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Machinations:
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J. L. Davis and A. P. Annan

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See table of contents

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Article abstract

Ground-probing radar is a high-resolution sounding technique that can map bedrock topography and soil strata. High-resolution sub-surface mapping is frequently required by geologists, geotechnical engineers and hydrogeologists for defining buried bedrock topography and soil stratigraphy.

Current ground-probing radar systems can sound to 20 m depth in resistive geological materials. New sounders such as the EKKOII electromagnetic profiler developed by Á-Cubed Inc. are more than doubling this depth. The principles of the radar method and three field examples are presented to show the potential of radar soundings and the versatility of the method. As with any geophysical technique, the radar soundings are most effective when used in conjunction with other techniques especially borehole logging.

Machinations

High-Resolution Sounding Using Ground-Probing Radar

J.L. Davis and A.P. Annan
A-Cubed Inc.
5566 Tomken Road
Mississauga, Ontario L4W 1P4

Summary
Ground-probing radar is a high-resolution sounding technique that can map bedrock topography and soil strata. High-resolution sub-surface mapping is frequently required by geologists, geotechnical engineers and hydrogeologists for defining buried bedrock topography and soil stratigraphy.

Current ground-probing radar systems can sound to 20 m depth in resistive geological materials. New sounders such as the EKKO II electromagnetic profiler developed by A-Cubed Inc. are more than doubling this depth. The principles of the radar method and three field examples are presented to show the potential of radar soundings and the versatility of the method. As with any geophysical technique, the radar soundings are most effective when used in conjunction with other techniques especially borehole logging.

Introduction
Over the past 10 to 15 years, ground-probing radar (GPR) has been used for many practical applications where high-resolution soundings in the ground are required. Geotechnical engineers, geologists and hydrologists use GPR to map bedrock, soil strata and the water table in coarse-grained soils.

In areas of overburden cover, the bedrock topography is often the major factor which has controlled overburden deposition. Good bedrock surface soundings can be used to design geochemical surveys; in particular basal till sampling programs. Stratigraphic mapping is of significant interest in the exploration of placer deposits. Mapping of coal and peat deposits and outlining sand and gravel reserves is practical using the radar. Hydrogeologists require detailed maps of soil stratigraphy to help determine the ground-water flow path especially in areas of hazardous waste impoundments.

Geotechnical site evaluations also require high-resolution subsurface mapping. The economic viability of many mineral deposits is controlled by the cost of mine development. Open-pit mining, rock quarries and tunnel development are dependent on a good knowledge of the overburden thickness and the competency of the rock. Radar has been demonstrated to be a valuable tool for these applications.

Radar has very high resolution and often can resolve features that are only a few centimetres thick with depth accuracies of a few tens of centimetres. Existing radars can sound to depths of 5 to 20 metres in low conductivity (about 1 $mS \cdot m^{-1}$) materials such as sand, gravel, rock and water. The range decreases to a few metres in conductive soils such as clays, silts or soils with saline or contaminated pore water. The EKKO II profiler, recently developed by A-Cubed Inc., has doubled the depth range with little or no reduction in resolution. The EKKO II profiler makes the sounding technique more economical and practical than the earlier radar systems.

Principles and Methods
The ground-probing radar is very similar in principle to reflection seismic and sonar techniques. The radar produces a short pulse of high frequency (10 to 1000 MHz) electromagnetic energy which is transmitted into the ground. The propagation of the radar signal depends upon the high frequency electrical properties of the ground which are primarily controlled by the water content of the soil. Variations in soil grain size are usually associated with changes in volumetric water content which in turn give rise to radar reflections.

Figure 1 conceptually illustrates the radar being used in the reflection profiling mode on soil over bedrock. Figure 2 shows the resulting radar record obtained when used in the idealized situation shown in Figure 1. Part of the radar signal is reflected whenever it encounters a change in electrical properties. The reflected signal is detected by the radar receiver where the signal is amplified and formatted for display and recording on a magnetic cassette tape recorder. The EKKO II profiler receiver digitizes the incoming signals and uses digital signal averaging to improve the signal-to-noise ratio. The data is stored on a digital magnetic cassette tape recorder and it can be displayed using a thermal plotter in the field. Further signal processing can be carried out in the camp or the hotel using a desktop micro-computer. The EKKO II profiler is portable and runs on 12V batteries. The antenna length and spacing between the antennae depend on the depth to the interface that is to be mapped and the resolution required.

The basic principles of the radar method are given in Morey (1974), Annan and Davis (1976), Ulriksen (1982), Benson *et al.* (1984), and Davis and Annan (1985). The radar system transmits and receives signals many thousands of times per second and physical contact with the ground is not necessary. As a result, radar survey data can be collected very rapidly. In rough, forested terrain up to 4 line kilometres can be surveyed in a day with stations at 5 m intervals. Greater distances can be covered in flat, open country.

The radar can be used on the ground surface, in tunnels, and boreholes, in the reflection-profiling mode or in the wide-angle reflection and refraction (WARR) sounding mode. The WARR sounding mode is the electromagnetic equivalent of seismic refraction. WARR soundings give an independent estimate of the radar signal velocity *versus* depth in the ground. Davis *et al.* (1984), Annan and Davis (in press), and Coon *et al.* (1981) discuss applying the radar in a wide range of environments.

Field Examples
Three field examples are offered in summary form to show how the radar can be used to obtain detailed information about the bedrock topography and soil strata in the overburden, and changes in rock from inside a mine tunnel.

Heart Lake. Figure 3 shows the EKKO II profiler data output obtained at Heart Lake located about 35 km northwest of Toronto, Ontario. Figure 4 shows the geologic section along the same section. Environment Canada personnel have regularly monitored the water quality in this lake for many years. The water had a conductivity of 25 $mS \cdot m^{-1}$. The lake has a maximum depth of 12 m and the bottom of the lake is covered by 0.5 m of unconsolidated organic soil over a fine-grained till.

The radar record in Figure 3 shows the reflection from the lake bottom even at 11 m depth. There are also a number of reflections to a depth of 20 m from within the till below the lake. Most lakes in rural areas have conductivities of less than 10 $mS \cdot m^{-1}$ and thus the depth range of the EKKO II profiler will be increased by a factor of between 2 and 5 depending on the water conductivity.

This example demonstrates that the radar can be used to obtain a high-resolution profile in water and soil strata in wet geologic materials.

Pit road. Figure 5 shows an unprocessed field radar record obtained with the antennae being towed behind a van. About 5 minutes were required to traverse the 300 m along the road. Each scan is obtained in a tenth of a second and thus the record is essentially continuous since a scan was obtained every 60 mm. The detail of the bedrock surface is very impressive and useful for locating boreholes in the best location for different applications.

Hydrogeologists have been studying the ground-water flow in this area for many years, and they require extensive knowledge of the bedrock topography and soil strata for their hydrologic model in order to predict the flow of contaminants in the ground water. The radar record shows that the bedrock varies from 15 and 25 m in depth with the deepest point to bedrock being at the 150 m position on the horizontal axis. The water table is located at a depth of 3 m. The reflections from within the fine sand unit are from thin silt and clay beds. The banding shown on the record is typical of that found in fluvial and aeolian sands in the area.

The radar data agrees very well with nearby borehole data. The radar offers an economic method of extending the effective horizontal extent of the borehole logs which is especially important to geotechnical engineers, geologists and hydrogeologists. The radar data can also be used to help place boreholes in the most effective locations.

Potash mine. Figure 6 shows a radar data output obtained in a potash mine located in Saskatchewan. Figure 7 shows the geologic section along the same section. The mine engineers require a method of determining the distance to the shales above the salt so as to be able to remove as much potash as is safe. They also require a method that can detect anhydride beds, solution collapse features and water in the salt. The radar has the potential to detect these.

The radar record in Figure 6 shows two hyperbolic-shaped reflections from tunnels located 15 m below the tunnel where the radar was located. Additional radar responses in the potash mine environment are given in Annan *et al.* (in press).

High-resolution sounding like this allows the mine engineers to plan ahead of the actual mining operations and to insure that the material around the tunnels is safe. The EKKO II profiler with its increased range will permit reliable soundings of 20 to 30 m and thus a reliable map of the shale beds over the salt should be possible.

Conclusions

The field examples demonstrate that ground-probing radar is a practical method for obtaining high-resolution soundings to a depth of 20 m in some geologic materials. The radar is best used with borehole information where it offers an economic method of extending the effective horizontal extent of the boreholes. The radar can also be used to plan a program for locating boreholes effectively. Further improvements are continually increasing the system performance of the EKKO II profiler and the new EKKO III profiler which incorporates the best characteristics of the existing radars. The EKKO III profiler should culminate in a routine penetration depth of at least 30 m in most geologic materials. With this performance, the radar can be used for many mining, geotechnical and hydrological applications that were previously either unsolvable or required survey techniques too expensive to be practical.

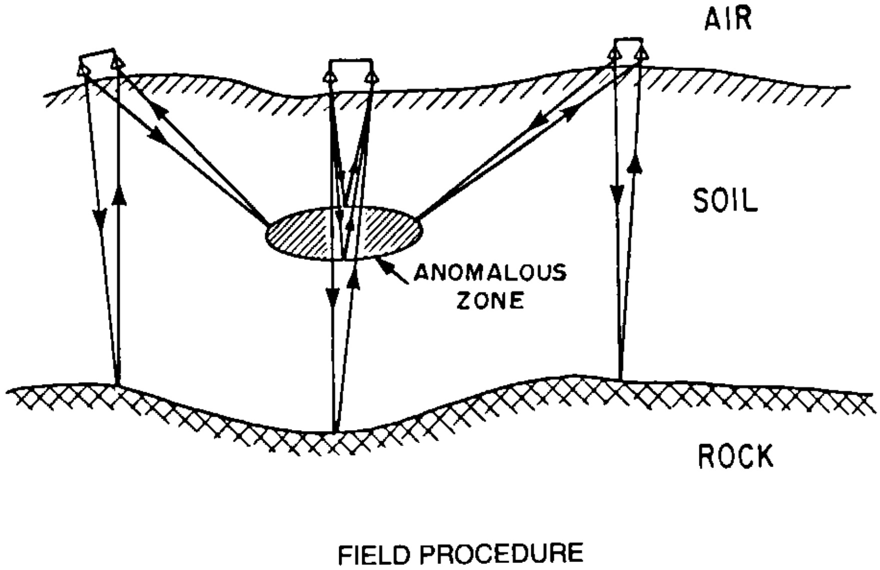

Figure 1 *A conceptual view of the radar being used in the profile mode on soil over bedrock.*

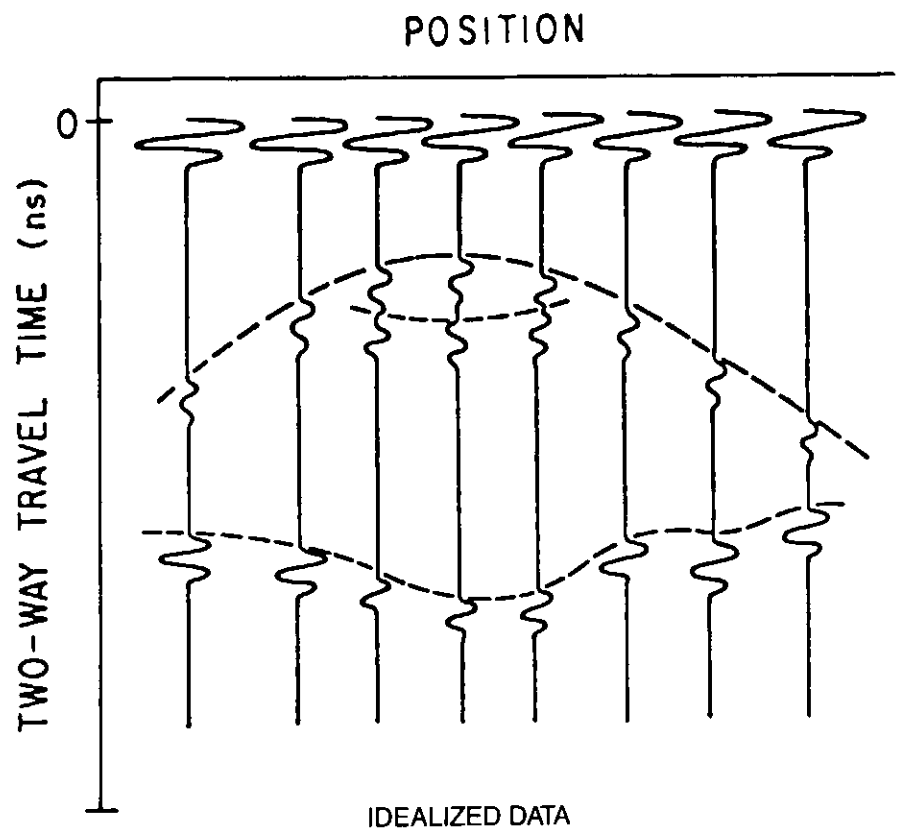

Figure 2 *The resulting radar record obtained from the idealized situation shown in Figure 1.*

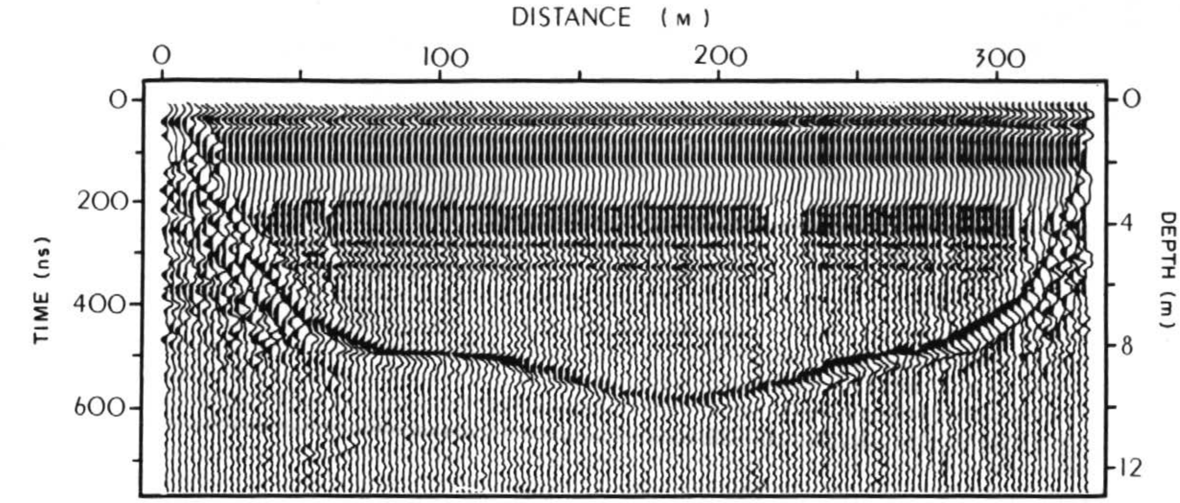

Figure 3 *The EKKO II profiler record showing the bottom of the lake to a depth of 10 m.*

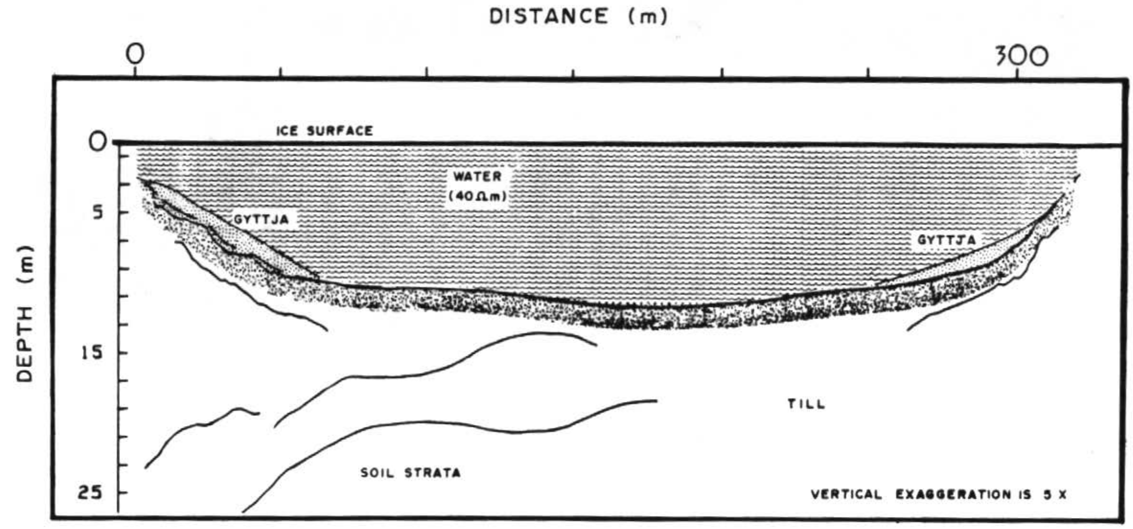

Figure 4 *The geologic section along the same line shown in Figure 3. Reflections from the soil strata under the lake are also shown.*

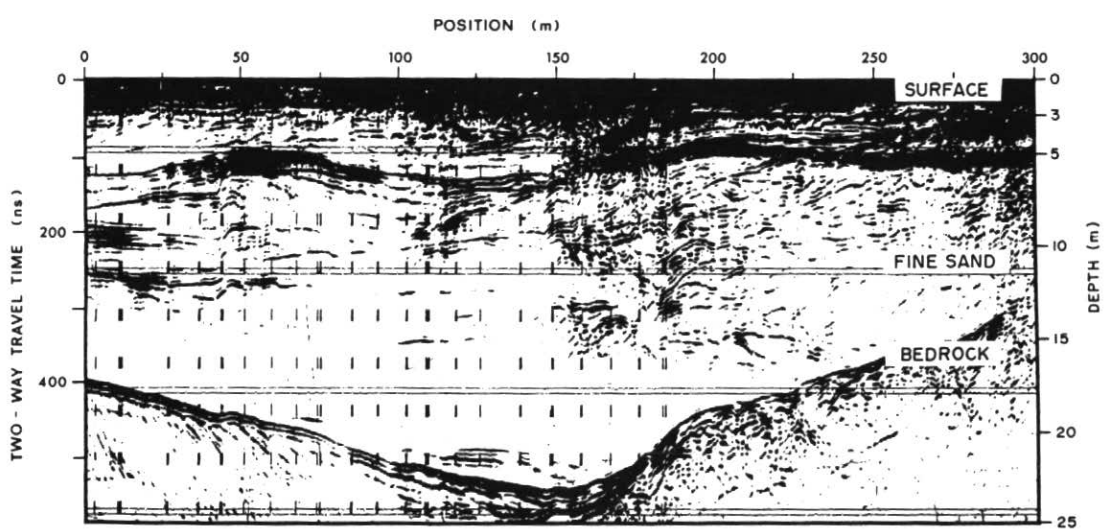

Figure 5 *An unprocessed field record showing bedrock under 15 to 25 m of fine-grained sand. The reflection from the water table is at a depth of about 5 m.*

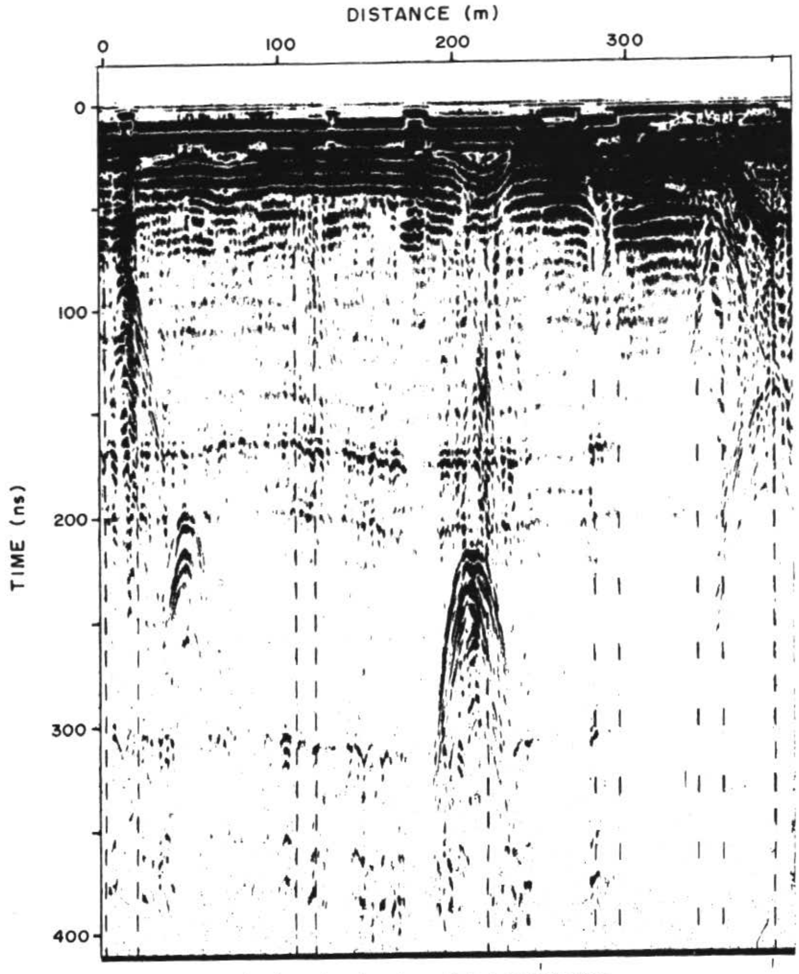

Figure 6 *A radar record showing reflections from two tunnels in a potash mine.*

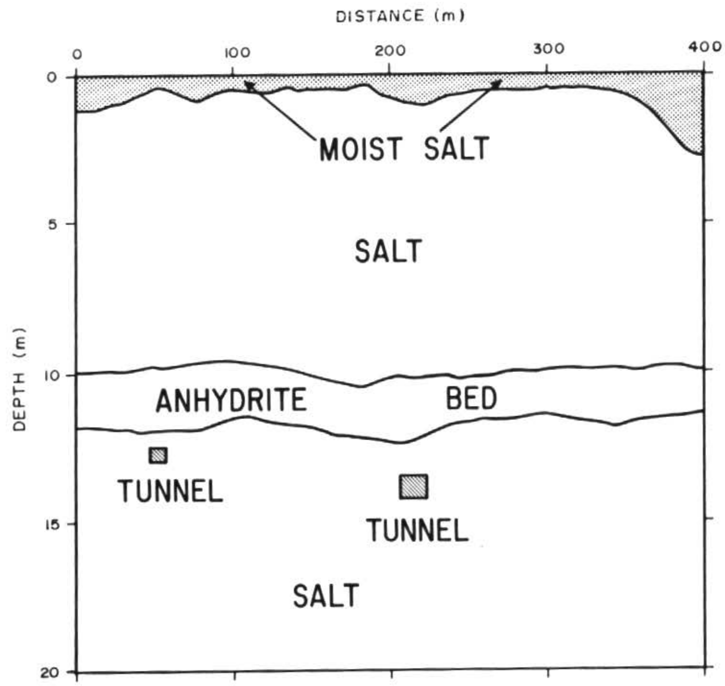

Figure 7 *The geologic section along the same line shown in Figure 6.*

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