ABSTRACT

Borehole radar is being applied to delineate tabular orebodies in South African gold and platinum mines. The radar is omni-directional in azimuth, leading to an ambiguity in the direction to a reflector. One way of resolving the directional ambiguity is through the use of a priori information. The regional dip and strike of the orebody are known, and can be used as a first approximation for the position of the reflector. A program called Fresco has been developed in which a candidate orebody can be manipulated, and its radar response can be modelled in real time. The model can then be manipulated until the modelled response agrees with the measured response.

The forward modelling approach has three advantages:

• It avoids the need for migration of the radar data. Migration must take into account the curvature of the borehole, which requires an implicit assumption about the direction to various targets.
• Borehole data remains inherently ambiguous in azimuth. The 3D forward modelling environment forces the interpreter to constantly confront the ambiguity.
• The position of the illumination line on the target is produced directly in 3D space.

In this paper the program, its development and use are described.

1. INTRODUCTION

Borehole radar is an application of Ground Penetrating Radar, where the radar antennas are contained within a borehole. It is becoming a routine tool for delineating tabular orebodies in South African gold and platinum mines (Du Pisani and Vogt 2004, Vogt, Van Schoor and Du Pisani, 2005). Low frequency, longer range borehole radars, like the Aardwolf (Vogt, 2002), cannot provide significant azimuthal directionality. A radar with a centre frequency of 40 MHz, operating in typical Witwatersrand quartzite with a relative permittivity of 9, produces a dominant wavelength of 2.5 m. Standard underground exploration boreholes have a diameter of 48 mm, which corresponds to a possible antenna aperture of just 0.02 λ. It is difficult to achieve directivity in such a small aperture.

The required product of interpretation is the 3D location of the reflection line on the target. The azimuthal ambiguity can be dealt with in a number of ways. The simplest interpretation is to assume that all the reflectors lie in section above and below the antenna. This method suffers from similar shortcomings to those encountered when interpreting conventional 2D reflection surveys acquired on surface. If the dominant reflectors are largely coplanar, and the borehole is drilled in the direction of dip, the assumption is valid (Vogt, Trickett and Wedepohl, 1997). As the borehole direction moves towards the strike direction, the illumination line on the reef moves further and further away from the section – its 3D position becomes less and less accurate. If the reflector is not flat, the illumination line also becomes three dimensional, further complicating interpretation.

It is also difficult to migrate borehole radar data, because in general the borehole is not straight. Separate migrations are needed for each azimuthal direction, in order to ensure that reflectors are placed correctly in space, although the resulting positions will still contain azimuthal ambiguity. One approach to interpretation is to identify specific reflectors, and correctly place them in 3D space, including their ambiguity – the kinematic mapping method of Simmat et al (2001). The ambiguous reflector can then be used to interpret the most appropriate location of the target body. Kinematic mapping is particularly useful for resolving the location of ‘blob’ orebodies from several boreholes: the same orebody creates reflectors in all the boreholes, and the intersection of the ambiguous reflections reveals the location of the orebody. For largely planar reflectors, kinematic mapping is less useful, because the ambiguous reflectors are from different parts of the orebody. It is still possible to match a best fit plane to two or more ambiguous reflectors.
2. INTERACTIVE FORWARD MODELLING

No borehole radar data interpretation occurs in a vacuum. The interpreter, usually a geologist, always interprets on the basis of a priori information and often tests evidence against a hypothetical model. For maximum use, a software tool should support the interpreter in the process, and produce the required output of illumination lines in 3D coordinates. The approach suggested here is the use of interactive forward modelling, embodied in a program called Fresco. The Graphical User Interface (GUI) consists of four components: a 3D view of the model space, a cross section or topography window immediately below it, a control panel to its left, and one or more radargram views (Figure 1).

![Figure 1](image)

**Figure 1.** View of the four components of Fresco: the control panel, the 3D view, the topography window and the radargram.

The process of interpretation is straightforward:

- The borehole survey information is placed into the model, in the coordinate system in which output is required. The borehole will then appear in the 3D model space, together with a frame for orientation.
- A radargram associated with the borehole is added to the Fresco environment, and appears in a radargram window. The radargram is simply a bitmap, and has its time and distance information entered manually.
- Fresco allows more than one borehole or radargram to be visible at a time.
- Once the boreholes and radargrams are available, candidate targets can be placed in the modelling space. A target always starts off as a flat plane with specified dip and strike. If a candidate plane would create a reflector on the current radargrams, the modelled reflector becomes superimposed on the radargrams as a line. The position of the target can be altered using the control panel, which also alters the modelled position of the line on the radargram. On the left in Figure 2, the flat candidate target is clear in the 3D view, and a linear reflector is visible on the radargram. Although the target is flat, the reflector on the radargram is curved because the borehole curvature is taken into account.
Once the plane has been manipulated into approximately the correct position, it can have topography added using the cross section controls. In the cross section window, features can be added that alter the topography of the plane in one direction. Small cylindrical features can also be defined that produce hyperbolic reflections in the radargram. The decision to limit topographic changes to 1D, in either the dip or the strike direction, was made to limit the degrees of freedom available to the interpreter. In practice, it does not restrict the interpreter from expressing a particular concept of the model. On the right in Figure 2, topography has been added to the candidate target. The topography only uses straight edges, and leads to a broken and angular reflector on the radargram. In Figure 3, the topography has been fitted to a smooth curve, leading to a smooth reflector on the radargram.

In the model window, the illumination line is visible on the target (Figure 1). This is the portion of the target that contributes to the modelled reflector, and is the only part of the target for which information is available. The three dimensional illumination line coordinates are available for export into other modelling environments.

Modelling is fast, interactive and simple. Fresco is not designed to be a complete interpretation environment; it is simply a tool to place target reflectors correctly in space as quickly as possible, while recognising the ambiguities in the data. Once the target reflectors are exported, they can be used to create models together with other information, including orebody location from drill hole intersection or underground surveying; or estimates of orebody position from other geophysical tools.

### 3. SOFTWARE DEVELOPMENT PROCESS
Fresco, is a study in user interface design rather than numerical computation. It was therefore developed in an environment that facilitated rapid ‘design-code-test’ cycles – an interpreted C tool called UnderC (Donovan 2002). Although C++ is a good flexible language for expressing both numerical and interface problems, it is slow to compile, which hinders rapid development. Rather than using a language like Python, UnderC allows C++ code to be interpreted directly. The execution speed was quite adequate for prototyping the model, and the resulting code could then be directly incorporated into a C++ Builder project and compiled for better deployment and efficiency. A 3D visualization environment was built using VTK, which is an open-source library for scientific data visualization that effectively uses OpenGL (Schroeder, Martin and Lorensen, 2004).

The modelling is simplicity itself: it assumes a constant propagation velocity everywhere in the modelling space, leading to straight ray paths. In a seismic environment, such a model is not a good reflection of reality, because seismic velocity generally increases with depth and pressure. The same is not true of radar, particularly in the relatively short distances involved in typical borehole radar surveys. The modelling assumes a monostatic configuration: transmitter and receiver are co-located in the borehole.

All the target planes are divided into rectangular strips. The borehole is sampled as a series of points at a specified interval. At each point in the borehole, a search is undertaken to determine whether a normal from each strip would pass through the point. If it would, then a reflector is presented on the radargram view at a time corresponding to the distance between the sampling point and the target. When the topography is not smoothed (Figure 2b), the strips match the topography geometry. When the topography is smoothed (Figure 3), the smoothed surface is approximated as a large number of narrow strips. As each strip is considered separately, the reflector can appear as a discontinuous line. There is no interpolation between line segments because the output is more than adequate for processing.

4. **RESULTS**

More than one model can satisfy any measurement that contains ambiguity. Fresco forces the interpreter to deal with the ambiguity by making it explicit in the 3D model. It is immediately apparent that many candidate targets could produce the measured reflectors – the correct choice of target position has to be made using other information and, even then, it can be wrong.

The 3D environment makes it simple to visualize the spatial relationship of potential targets. For example, it is easy to see how predominantly horizontal reef targets interact with a predominantly vertical dyke target (Figure 4). When information from more than borehole is combined, it is also straightforward to see how features such as faults and dykes correlate from borehole to borehole, which leads to an improved geological model (Du Pisani and Vogt, 2004). The 3D environment does not allow for the importing of other data, including mine plan or survey peg data. However, integration with other kinds of data is easily achieved within other visualization or modelling environments once the illumination lines have been exported.

Fresco has been in use at CSIR for two years, and has become an important part of the interpretation data flow for borehole radar data.

5. **CONCLUSIONS AND RECOMMENDATIONS**

An interactive fast forward modelling tool has been developed for interpreting azimuthally ambiguous borehole radar data. The development process was guided by the need for visualization, interactivity and a productive user interface. Interactive forward modelling has a number of advantages over other techniques:

- It can directly produce the position of the illumination line in 3D coordinates.
- It avoids the need for migration of the radar data. Migration must take into account the curvature of the borehole, which requires an implicit assumption about the direction to various targets.
- Borehole radar data remains inherently ambiguous in azimuth. The 3D forward modelling environment forces the interpreter to constantly confront the ambiguity.

If kinematic visualization were added it would further assist the interpreter, particularly for situations where the target position is not as clearly defined as it is for tabular orebodies. Fresco could also be extended through further target manipulations, including 2D manipulation of the target surface.

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REFERENCES


