A SLIMLINE BOREHOLE RADAR FOR IN-MINE USE
Declan Vogt
CSIR Division of Mining Technology
PO Box 91230, Auckland Park, 2006, South Africa
dvogt@csir.co.za

ABSTRACT
Borehole radar has shown its value in delineating geological features, especially orebody geometry, in deep level gold and platinum mines in South Africa. At the same time, the cost of the critical components of a radar system has decreased dramatically while their performance has increased. The time is ripe for the introduction of a 100 MHz bandwidth instantaneous sampling slimline borehole radar to fit into 38 mm boreholes.

A new generation of low cost, low current, fast analogue to digital converters (ADCs) has made it possible to implement instantaneous sampling in the probe. Memory speed is still limited, with speeds beyond 100 MHz not readily available. The borehole radar design uses four 8 bit 100 MS/s analogue to digital converters (ADCs) in parallel, each feeding its own First-In First-Out (FIFO) memory. The four ADCs are each clocked 2.5 ns apart, to achieve a sampling rate of 400 MS/s. Once the trace has been acquired, it is downloaded from the FIFOs to the onboard microprocessor, where it is stacked. The resultant trace is transmitted out of the borehole using a 115 kbaud serial link over an optical fibre cable and displayed in real time on the surface control unit.

Data is processed using conventional GPR processing techniques. Once the data has been filtered, it is transferred to a 3D visualization environment, where reflectors can be compared to inferred target horizons. More complex environments can only be interpreted by using data from multiple boreholes, or by using directional antennas.

Keywords: borehole radar, instantaneous sampling, slimline, 3D visualization

INTRODUCTION
The technique of borehole radar has proven itself for mapping specific economic horizons in South African gold mines, in particular the Ventersdorp Contact Reef or VCR (Trickett et al., 1999, 2000). The potential economic benefit of applying the technique is sufficiently large to warrant development of a borehole radar specifically for the deep level hard rock mining environment. The environment imposes four specific requirements:

• Ideally, the probes should fit into boreholes 38 mm in diameter. The maximum borehole size normally available is 48 mm.
• The probe has to operate in virgin rock temperatures of 50° C – 70° C.
• The whole system has to be robust and watertight. The underground environment is very wet with high humidity and the water is corrosive.
• A system of access is required for boreholes that are horizontal or that are drilled upwards.

At the same time that the need for a slimline system became apparent, technology has developed to the point where it is reasonable to build a pulse radar with instantaneous sampling inside the borehole probe. Instantaneous sampling is attractive to the radar designer, because it overcomes the need for the very accurate timing system required in stroboscopic systems and it enjoys good time efficiency (Wright et al., 1989). This paper describes a borehole radar called the Aardwolf BR40 that applies instantaneous sampling to acquire radar data with the required bandwidth and dynamic range.

PERFORMANCE REQUIREMENTS
The majority of South African gold mining occurs on thin tabular orebodies, locally referred to as reefs, generally less than 1.2 m thick. The reefs occur along the rim of the 300 km wide Witwatersrand Basin and typically dip gently at 10° – 30°. They are gold bearing conglomerates, and are not good radar reflectors, but many reefs have associated reflective markers.

A typical mine layout is illustrated in Figure 1. Haulages are developed along the strike of the reef, typically 60 m below it. At regular intervals along the haulage, a crosscut is developed in the dip direction of the reef, until it intersects the reef plane. From the reef intersection, mining proceeds up the reef plane.

The geophysical problem is to determine the reef geometry before mining begins. Dislocations to the otherwise planar...
reefs are due to faulting, rolling (Figure 1b) or intrusion of dykes. Advance knowledge of dislocations allows the mine planners to optimize footwall development to improve rapid access and maximize profits.

The best access to map the reef is from cover boreholes drilled to provide advance warning of water fissures and methane ahead of crosscut and haulage development. Before one of these tunnels is developed, a cover borehole is drilled along its proposed line, angled at about 5° up. If borehole radar is applied in the cover hole, it can provide information about the reef profile in a line along the reef above the tunnel. A typical cover borehole is about 120 m long, 48 mm in diameter, is more than 50 m from the reef plane near its start, and is angled upwards. The virgin rock temperatures at the deeper extents of current mining exceed 50° C.

The reef elevation must be mapped to an accuracy of better than 3 m. If a dislocation to the reef is less than 3 m it can be mined via trenching. Larger dislocations require redevelopment. The required accuracy implies an upper bound on the radar wavelength of 6 m. The majority of reefs in the Witwatersrand Basin are hosted within quartzite, which is highly resistive. The relative permittivity is typically around 9, leading to a minimum required bandwidth of 16 MHz. The range requirement is set by the desire to map over the vertical distance between two levels, and is typically 60 m. Better than the required range and resolution can be comfortably achieved at 25 MHz. Ranges in excess of 50 m have been achieved in particular locations using a bandwidth as high as 100 MHz (Trickett et al., 2000).

In Bushveld platinum mines, the target geometry, the required range and the rock electrical properties are all similar to those of the Witwatersrand gold environment. The major challenge for borehole radar is the prediction of potholes, which are expressed by changes, often drastic, in the dip of the platiniferous horizons. The standard exploration borehole is 38 mm in diameter, rather than the 48 mm common in the gold mines. Platinum is the other major South African hard rock mining commodity and is rapidly replacing gold as the country’s major earner of foreign exchange.

The target geometry and host electrical properties define the performance requirements for the radar: it must be capable of resolving a planar feature with a resolution of 3 m at a minimum range of 60 m in a host with a loss tangent of approximately 0.1. The resolution dictates a system bandwidth of at least 16 MHz. The nomograms in Noon et al. (1998) indicate that a loop gain in excess of 140 dB is required. Plumb et al. (1998) discuss other performance requirements. In the deep level gold and platinum environments, the most important requirements are long range and acceptable resolution.

DESIGN PHILOSOPHY

Several priorities were assigned to assist in making design decisions:

Low cost: Geophysical instruments generally sell in very low volumes. Design time is the major expense for low volume developments, so as far as possible, off the shelf solutions were used to minimize design time. All the components used in the design had to be standard items, readily available in small quantities.

Slimline: Exploration and cover boreholes are typically AX, 48 mm in diameter, or EX, 38 mm in diameter. The borehole radar must be able to travel in narrow holes with a low risk of snagging.

Battery powered: The borehole radar is suspended on optical fibres, so it has to be battery powered. Battery life limits the power available for transmission, and the current available for the receiver.
Excellent robustness and ease of use: A survey instrument will not find work if the field crews find it difficult to use or unreliable.

IMPLEMENTATION

The system is illustrated in Figure 2. The transmitter is free-running with a pulse repetition frequency (PRF) of 1 kHz, and it triggers the receiver via an optical fibre connecting cable. The transmit pulse has a peak voltage of 1000 V, and a bandwidth of up to 125 MHz, limited by the antenna. The receiver acquires data instantaneously at up to 400 MB/s, with 8 bit resolution. Up to 256 traces are stacked within the receiver before the resultant trace is transmitted out of the borehole over a digital optical fibre link. A rugged PC is used to control acquisition and display data as it is acquired. Four traces, each consisting of 256 stacks, are acquired and displayed per second.

Antennas

Both the transmit and receive antennas are dipoles made up of a conductive arm and a resistively loaded arm. The length of the conductive arm sets the center frequency, and the resistively loaded arm broadens the bandwidth (Claassen et al., 1995). The conductive arm contains the battery and the electronics. The resistively loaded arm is designed with a Wu-King taper (Wu and King, 1965), and implemented using 1/4 W metal film resistors.

Transmitter

A high voltage generator charges a capacitor up to a potential of 1000 V. A field effect transistor rapidly switches the high voltage onto the antenna in under 10 ns. The pulse then falls slowly to zero over a period of a few µs as the capacitor recharges.

The transmitter is triggered by an internal free-running oscillator at the PRF of 1 kHz. The trigger pulse is also transmitted via an optical fibre link to the receiver. Conceptually, transmitter and receiver could both be triggered by an external trigger oscillator to make cross-borehole measurements, for example.

Transmit-receive trigger link

Optical fibre is used for the trigger link to improve electromagnetic isolation of transmitter from receiver. There is no way to avoid the making and breaking of the optical fibre connections of this link in the field, so they have been designed for improved reliability. Plastic optical fibres with a diameter of 1 mm are used. The connectors have simple butt-joints, but the large diameter of the fibres ensures a successful connection even if small particles of dirt obscure part of the surface. Plastic optical fibres are also easy to replace or repair in the field, unlike the majority of glass fibres.

Receiver

The receiver is the heart of the radar (Figure 3). The front end consists of a gain block and a variable gain amplifier. The amplifiers have a bandwidth of 90 MHz to act as the Nyquist filter. The gain can be varied by 60 dB but it cannot be varied during a single trace acquisition. If time varying gain is required, an artificial trace can be generated by combining data acquired at different gain settings (Siever, 2000).

Time varying gain can be ignored: much borehole radar data is interpreted without considering amplitude. If the amplifiers can recover from saturation quickly enough, fixed gain is adequate for many purposes. Saturation limits the minimum detectable target depth (Plumb et al., 1998) but this performance measure is not important for in-mine targets.

Memory speed is not increasing at the same rate as the speed of other electronic components and is now the limiting factor on cost effective fast data acquisition. Low power memory faster than 100 MHz is not readily available. The radar system is designed around a memory queue, implemented using 100 MHz First-In First-Out (FIFO) circuits. Each FIFO is driven by a low power 100 MS/s, 8 bit ADC. The ADC has
an analogue bandwidth of 475 MHz. The full sampling rate is achieved by running four ADC-memory circuits, offsetting the sample clock of each ADC by 2.5 ns.

The ADCs convert continuously, but the FIFOs only start to queue data on receipt of a trigger signal from the transmitter. Each FIFO then runs until full, up to a maximum of 2048 samples. After the FIFOs are full, the microcontroller downloads the samples, one from each of the four FIFOs in turn, into its internal memory. The microcontroller is a 16 bit Hitachi H8S/2138 running at 18.432 MHz, with 3.8 kBytes of RAM and 128 kBytes of Flash program memory. It stacks up to 256 8 bit traces, restricting the final data point size to 16 bits. As a trace is stacked, the previous trace is transmitted to surface.

Available memory allows trace lengths of up to 750 samples. The microprocessor was selected on the basis of physical size, speed and internal RAM size.

The trace rate is ultimately limited by the stacking speed in the microcontroller. The stacking inner loop executes in slightly under 1 µs. It takes 192 ms to stack 750 data points 256 times. Allowing for housekeeping, 4 traces/second is a reasonable trace rate. If the data format is ASCII HEX, at 115 kBaud a single 750 sample trace is transmitted in 261 ms; a good match for the stacking rate. A PRF of 1 kHz leads to an RMS transmitted power of 2 W, which is appropriate for a battery supply.

Battery packs

Maximum flexibility is achieved by the use of separate battery packs. The battery itself consists of twelve C size nickel cadmium cells and has a capacity of 2200 mAh at 12 V – 14.4 V. The battery pack is currently constructed within a 38 mm diameter stainless steel tube.

However, flexibility comes at a price. The bare metal tube that houses the battery pack is electrically lengthened by the surrounding water and rock, and leads to a center frequency well below the desired center frequency. The battery pack is being redesigned with a dielectric housing and a smaller diameter to allow operation in 38 mm boreholes.

Receiver-control unit link

The receiver is supported on an optical fibre cable, to minimize cable interference effects. Unlike the transmit-receive link, the cable cannot be large diameter plastic, because the optical losses in plastic are too high. The cable is standard 50/125 µm multimode harsh environment optical fibre. In order to overcome the need for making and breaking the optical path in the field, the cable is terminated in a cable head. The link between the cable head and the receiver is then made using a standard Gearhart-Owen logging connector.

Control unit

The control unit is a standard PC running Windows. The prototype control unit is based on a Single Board Computer with 192 MBytes of Compact Flash storage and a 640×480 pixel colour LCD screen. The processor, a 266 MHz Geode, is comfortably able to display 4 traces per second in real time.

The receiver communicates with the control unit using a 115 kBaud ASCII serial protocol over RS232. The control software will run on any available notebook computer or sealed rugged computer. Because the control unit does not require any specialized hardware, it is possible to use well-supported standard commercial products.

Borehole access

A probe will not feed due to gravity in boreholes shallower than about 30° downwards. For shallower holes, and those drilled upwards, it is necessary to install an anchor at the end of the hole to pull the radar along or up the hole. For holes shorter than about 200 m, a borehole crawler was developed (Berger, 1997). The crawler consists of two sections each containing a pair of spring loaded cams. The two sections are joined by a strong spring. Two ropes connected to the crawler allow it to inch up the borehole in a manner similar to a caterpillar. At the top of the hole, one section of the crawler is removed leaving the other section as an anchor, supporting a rope around a pulley. The rope is used to pull the radar probe along the borehole.

The crawler body is made of plastic, and can easily be drilled through if it blocks the borehole. Beyond about 200 m, stretch in the hoist rope and friction along the borehole make it steadily more difficult to move the crawler. For longer holes, an anchor is usually inserted using the drill rig.

DATA PROCESSING

The borehole radar produces data in its own custom format. After acquisition ends the data is converted to SEGY. It is initially processed using a standard GPR processing flow: DC is removed; the data is band limited; the background trace is removed to remove the direct arrival; and time varying gain is applied. Some image processing has been found to be useful to enhance targets, particularly histogram equalization.

Borehole radar operates in a 3D environment. When using conventional GPR, it is relatively easy to ignore the third dimension, but the omnidirectional nature of a borehole radar antenna is ignored at your peril.

Currently, the processed image is inserted into a 3D visualization environment (Drummond et al., 2001). The screen...
The borehole passes through volcanic rocks and the VCR orebody, and terminates in the footwall quartzites. The rock at the test site is known to be more conductive than in similar geology underground, partly because of contamination by acidic groundwater.

In Figure 6, the result from the Aardwolf BR40 is compared to a result from the same borehole measured with a Malå Ramac 20 MHz antenna. The VCR is clear in both images. The result is not intended to provide a comprehensive comparison, because the acquisition and processing is not identical in the two cases. However, it does show clearly that the 8 bit instantaneous sampling system is capable of producing similar results to those produced by a 16 bit stroboscopic system.

The bandwidth of the system is lower than originally anticipated. This has turned out to be a two edged sword: the resolution is lower than hoped for, but the range is correspondingly increased. The low bandwidth is caused by the bare metal battery packs that form part of the conductive arm of the dipole antenna. The bare metal is electrically lengthened by being immersed in the surrounding medium. The new probes currently being constructed are expected to deliver wider bandwidth.

CONCLUSION AND FURTHER WORK

Instantaneous sampling and stacking downhole is a feasible and effective method of recording borehole radar data in a pulsed radar system. The unique combination of downhole data acquisition and slim probes that can be used in boreholes up to 1000 m long has been achieved using standard, widely available electronic components. Windows-based data acquisition provides a fast, graphical review of data quality. The tool can provide a proven, cost effective solution towards more profitable mining.

At the time of writing, the system has only been tested on surface. Underground tests are scheduled to begin at the end of January 2002. Work is underway to construct probes that will operate at a higher frequency, with a target system bandwidth of 90 MHz. Research on the 3D visualization environment continues, with the aim of allowing potential targets to be manipulated in 3D space, for immediate comparison of the modelled target response with received signals.

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Figure 6: Results from the Aardwolf BR40, compared to those from the Malá RAMAC system 20 MHz antenna.

REFERENCES


