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Advancements in Ground Penetrating Radar Technology for Mineral Exploration

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Summary

Although GPR has been applied to mineral exploration for over half a century, the technique is limited to specific use cases in ideal conditions due to its limited penetration compared to other geophysical methods. GPR penetration is a function of equipment design, antenna frequency and most critically, the subsurface electrical properties. Dry and electrically resistive environments allow the deepest radar penetration, which is generally limited to the upper 10 – 20 m.

Increasing penetration of GPR would expand its applications in mineral exploration. Increasing transmitter peak power does not yield substantial improvements in penetration, and beside being illegal in North America and Europe, can be highly dangerous. Rather, penetration can be significantly improved through increasing the SNR of the recorded reflections, as well as using complex transmitter waveforms.

Longer wavelengths can also improve penetration, albeit using unwieldy antenna lengths and with lower resolution results. Magnetic antennas, which can reduce antenna size ten- or twentyfold can be used in place of traditional electrical dipoles to crease highly mobile low-frequency GPRs capable of penetrating 100+ m in suitable ground. The size of these antennas is sufficiently small to be mounted on a medium drone. This further expands the applications for deep penetration over difficult or vegetated terrain.

Introduction

Ground penetrating radar (GPR) has a long history of applications in mineral exploration. With the release of the first commercial GPR systems in the 1960s, experiments were being made on coal seam thickness, hanging wall parting planes and from within boreholes to detect voids and ore bodies (Cook, 1971). Previous to these studies, academic research in radioglaciology had successfully profiled deep glaciers and ice caps in Greenland and Antarctica to depths of hundreds of meters.

These early radar systems were entirely analogue and had limited data storage capabilities with minimal signal to noise ratios. Nevertheless, success was found with radar penetration through some types of coal, carbonates and other electrically resistive rock types.

GPR is an electromagnetic (EM) geophysical method which uses pulses of EM energy, usually in the 10 MHz – 1 GHz range. Most GPR instruments use impulse transmitters which excite dipole or bow-tie ultra-wideband (UWB) antennas with short pulses of voltage (10s of 100s of V). These antennas radiate energy both into the dielectric (the subsurface) as well as the air. Smaller antennas above 100 MHz may be shielded to mitigate reflections from above-ground objects. The down-going energy partially reflects off changes in dielectric permittivity (mainly a function of water content) and electrical conductivity. These reflected waves propagate back to the surface where they induce small voltage fluctuations in a matched antenna. These fluctuations are then sampled and digitized by a receiver which stores the amplitude of the reflections for later processing on a computer. The equipment is then moved along a line, usually at 50 cm or 1 m steps, and the process is repeated to eventually produce a 2D representation of the subsurface. This radargram is not a direct image of subsurface geology, but a representation of the changes in electrical and dielectric properties of the ground within the range of the radar. Expertise is required to interpret radargrams through an understanding of the interaction of radio waves with geological features.

Ostensibly, GPR should find vast applications in mineral exploration, considering the wavelengths of radar energy and thus the resolution of the resultant radargrams are orders of magnitude higher than other geophysical methods. Unfortunately, the physics of EM wave propagation in dielectrics dictate that a number of loss mechanisms, such as geometric spreading and Ohmic losses, limit the penetration of radar energy to generally much less than 15-20 wavelengths. The deepest penetration is achieved in highly electrically resistive soils and rocks which are ideally arid. To map layers of objects on the order of decimeters, wavelengths of approximately 1 m are needed, which suggests antennas approximately 1 m in length.

Increasing GPR Penetration

In the best radar environments 100 MHz antennas may achieve approximately 15 m penetration, and in typical situations less than 5 m. In most mineral exploration scenarios significantly deeper penetration is required. It may be assumed that simply increasing the transmitter output power would gain additional depth. However, the radar range equation dictates that to double penetration, 32 times more power is required. Most modern low frequency (< 100 MHz) GPR systems pulse approximately 400 V into the antennas, suggesting that to double penetration, 12,800 V would be required. What dictates penetration with GPR is the mean power, not the peak power. It is possible to construct a transmitter with 5,000, 10,000 or greater peak volts, but such transmitters cannot pulse faster than approximately 1 kHz. Conversely, a typical radar system can pulse at 200 kHz at 400 V. This results in significantly greater mean power and thus greater penetration.

In addition, high voltage transmitters for GPR systems are well outside legal limits in Canada, the US, Europe and elsewhere and can pose a significant risk to nearby electronic circuitry including pacemakers. Thus, simply increasing the peak transmitter power is not a solution to significantly increase penetration.

A more effective approach to gaining range with GPR is by increasing the signal to noise ratio (SNR) of the radar system. All GPR systems use stacking to minimize spurious EM interference and enhance actual EM reflections. Commercial GPR systems are generally limited to 16 or 32 stacks for a reasonable survey speed. In recent years, real-time sampling (RTS) systems (Francke and Utsi, 2009) have enabled stacking of 128,000 times with low-frequency radars. If the limit of penetration is the noise floor in a given environment, stacking can double or triple penetration depths and increase the bandwidth of the system substantially. Despite these benefits, RTS systems cannot overcome the limitation of GPR systems when attempting to penetrate through conductive clay or saline water.

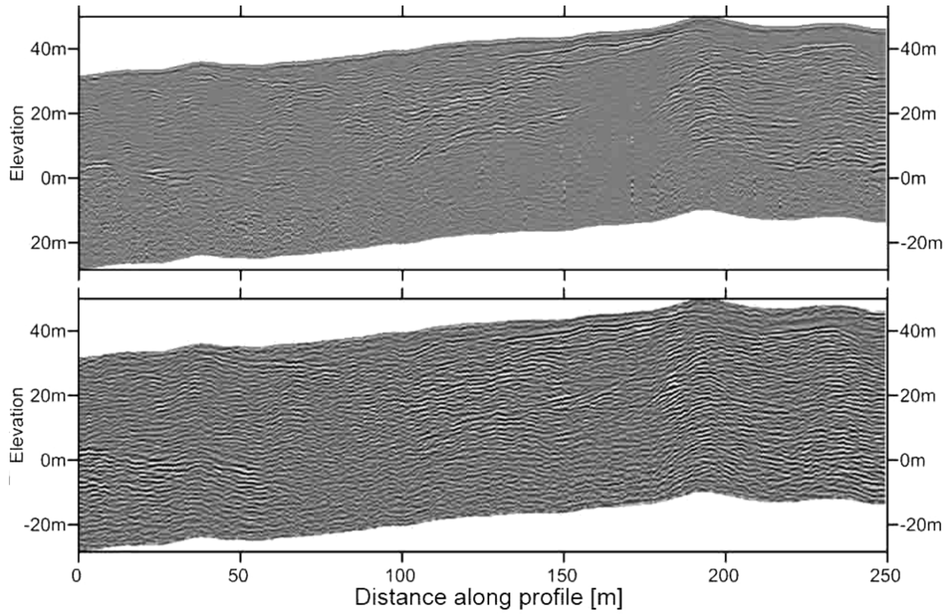

Figure 1 – Comparison of conventional GPR (top) and RTS UltraGPR (bottom) over sand dune showing significantly improved penetration

To increase penetration further, longer wavelengths can be used. Figure 2 shows an example of a towed 10 MHz system used for seismic static corrections in Libya to 200 m+. Whilst an improvement in penetration, the compromise of such systems is that the resolution of the wavelengths is on the order of multiple meters and the towed antennas are nearly 30 m in length, limiting their use to vehicle-towed surveys in open terrain.

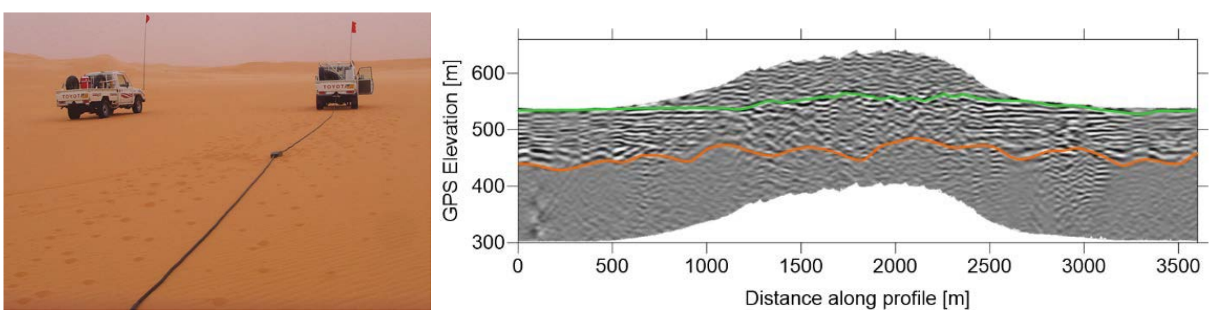

Figure 2 – 10 MHz RTS GPR being used for seismic static corrections in Libya to 200+ m (Francke, 2016)

Electrical field dipoles are generally half the wavelength antennas, with the corollary that longer antennas produce more penetration. However, if the magnetic field was to be excited with magnetic antennas, the antenna length is a function of sensitivity rather than frequency. It is possible, for example, to construct a magnetic antenna operational in the 1 – 20 MHz bandwidth which is only a few decimeters in length.

With such an antenna, coupled with an RTS radar receiver and other SNR-enhancing methods such as coded transmitter waveforms, significant improvements on depth penetration are possible in suitable environments. Even in regions of high clay fractions, the low frequency component of UWB radar can penetrate to substantial depths.

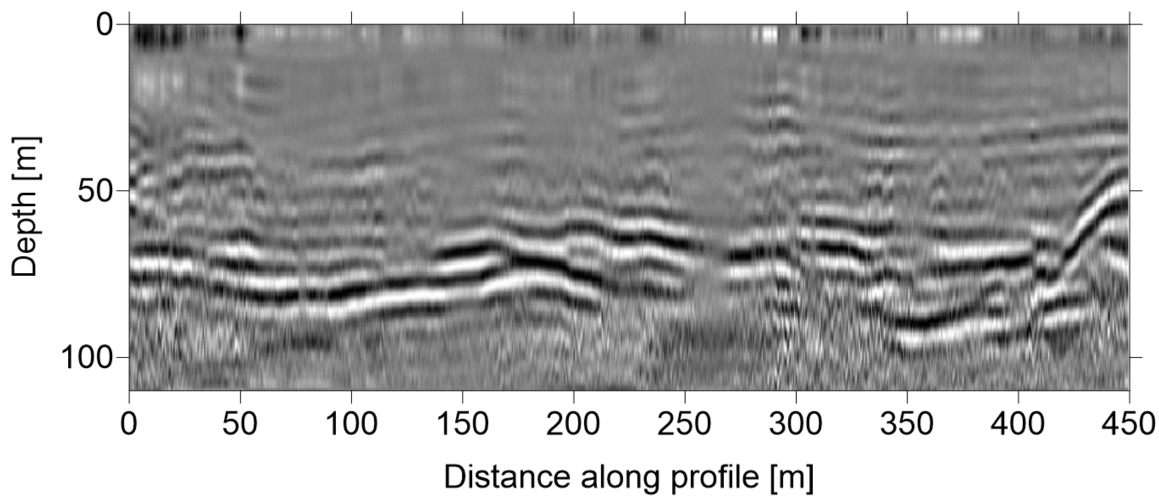

Figure 3 – Data from an RTS UltraGPR filtered to show only the 1 – 10 MHz bandwidth

UAV GPRs

In recent years, manufactures have created lightweight GPR systems in the range of 100 MHz – 1000 GHz for deployment on unmanned aerial vehicles (UAVs). Although tantalizing, airborne GPR systems are limited by both legislation and physics. In Canada, the USA and Europe, regulations limit the use of GPRs to within 1 m of the ground surface.

When radar antennas are decoupled from the dielectric, such as when lifted off the ground, there are several additional factors which must be considered when compared to conventional ground coupled GPR. Perhaps the most impactful limitation is the degree of energy loss at the air-ground interface, both on initial transmission as well as at the ground-air interface upon reflection and return to the antenna. The amplitude of a reflected radar signal is a function of the contrast in dielectric permittivity between the two media. In most soils, well over 50% of the imparted energy is lost at the air-ground interface (Francke and Dobrovolskiy, 2021).

The antenna radiation pattern is also a limiting factor for UAV GPR applications. When lifted off the ground, the illumination zone of the antenna increases significantly, allowing more energy to reflect upwards at angles away from the radar receiver. This larger illumination zone on the ground surface is then further spread as the energy enters the ground. Therefore, planar surfaces such as geological horizons and large discrete targets can be surveyed at greater heights, whereas small targets must be surveyed close to the ground (ideally within 1 m).

Although subject to the same limits of legislation and physics as electric field antennas, magnetic antennas at very low frequencies can be used from UAVs for deep exploration profiling, as such applications are generally mapping horizons rather than discrete targets.

Applications of Deep GPR to Mineral Exploration

Deep GPR systems using RTS and coded transmitters have been used successfully over the past decade for nickel laterite, bauxite, mineral sands, iron ore (BIFs), paleochannels and hard rock lithium deposits to depths exceeding 100 m. The development of magnetic antennas should herald a broader scope of applications in the industry in the coming years.

Conclusions

GPR has had a long history in mineral exploration, despite its limited penetration in most geological settings. Recent developments in increasing the SNR of deep radar systems with real time sampling receivers have more than doubled the penetration of GPR in electrically resistive environments. Nascent designs of magnetic antennas promise to increase penetration further with instrumentation a fraction of the size and weight of existing systems. These systems could be mounted on terrain-following UAVs to enable larger areal coverage to depths exceeding 100 m, thereby expanding the potential applications of GPR to mineral exploration.

References

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