} \quad (5)$$

Note that for the given geometry, the angle of incidence is independent of the physical size, l.

To determine the lag between the signals on each antenna, the wavelet of interest is isolated, and the time shift between recorded signals is determined using cross correlation. To determine time shifts of less than one sample period, the data is interpolated prior to cross correlation. Interpolation is done using the IDL routine CONGRID [6], with CUBIC_INTERPOLATION set to -0.5. This closely approximates the theoretically optimum sinc interpolation function using cubic polynomials and does not introduce higher frequencies into the time domain signal.

1.1 Effect of Mutual Coupling

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.

Mutual coupling between antenna elements as close as 1/60th of a wavelength is likely to be high [1]. The 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 [4].

IV. EXPERIMENTAL METHOD

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 3). 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.

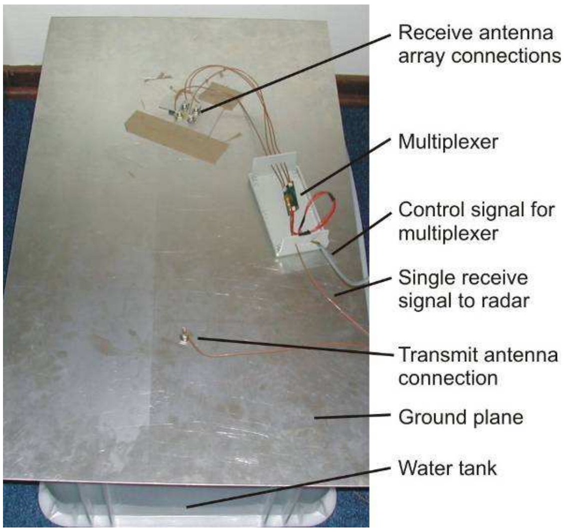

Figure 3. Water test tank showing the ground plane. Antennas are constructed downwards from the ground plane into the water below.

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 water, 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 2. 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°.

V. 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.

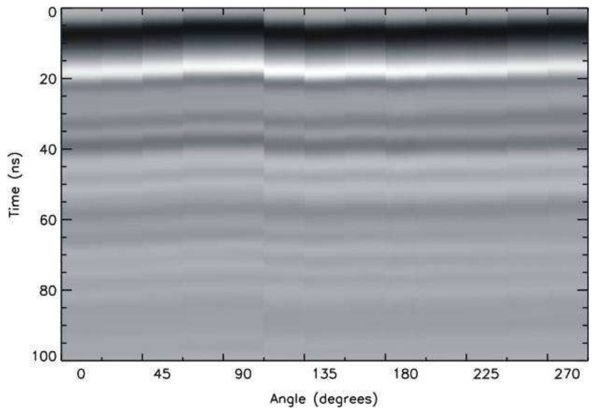

Figure 4. A composite radargram of 100 traces in each of 13 directions.

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.

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.

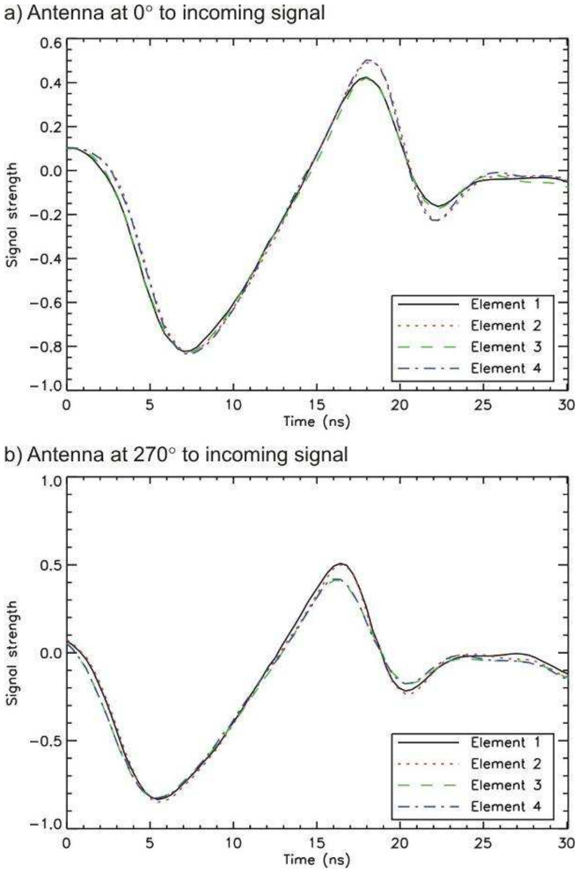

Figure 5. Results for receive antenna at two angles of incidence.

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). By contrast, the numerical modelling results in [4] showed lags that were greater than predicted from Equations 1 to 3.

The modeled 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.

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.

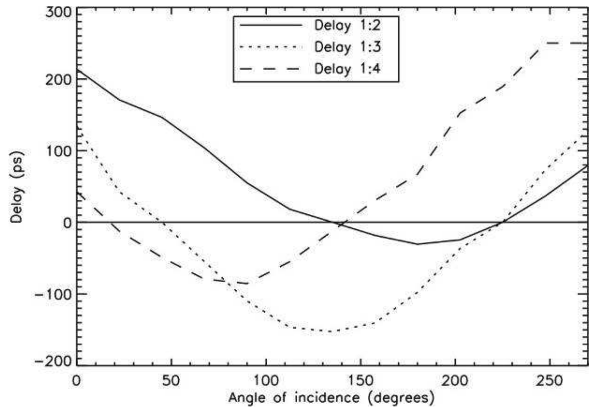

Figure 6. Lag between antenna elements for each of 13 angles of incidence.

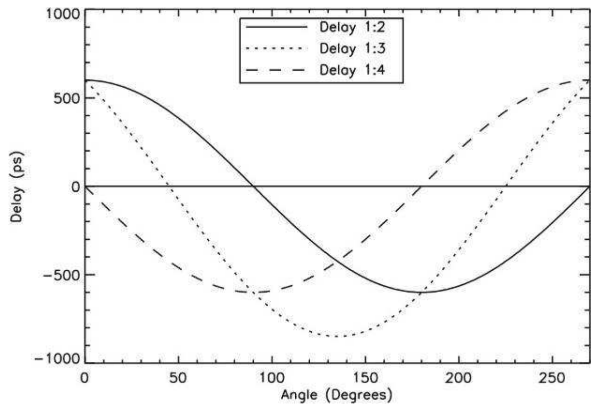

Figure 7. Calculated lag between two antennas for angles of incidence up to 270°.

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
L_{12}	-401	5.33
L_{13}	-280	3.43
L_{14}	-41.4	5.22

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. The error between measured and actual angles is plotted in Figure 9. Almost all the estimates lie within +15°/-5° of the correct angle.

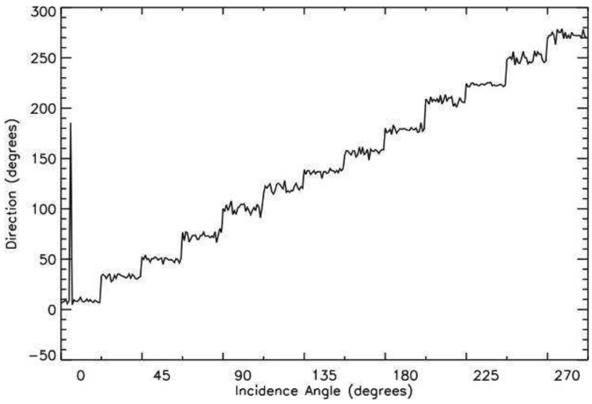

Figure 8. Direction of incoming wave estimated for 25 traces in each of 13 directions.

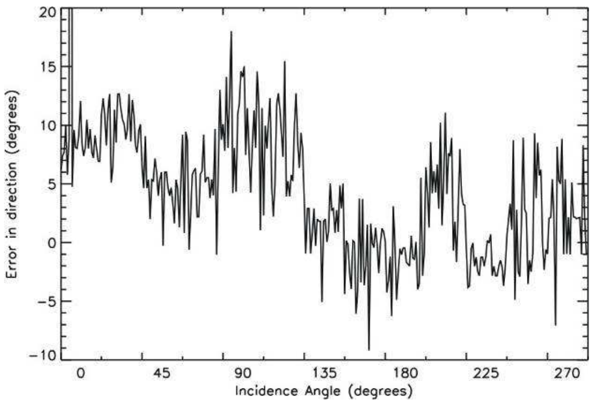

Figure 9. Error in measured direction compared to actual direction.

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 (Figure 10), without filtering it is not possible to determine the direction of the radiation striking the receiver, although a trend is still visible (Figure 11).

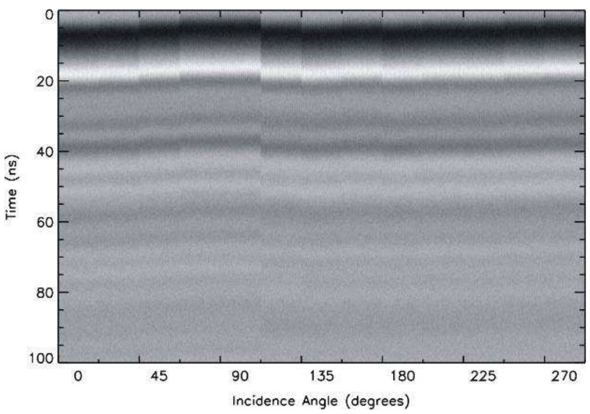

Figure 10. Effect of the addition of 10% noise to the data shown in Figure 4.

If the radargram with noise is filtered, so that noise outside the bandwidth of the system is eliminated, the estimation of direction is somewhat improved (Figure 12). If 50% noise is added, it is not possible to extract even a poor estimate of direction of the reflector.

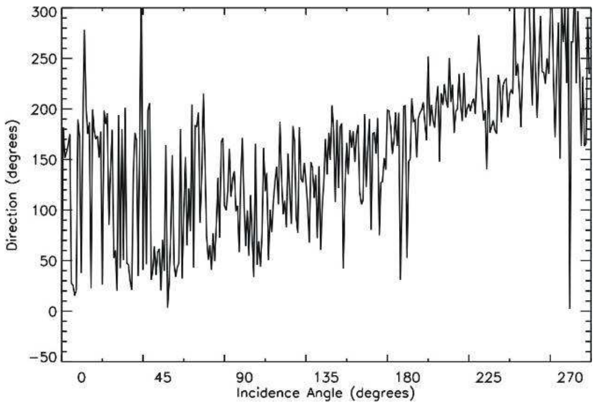

Figure 11. Effect of 10% noise on directional determination.

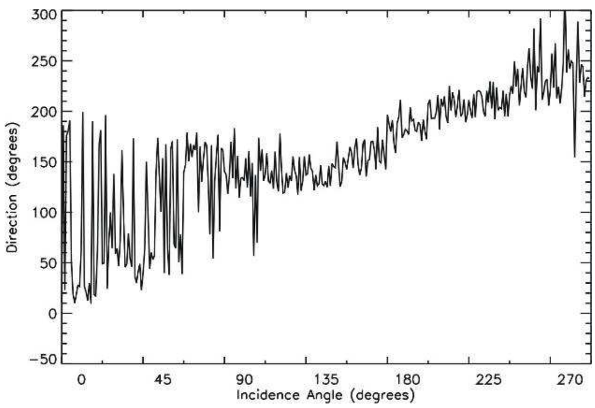

Figure 12. Improved direction estimation when data is band-pass filtered to exclude noise outside the bandwidth of the radar signal.

VI. 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 [4], 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 structure between the antenna elements of the proposed antenna needs to be investigated to determine the optimal tradeoff between mutual coupling and delay.
- 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 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.

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REFERENCES

[1] Balanis, C. A., *Antenna Theory, Analysis and Design*, John Wiley and Sons, New York (1982).

[2] Bray, A., Sindle, T., Mason, I., Palmer, K., Cloete, J., Steenkamp, J., Du Pisani, P., Trofimczyk, K., “Using slimline borehole radars from cover holes” in *10th SAGA Biennial Technical Meeting and Exhibition*, Wild Coast 24 - 26 October, 184 – 189 (2007).

[3] Dobrin, M. B., and Savit, C. H., *Introduction to Geophysical Prospecting*, 4th Edition, McGraw Hill, New York (1988).

[4] Nyareli, T., and Vogt, D., “Small directional borehole radar antennas; numerical modelling method” in *10th SAGA Biennial Technical Meeting and Exhibition*, Wild Coast 24 - 26 October, 171 – 175 (2007).

[5] Osman, N., Simmat, C., Hargreaves, J and Mason, I., “Three dimensional kinematic imaging of borehole radar data” in *Exploration Geophysics*, 34, 103- 109 (2003).

[6] RSI, *Using IDL*, Research Systems, Inc., Boulder, CO (1995).

[7] Sato, M., and Takayama, T., “A novel directional borehole radar system using optical electric field sensors”, in *IEEE Transactions on Geoscience and Remote Sensing*, 45:9, 2529 – 2535 (2007).

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

[9] Takayama, T., and Sato, M., “A novel direction-finding algorithm for borehole radar”, in *IEEE Transactions on Geoscience and Remote Sensing*, 45:9, 2520 – 2528 (2007).

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

[11] Van Schoor, M., Du Pisani, P., and Vogt, D., “High-resolution, short-range, in-mine geophysical techniques for the delineation of South African orebodies” in *South African Journal of Science* 102, 355-360 (2006).

[12] Wu, T. T., and King, R. W. P., “The cylindrical antenna with non-reflecting resistive loading” in *IEEE Transactions on Antennas and Propagation* 13, 369-373 and 998 (1965).