Determining radar velocity of rocks in-situ using a modified borehole radar system

Declan Vogt
CSIR Natural Resources and the Environment
Johannesburg, South Africa
email: dvogt@csir.co.za

In submitting this paper for EuroGPR2008 I hereby assign the copyright in it to the University of Birmingham and confirm that I have had the permission of any third party for the inclusion of their copyright material in the paper. The University of Birmingham will license EuroGPR to use this paper for non-commercial purposes. This will be the sole use of this material.

Abstract - It has been shown previously that if a borehole radar tool is suspended on a conductive cable, the cable will support a traveling wave that travels at the velocity of the rock immediately surrounding the borehole. Modelling results showed that the effect is more pronounced when the borehole is water filled, but that it is also present when the borehole is air filled. In this paper, field trials are undertaken to show how the technique may be applied in practice.

A case study was undertaken in a vertical borehole in the norites of the Main Zone of the Bushveld Complex in South Africa. Results confirm the basis for the technique. An algorithm for automatically creating velocity logs is presented, based on using cross correlation to determine the time shifts between adjacent traces, but it is shown that the algorithm does not perform well in the presence of noise. Manual picking of the reflectors caused by wire guided wave modes is used to determine the velocity of propagation of radio waves in the rock surrounding the boreholes.

The case study highlights the shortcoming in the technique: reflectors are required to cross the borehole for wire-guided reflections to appear in the radargram. The performance of the technique is also lower in air-filled boreholes, compared to water-filled boreholes.

The technique has a place where velocity must be determined cost effectively, but will not become a routine tool until analysis methods are refined to work more effectively with noisy data and data that contains interfering reflectors.

Keywords - Borehole radar, radar velocity log.

I. INTRODUCTION

It has been previously shown [5] that a borehole radar can be adapted to log radar velocity as it goes down a borehole, by suspending the radar on a conductive cable. The principle of using a wire to guide a propagation mode along the borehole was independently described in [1], although not identified there as a method of determining radar velocity.

At the top of Figure 1, a borehole radar layout is presented horizontally. As the radar tool travels along the borehole, it will transmit and receive largely in the radial direction, typically reflecting off contrasting sub-surface structures to produce the solid reflectors shown in the radargram below.

However, if a conductive support is present, the radar will also transmit a signal that is supported by the cable to travel axially along the borehole, until the borehole crosses an electrical discontinuity that can reflect part of the pulse. The conductor supported axial wave produces the dotted reflector in the radargram in Figure 1. The slope of the reflector is determined by the velocity of propagation of the wave along the borehole.

In [5], it was shown numerically that the conductor supports a number of coaxial waves traveling at difference velocities, but that one mode was present that traveled at the velocity of the surrounding rock. In Figure 2, modelling results from [5] are presented for two models, the left where the borehole is filled with air and the right where the borehole is filled with water. In each case, the radar antenna is at C, hanging on a conductor that runs vertically up the left hand edge of the modelling space. The model is rotationally symmetrical about its left hand edge and is filled with a material that has electrical properties similar to those of quartzite, with a relative permittivity of about 9, and a low loss tangent of about 0.02.

The radial wavefront from the antenna is clear, at B. In the absence of a conductor, the radial wavefront tends to zero in the axial direction but is supported here on the borehole
conductor. In each case, the wavefront A is traveling at the velocity of the material filling the borehole.

![Air around borehole, t=160 ns](image)

![Water around borehole, t=280 ns](image)

Figure 2. Comparison of wave propagation modes in boreholes with air and water filling (from [4]).

In Figure 3, the results are presented for a full radargram. It is created by modelling the scenario illustrated in Figure 2 for various distances between the antenna, C, and a reflective interface running horizontally across the bottom of the modelling space. In both cases, there are no geological reflectors in the model, just the reflectors due to coaxial wave modes.

The reflector labeled A is traveling at the velocity of the material in the borehole, and is slower in the case where the borehole is filled with water: its slope shows that it does not move out as far in time for the same distance from the reflector as in the air-filled borehole case.

The reflector labeled B is caused by the axial guided mode of the borehole conductor that travels in the surrounding rock as shown in Figure 2, and also labeled B.

In both cases, the area labeled C contains artifacts produced by the Finite-Difference Time-Domain modelling code.

The modelling undertaken in [5] and supplemented here, suggests that the proposed procedure could provide a continuous log of radar velocity, but that to make it a useful tool would require additional software development to extract velocity log information.

II. CASE STUDY

A case study has been undertaken on a vertical borehole in the Bushveld Complex of South Africa. The borehole was chosen for its availability, rather than for the presence of significant targets. The borehole starts in conductive clay overburden, then travels through norites of the Main Zone of the Bushveld Complex [2]. Some vertical structure is present near the hole.

![Figure 3. Results from modelling borehole radargrams with the borehole filled with water (top) and air (bottom).](image)

The first 180 m of the borehole was surveyed. The radar and the method of connecting the conductor to it are illustrated in Figure 4.

![Figure 4. The velocity logging system in use. Left: the borehole radar system, consisting of transmitter and receiver probes; Top right: connecting a conductor to the receive antenna body; Bottom right: feeding the tool into the borehole.](image)
The radar used in the study is the Aardwolf BR40, which has a bandwidth of about 40 MHz [4]. The antenna is a dipole with one arm resistively loaded. The other arm contains the electronics. In the case of the receiver, the conductive arm is electrically attached to the cable head, hence connection of the borehole conductor is by attachment direct to the cable head, as shown in Figure 4. A direct connection is not necessary: a gap between the probe and wire of less than about an eighth of a wavelength will also work [1].

Results are presented in Figure 5. In all the figures, band pass filtering and time varying gain have been applied. The top radargram is as acquired, without a conductive support cable. The other two radargrams show the effect of the conductive cable: it introduces the reflectors A and B and the family of reflectors C. Also visible in the original radargram, is a hyperbolic diffraction, labeled D. There are other reflectors delineating radar targets in the subsurface, but they are not considered further here.
The top 20 m of the borehole travel through highly conductive overburden, so no data was acquired. The water table at the test site was at 128 m, and it is the interface between air and water in the borehole that provides the reflection for the main conductor guided wave along the borehole.

Two conductor guided waves are visible, A traveling at the velocity of propagation in water, and B traveling at the velocity of propagation in the host rock. There is a third set of reflections, C, which appear to be conductor guided, as they are not clearly resolved in Figure 5a. These are reflections off the interface between norite and conductive cover. They are not as well resolved as reflectors A and B, probably because the borehole contains air in the zone where C is recorded, not water as it does in the zone where A and B are recorded.

The results in Figure 5 qualitatively match those from modeling in [5] and depicted in Figure 2 and Figure 3: the rock wave, B, is paired with a water wave, A, and the wire guided wave is more visible when the borehole is filled with water than when it is filled with air.

III. PROCESSING AND RESULTS

Radio velocity logging will not become a routine technique until tools exist to create velocity logs in an automated or semi-automated manner. At the CSIR, borehole radar processing is conducted using an in-house program called Framework, written in IDL [3]. The package allows annotation lines to be placed on the radargram. For the purposes of velocity log creation, the annotation tool is used to identify reflectors that can be used for velocity estimation. In Figure 6, the selected reflector, B from Figure 5 has been annotated with a red line, just visible on the upper radargram.

Where the annotation line crosses each trace, a Hanning window is used to remove data from the trace except in the region selected by the annotation. The Hanning window is given by:

$$w(k) = \alpha - (1 - \alpha)\cos(2\pi k / N)$$

where $\alpha$ is 0.5 for the Hanning window, $N$ is the number of points in the window, and $k$ runs from 0 to $N-1$. The result after masking the radargram with the Hanning window is shown on the lower radargram in Figure 6.

The trace-to-trace time delay is determined by comparing adjacent traces using cross correlation. For the reflector in Figure 6, the result is presented in Figure 7. The portion of the trace that it is used to determine velocity is limited in time to a short portion of each radar trace either side of the position of the annotation line. At the top of Figure 7, the traces in this area have been shifted in time to produce a radargram that includes just the portion of the data used for velocity estimation. It is then possible to compare velocity estimates with the reflector that they come from.

$$\alpha$$

Two estimates of velocity are plotted in Figure 7: the solid line is a twenty point moving average of the velocity determined from trace-to-trace correlation. The dotted line is the measured slope of the annotation line in Figure 6, and is a manual estimate of velocity.

The two estimates are significantly different. The algorithm for determining trace-to-trace delays using cross-correlation is not reliable in the presence of noise. For comparison, the diffraction hyperbola, D, in Figure 5, can be fitted to a background velocity of 0.11 m/ns. Electrical property measurements of norites place the velocity in the range of 0.12 m/ns – 0.08 m/ns.

The two reflectors marked A and C in Figure 5 have also been processed to velocity logs. In Figure 8, the reflection caused by waves traveling in the water in the borehole is illustrated. The poor quality of the automated velocity pick is evident, but the segment of radargram at the top of the figure shows the poor data quality that the algorithm...
had to work with. On the original radargram it is possible to follow the reflector by eye, although the estimate of velocity from annotation, 0.042 m/ns, is only within 30% of the correct value for water of 0.033 m/ns.

IV. CONCLUSION

While modeling and experiment have shown that borehole radar can provide a measurement of the velocity of propagation of radio waves in the rock surrounding the borehole if it is attached to a conductive support, there are a number of practical problems with the technique:

- It can only provide information if there are good reflectors that intersect the borehole. Here, only two reflectors intersect the hole: the overburden/rock interface and the air/water interface in the borehole itself. The lack of good reflectors for analysis removes the possibility of providing velocity logs for most of the hole.
- Good quality reflectors are more easily produced if the borehole is water filled. While water can be added to boreholes, the effort is not currently warranted based on the results achieved.
- If radar velocity logging is to be added to the suite of standard geophysical logging tools, the process of producing velocity logs has to be automated. The semi-automatic approach demonstrated here is not capable of producing reliable results in the presence of significant noise.

At present, the technique is useful in limited situations where the geology cooperates, and velocity measurements are required for other purposes. As a general purpose logging tool, work is required to develop reliable algorithms for automatic picking of velocity.

ACKNOWLEDGEMENTS

I thank Anglo Platinum for permission to use the borehole discussed here and to publish results obtained from it.

REFERENCES