GROUND PENETRATING RADAR

Stephen Griffin[1] and Timothy Pippett[2]

[1] Geophysical Technology Limited. 15 Jedda Street, Tallebudgera, QLD 4228. E-mail: stevegriffin@geotec.com.au

[2] Alpha Geoscience Pty. Limited. Suite 7, 852 Princes Highway, Sutherland, NSW 2232. E-mail: tpippett@alpha-geo.com

1. INTRODUCTION

Ground penetrating radar (GPR) also known as ground probing radar, impulse radar or subsurface interface radar, is a geophysical method used for high resolution imaging of shallow subsurface features. It is similar to air-directed radar in that it transmits a burst of electromagnetic energy and then waits for reflections from targets to be received before repeating the process continuously. However, it differs significantly from that better known form by transmitting the energy instantaneously over a wide frequency range, utilising a very short transmission pulse and a broadband antenna design. The usual operating frequency varies between about 25 MHz and 1000 MHz (covering the VHF/UHF bands).

The energy is transmitted into the ground using antennas that are in direct contact with the surface, and as this energy propagates to greater depths, a series of reflections are directed back to the surface where they are detected by the receiving antenna. The method is only suitable for shallow investigation (up to tens of metres in the best conditions) because the ground absorbs the energy at a rapid rate, and as it propagates to greater depths. Eventually there is insufficient energy to generate a reflection from a deep target that can be redirected back to the surface and detected by the receiver.

Although the GPR method has been widely applied to a range of applications in Australia, there are only a limited number of applications where it can be regarded as having been successful, compared to the extent in which it is used in say Europe and the USA,. The main reason for this is the occurrence of soils that are generally more conductive than those in other countries. Despite this fact, there are at least four groups in Australia who have designed and built world class systems for specialised applications. All of the commercially available systems are well represented by a sales agents and consultants, and the number of practitioners has risen greatly in the twenty years since it was first introduced here.

2. DESCRIPTION

The GPR method provides a high-resolution image of subsurface features in the form of a cross-section view that is essentially a map of the variation in ground electrical properties. These can be correlated with physical changes such the soil/bedrock interface, the boundary between different soil types, the water table, underground structures such as pipes, cables and tunnels as well as voids and cavities. Features in the GPR section will correlate with geological cross-sections if for instance stratigraphic boundaries representing different rock types correspond to significant variations in the electrical properties, but not necessarily to other physical properties such as density, grain size or chemical composition.

The short pulses of RF energy are radiated into the ground from a transmitting antenna placed either on the ground surface or in close proximity. Energy reflected back to the surface from subsurface targets is detected by the receiving antenna, also located in close proximity to the surface. The antennas physical size or dimension limits the frequency (or wavelength) of the transmitted pulse. A high frequency waveform (short wavelength) will provide a more detailed or higher resolution image than a low frequency waveform, but the higher frequencies are attenuated or absorbed at a greater rate

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so the penetration depth is not as great as lower frequencies. For any specific application, the appropriate choice of antenna frequency involves a compromise between resolution (or size of objects/features to be detected) and the depth of interest.

The transmission is characterised as a single burst of energy after which the receiver then 'listens' and records any reflected energy such that the recording time (from the point of transmission) represents the depth to the source of the reflection. That is, a reflection from a deeper target will appear later in time in the GPR section since the energy has travelled further than for the shallower targets. At any instance, the receiver is only on for a finite period of time (of the order of several hundred nanoseconds) after which another pulse is transmitted to repeat the process. The GPR section is actually a time section, however with knowledge of the propagation velocity, time is converted to depth.

The two most important soil and rock electrical properties are the dielectric constant and conductivity. Both are greatly influenced by water (eg. soil moisture content) therefore water has a significant influence on GPR performance overall. Soil conductivity limits the maximum depth of energy penetration (or target detection depth) since it influences the rate at which the energy is absorbed. A more conductive soil (one that is wetter and/or has a higher clay content) will absorb the energy at a far greater rate than a low conductivity soil such as dry sand. The penetration depth in dry clay soils will typically be in the range of one or two metres and a wet clay will reduce penetration to less than one metre, whereas dry sandy soils will allow penetration to more than 10 metres. Rock types with low conductivity (high resistivity) include limestone, coal, granite and other crystalline rock, whereas rock types that are more conductive include basalt, shales and mudstones or any weathered terrain with reasonably high porosity.

The RF energy propagates through the ground at about one-third the speed of light or 10 $cm.ns^{-1}$ (the units are chosen for convenience only, and some people may prefer to express this velocity as 0.1 $m.ns^{-1}$). The velocity of propagation will vary for different earth materials, but will generally be within the range $8 \rightarrow 12$ $cm.ns^{-1}$ and is determined by the relative dielectric constant (expressed as a quantity relative to the value of air). All materials of interest will vary between the range 1 (for air) and 81 (water). Geologic materials will generally fall within the range 5 - 15.

A reflection will occur in response to changes in the dielectric constant, and this may not necessarily correlate with properties such as density, which most people intuitively understand from their experience with seismic methods. However, the dielectric constant or electrical permittivity is analogous to the acoustic impedance in seismics, in a mathematical sense. That is, as well as determining velocity, the change or contrast in the dielectric constant with different earth materials will cause a reflection whose strength (or amplitude) is dependent on the magnitude of that contrast.

To summarise the importance of water in understanding GPR performance, a higher moisture content in the soil will reduce the possible depth of penetration, but may provide for a stronger reflection (since the presence of water will increase the dielectric constant significantly. This will therefore also cause the velocity of propagation to be higher, which in itself will influence resolution through its relationship with frequency and wavelength.

3. FIELD PROCEDURES

Most GPR antennas are able to be easily man-handled, and the usual method of operation is to drag the antennas slowly across the ground surface in a straight line traverse, transmitting and receiving continuously, so that a profile picture builds up (referred to as a GPR section). This represents the accumulation of reflections that have been received. The series of single waveforms combine together to give the effect of mapping layers and objects in the ground. The receiving antenna and circuitry records for a finite period of time, so that the derived time record or waveform has an early time period corresponding to reflections from shallow targets and later time corresponding to deeper targets, with amplitude representing the strength of the reflection. For this reason the GPR sections can be thought of as a depth section or profile view of the subsurface conditions below the traverse line.

Generally, operation of a commercial GPR system requires two operators, one to drag the antennas along the ground, the other to control the instrument operations from a console which is often simply a laptop personal computer and another electronic module connected to the antennas by cable or optic fibre. Many commercial operators may use vehicles such as 4WD's or 4-wheeled motorbikes to assist with both instrument carriage and antenna mobility.

Instrument configuration and survey design is determined by the survey objectives and physical factors such as the terrain and site layout - especially the roughness of the ground surface and the presence of obstructions such as water courses, trees, gullies, rocks or man-made structures.

Distance control along a traverse line can be provided by a range of means that include odometers attached to wheels or cotton on a spool tied off at the starting point, fiducial marking (manually inserting a mark into the data say with an electronic push-button, corresponding to known points along the traverse), and differential GPS.

To a great extent, the appropriate field procedures are determined by the actual system being used, and while the commercial systems have certain similarities, there are some that are better suited to particular applications than others. For example, to gain data quality improvements using the low frequency antenna it is recommended that the antenna should be manhandled to each measurement point and kept stationary for the duration of the recording time in order to obtain the best possible result. They can be used by continuous dragging across the ground, either by man or vehicle, however the data quality will be reduced. Such as system might be more time consuming but the tradeoff is the best possible result.

The survey objective has a significant impact on instrument configuration as well as field layout by determining in the first instance the appropriate antenna frequency. Other factor such as the target size determine line spacing and number of samples required along the traverse line in order to satisfy basic spatial sampling criteria, according to such factors as target depth, antenna frequency, reflector geometry and instrument measurement parameters (pulse characteristics and high frequency signal sampling).

4. INSTRUMENT TYPES AND CONFIGURATIONS

The following is a list of commercially available systems in Australia, with a brief summary of the key similarities and differences, and how this relates to certain limitations.

1. Geophysical Survey Systems, Inc. of Burlington, New Hampshire, GPR system includes the SIR2000, SIR10 systems. These systems have a range of in-house and third party antennas ranging in frequency from 40 to 1500 MHz and all being shielded antennas.

2. Mala Geosciences Inc. of Mala, Sweden, have the RAMAC/GPR system. The RAMAC system has a full range of antennas from 25 to 1,000 MHz including borehole probes, either 100 or 250 MHz. The RAMAC system console controls both the unshielded and shielded antennas and the borehole probe with a PC Notebook computer as the acquisition, display and storage device. The Mala range of antennas include 25, 50, 100 and 200 MHz unshielded and 100, 250, 500, 800 and 1,000 MHz shielded.

3. Sensors and Software, Inc. of Toronto, Canada, includes the pulseEKKO100 and pulseEKKO1000 systems and the Nogun systems. The pulseEKKO100 system is designed for low frequency systems using unshielded antenna and the pulseEKKO1000 system is for the higher frequency applications using shielded antennas from 200 MHz to 900 MHz. The Nogun systems are a single

frequency unit with either 250 or 500 MHz. Both pusleEKKO and the Nogun systems use a PC Notebook computer as the acquisition, display and storage device.

5. DATA PROCESSING

One of the great advantages of the GPR method is the fact that the raw data is acquired in a manner that allows it to be easily viewed in real time using a computer screen. Often very little processing is required for an initial interpretation of the data, with most of the effort directed towards data visualisation. On the other hand, depending on the application and target of interest, it may be necessary to perform sophisticated data processing, and many practitioners find that the techniques common to seismic reflection such as deconvolution and migration can be successfully applied.

As stated earlier, the basic form of the data is a profile or section view of subsurface features beneath a straight-line traverse, with the vertical dimension being two-way travel time (usually expressed in nanoseconds) just like seismic sections. However, because most people are interested in converting this to a depth section, it is necessary to have some knowledge of the propagation velocity through the soil and rock in order to rescale the data appropriately. Depending on the required accuracy, this can be as simple as applying a nominal velocity based on textbook data and some knowledge of the likely soil/rock type and moisture content. Alternatively it can involve simple data processing using seismic processing techniques such as common mid-point and velocity analysis of a normal moveout section. Calibration through direct measurement of the depth to certain recognisable features using either drilling or trenching is also commonly applied.

6. DATA INTERPRETATION

GPR sections can be presented as greyscale or colour images that use the different shades of grey or colours to represent the variation in the signal amplitude. The examples shown in the Applications Section illustrate some of the various displays available to the interpreter.

Although it is generally assumed that at any instance the recorded waveform is composed of reflections from targets located directly below the antenna, the image is often complicated by the fact that the waveform spreads out on a spherical wavefront, so that strong reflectors off to the side will be superimposed over other weaker reflections from another location. Another complication will occur when reflections from above ground sources may be superimposed on the below ground reflectors.

7. APPLICATIONS

Figures 1-5 illustrate some of the various applications that the GPR technique can be used for.

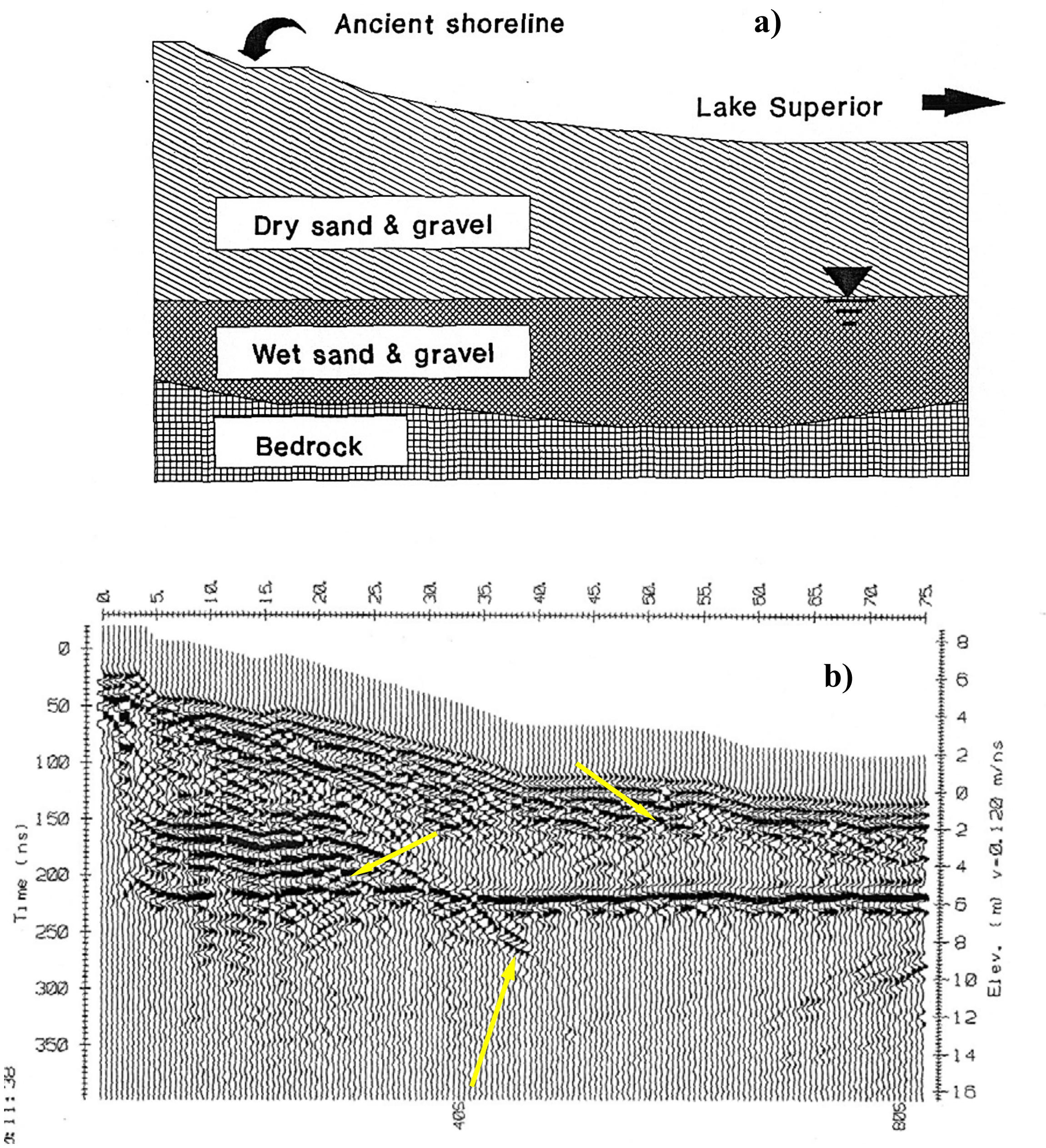


Figure 1 a and b. An application of using the GPR technique to map the groundwater surface and the sand / gravel-bedrock interface (Scaife and Annan, 1991).

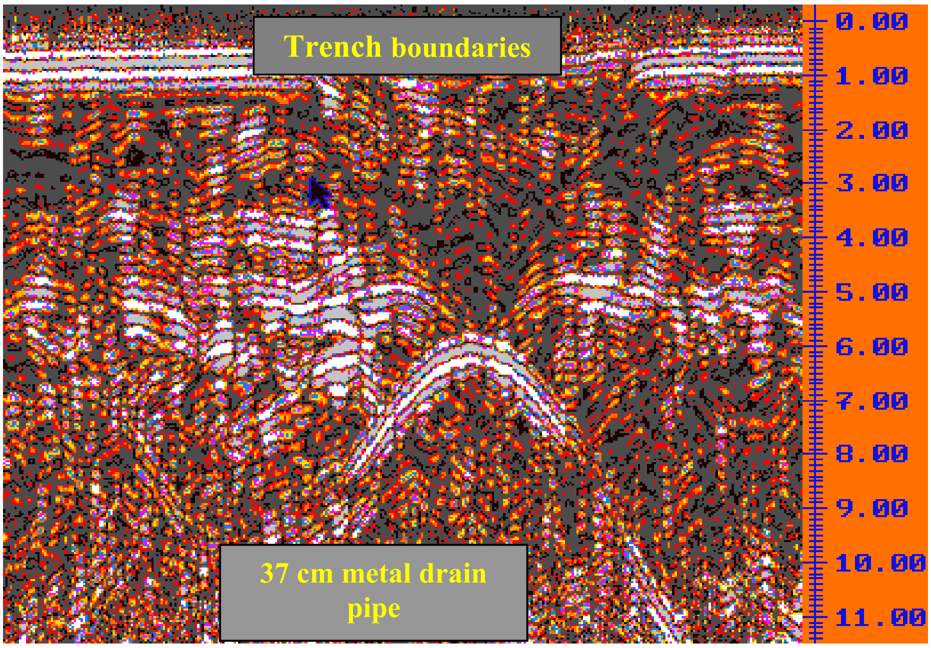


Figure 2. This section illustrates the use of GPR for the location of underground services and in this case a pipe buried at approximately 2 metres (Courtesy of Mala Geoscience).

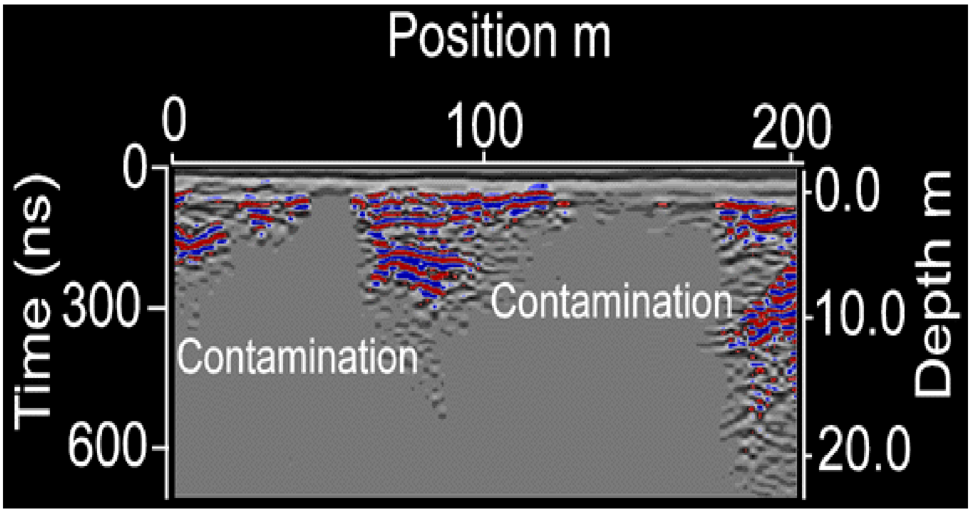
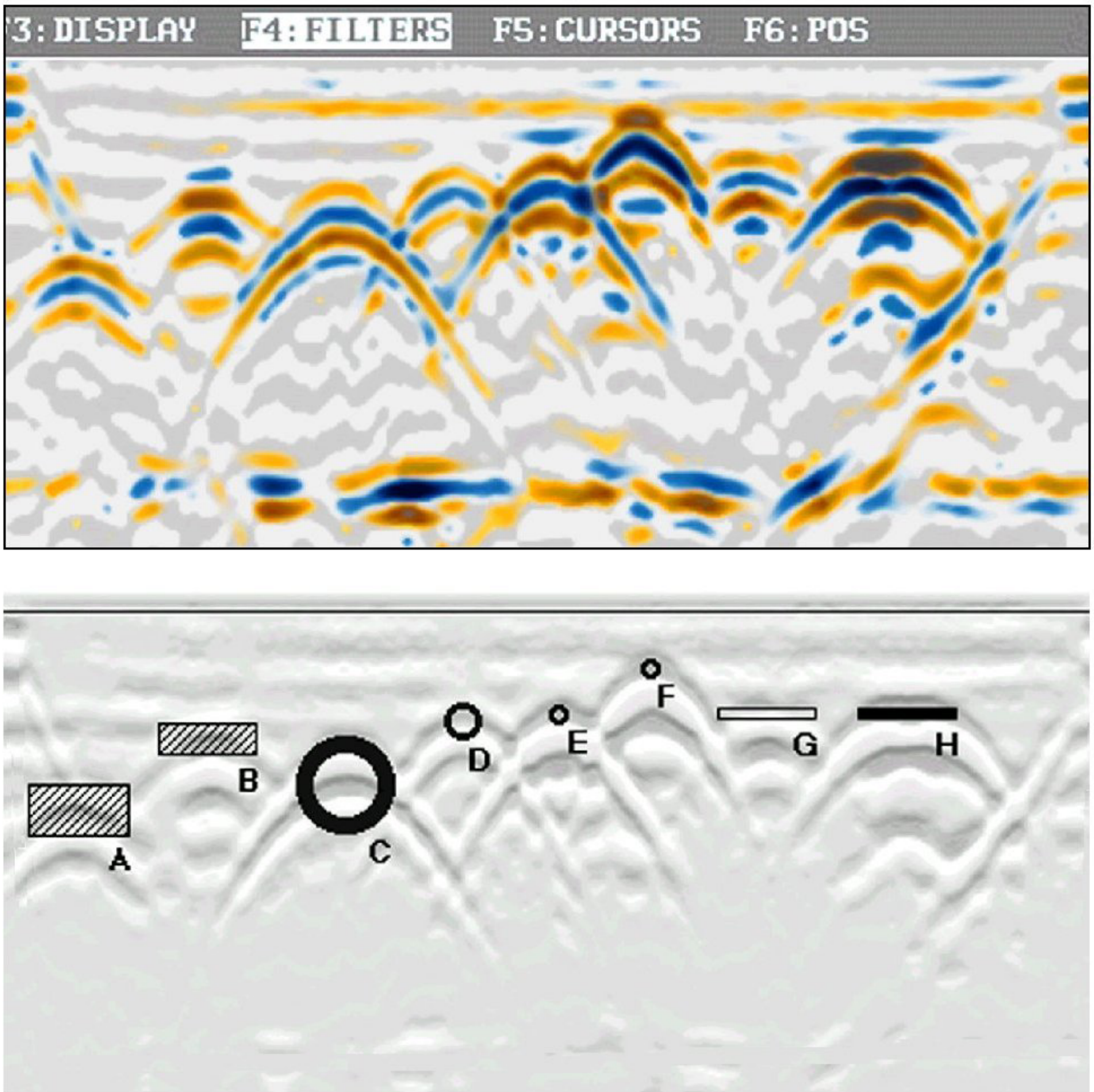


Figure 3. Radar section across an area that has two plumes of contaminated groundwater present. Note the lack of GPR signal penetration due to the contamination having a much higher conductivity than the surrounding ground (Davis and Annan, 1989).



A) Polystyrene disc ø60 cm, H: 30 cm, Appr. depth: 100 cm (top)
B) Polystyrene disc ø60 cm, H: 15 cm, depth: 60 cm (top)
C) Concrete tube ø60 cm, Appr. depth: 100 cm (center)
D) PVC tube ø20 cm, Appr. depth: 60 cm (center)
E) Iron tube ø6.35 cm, Appr. depth: 60 cm (center)
F) Iron tube ø6.35 cm, Appr. depth: 30 cm (center)
G) Wood disc ø60 cm, H: 4 cm, Appr. depth: 60 cm (top)
H) Iron disc ø60 cm, H: 4 cm, Appr. depth: 60 cm (top)

Figure 4. This illustrates the versatility of the GPR system to locate various different items made of different material at various depths (Courtesy of Mala Geoscience).

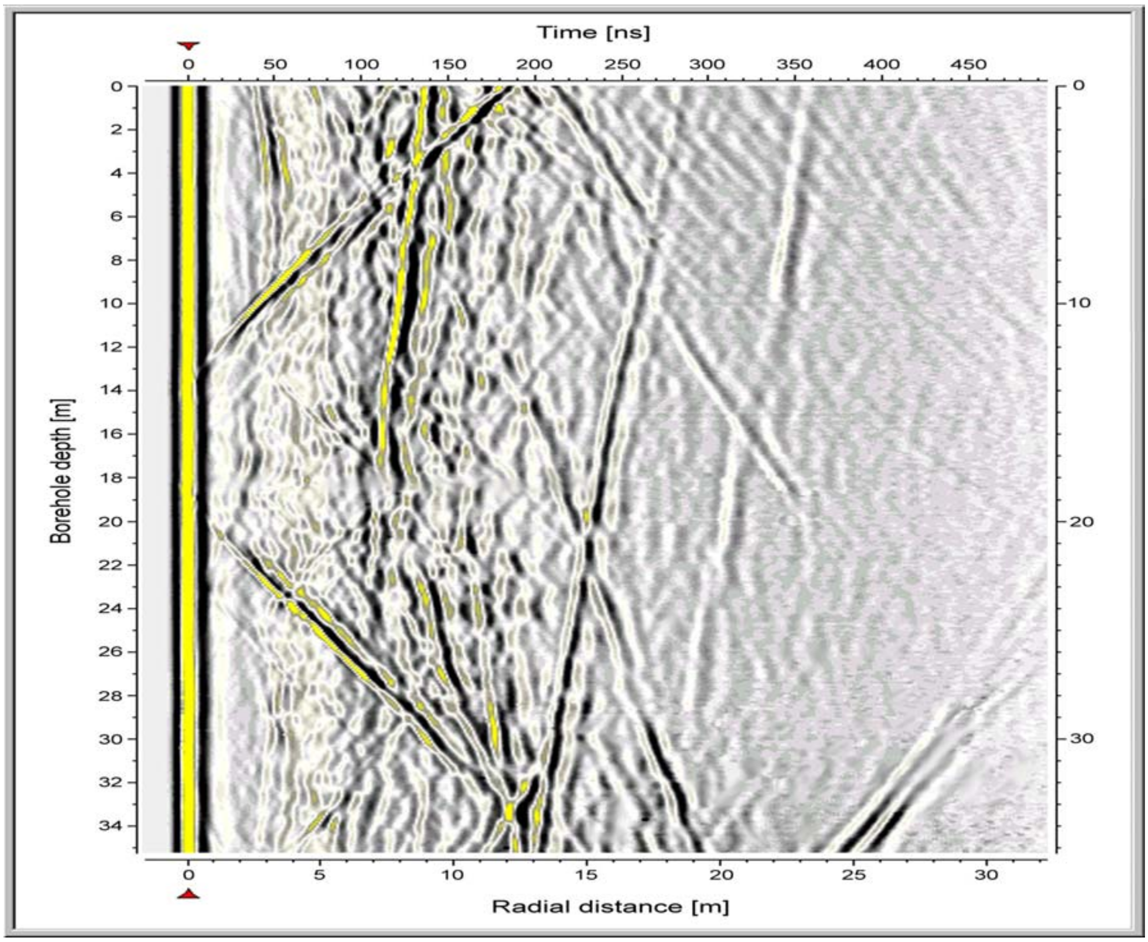


Figure 5. An example of a borehole radar section obtained with a Mala Geoscience borehole probe. Note that the probe is omni-directional and the reflector coming in at approximately 45° is the same one that is going out at 45° but the other side of the borehole (Courtesy of Mala Geoscience).

8. LIMITATIONS AND PROBLEMS

There are a number of limitations and problems for the GPR technique. These include:

1. Ground conductivity – which will limit the overall depth of penetration and thus the usefulness of the technique;

2. Time consuming;

3. Large quantity of data is accumulated - makes processing and interpretation task difficult without the right software tools;

4. Competing with intrusive methods, ie. backhoe, and thus the technique needs to produce results on the spot and at an economic price;

5. Suitability of instrument available for particular applications, different units are more suitable for particular applications and ground conditions than others;

6. Need to dig holes to 'have a look' in order to get best possible calibration or correlation; and,

7. Frequency dependent dispersion - spreading of pulse to reduce resolution - because different portions of the energy will slow down, increasing the wavelength.

9. SURVEY ORGANISATIONS

Groups who manufacture GPR systems in Australia for specialised applications include Monash University, Queensland University (CSSIP), CSIRO and Sydney University.

The following is a list of agents for the commercially available systems in Australia and New Zealand:

- **GSSI Systems**

  Detection Solutions
  P.O. Box 38-061
  Howick, Auckland. New Zealand.
  Tel: 0-9-576-8000
  Fax: 0-9-576-4641
  Mobile: 025-327 292
  Contact: Mr. Steve Simmons
  E-mail: detectso@ihug.co.nz

  Geophysics Australia
  3061 Great North Road
  New Lynn, Auckland, New Zealand.
  Contact: Mr. Grant Roberts
  Tel: 64-9-826-0700
  Fax: 64-9-826-0900
  E-mail: g.roberts@geophysical.com.au
  Website: www.geophysical.com.au

- **Mala Geoscience**

  Alpha Geoscience Pty. Limited
  Suite 7, 852 Princes Highway
  Sutherland, NSW. 2232. Australia.
  Tel: 61-2-9542-5266
  Fax: 61-2-9542-5263
  Mobile: 61-412-663-541
  Contact: Mr. Timothy Pippett
  E-mail: sales@alpha-geo.com
  Website: www.alpha-geo.com

- **Sensors and Software**

  Fugro Instruments
  21 Mellor Street
  Sydney, NSW. 2114. Australia.
  Tel: 61-2-8878-9000
  Fax: 61-2-8878-9012
  Contact: Mr. Simon Stewart
  E-mail: sales@fugroinstruments.com
  Website: www.fugroinstruments.com

10. COSTS

The cost of the various systems depends very much on the antennas selected, the range of investigations required, and the processing software required. The pricing of the systems will also depend on the country of manufacture as the prices have been affected by the exchange rate, ie. the $US has been more affected than the Euro.

To gain up to date pricing, it is recommended that an approach be made to the manufactured representative in Australia or New Zealand.

1. The cost to rent the radar systems will again depend on the configuration selected but would be in the vicinity of $ 350 to $ 500 per day or $ 1,750 to $ 2,500 per week.

2. A professional consultant to run the radar system or train operators on the use of the system would be in the vicinity of $ 500 to $ 750 per day (depending on experience).

REFERENCES

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Davis, J.L. and Annan, A.P., 1989. Ground penetrating radar for high-resolution mapping of soil and rock stratigraphy. Geophysical prospecting 37: 531-551.

Scaife, J.E. and Annan, A.P., 1991. Ground penetrating radar - a powerful, high resolution tool for mining, engineering and environmental problems. In: 93rd CIM Annual general meeting, Vancouver, British Columbia, April 1991, 6 pp.