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Realistic Expectations of GPR Performance in Mineral Exploration

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ABSTRACT

Astonishing claims of ground penetrating radar (GPR) performance have plagued the technique since its commercialization. In recent years, GPR-related devices have been marketed in the mineral exploration sector which claim hundreds of metres or even kilometres of penetration through a wide variety of soils and crystalline rocks, some with the ability to resolve discrete targets or thin layers on the scale of decimetres. Whilst some promoters claim to have discovered new modes of electromagnetic (EM) propagation, their descriptions are often vague and intentionally obfuscated to protect intellectual property, with no previous publication which may form the basis of their claims.

This paper discusses expected radar performance for mineral exploration applications and addresses recent claims of extraordinary GPR penetration.

INTRODUCTION

Over a century since the first patents describing ground penetrating radar (GPR) were issued in Germany, the technique has matured to be a valuable instrument in the geophysicist's toolbox. Given that GPR is the highest resolution geophysical imaging tool with wavelengths on the scale of centimetres or metres, applications such as buried utility mapping, concrete inspection and pavement analysis account for the vast majority of the tens of thousands of systems in use worldwide. These applications systems employ antennas operating in the 100 MHz–1.5 GHz range, spanning the VHF and UHF bands of the radio spectrum. Due to limitations caused by ohmic losses, scattering, geometric spreading, etc., the maximum penetration of these systems is on the order of a few metres.

Deeper radar systems require low frequency antennas, and thus produce lower resolution images. For example, a 25 MHz antenna may penetrate to 30 m in suitable conditions with a wavelength of 4 m, which is still considered high resolution for geophysical imaging. Over the past 20 years, applications for GPR in mineral exploration have grown from initial trials to map alluvial paleochannels to now include a wide variety of exploration challenges, including tropical weathering sequences, void detection in carbonates, iron ore, kimberlite mapping and others (Francke, 2012). In these applications, the expected penetration of the deepest GPR instruments is of the order of 10s of metres. In particularly resistive and dry crystalline carbonates, voids to 100 m depth have been imaged.

Regardless of the instrumentation, radar technology is limited by fundamental electromagnetic (EM) constraints, as well as by practical considerations. Whilst in an ideal environment, GPR is generally able to penetrate to depths of approximately ten wavelengths (Bradford and Deeds, 2006), in electrically conductive environments, ohmic losses can limit penetration to one or two wavelengths. Increasing penetration by lowering the radar frequency is possible, although at the cost of physically larger antennas and lower resolution.

GOVERNING PHYSICS

The fundamental operational concept of most GPRs is simple. A radio transmitter emits an impulse of energy into an antenna, which radiates ultra-wideband radio waves both into the air and the ground. Some of that energy reflects off changes in electrical properties within the ground and returns to the surface, where it is detected by a matched receiving antenna. A radar receiver measures and digitizes the subtle voltage fluctuations in the antenna, storing the values for later analysis.

Since GPR energy consists of EM waves, the foundations to quantitatively describe them are described by Maxwell's equations and the properties of the material being penetrated. Whilst a discussion of EM theory is beyond the scope of this work, it is important to consider the parameters which control propagation of energy through the ground, viz., electrical permittivity, electrical conductivity, and magnetic permeability. In most geological environments, the magnetic component is not considered, leaving permittivity (primarily a function of water content) and conductivity as the determinants of radar performance.

As a general guide, GPR systems are capable of penetration to approximately ten wavelengths in the most suitable ground conditions. The factors which limit effective penetration include geometric spreading, ohmic losses and scattering. The best possible radar environment is described as one where losses from conduction (ohmic) and those from displacement currents (dielectric) are minimal, such as dry sand or ice. In order for radar to be effective, there needs to be adequate signal to noise ratio for the system, sufficient difference in dielectric permittivity of the target from the host media to cause a

In "Proceedings of Exploration 17: Sixth Decennial International Conference on Mineral Exploration" edited by V. Tschirhart and M.D. Thomas, 2017, p. 817–820

reflection, and the ability to discern the returned reflection from other clutter (Daniels and Utsi, 2013).

A radar system's performance is most typically defined as the dynamic range, or the ratio of mean power output from the transmitter to the minimum detectable power to the receiver. Most GPR systems transmit a mean power of approximately 1 mW, and receivers are able to detect signals in the 1 pW range, suggesting a typical dynamic range of 90 dB. The actual strength of the signal which returns to the surface is what remains after a series of energy losses encountered by the radar waves, including losses due to transmitting antenna efficiency, ohmic losses on the outgoing path, geometric loss, the target's radar cross-section, ohmic losses on the return path, return geometric loss, losses due to the receiver antenna efficiency, and losses within the receiver electronics itself. If the sum of these losses is greater than the radar system's dynamic range, the target will not be detected (Daniels and Utsi, 2013).

INCREASING GPR PENETRATION

The most prevalent limiting factor for the greater adoption of GPR in mineral exploration is its inherent limited penetration as compared to other geophysical methods. Penetration can be increased using a number of methods, each with a performance, logistical and/or safety penalty. A common approach to increasing depth range is to lower the frequency of the emitted waves. Lower frequencies penetrate deeper and in moist conditions, are less impacted by ohmic losses, but at the cost of increased antenna sizes and lower resolution. For example, a 200 MHz antenna typically used for shallow (< 5 m) surveys has a length of 0.5 m (λ/2) and a spatial resolution of 0.125 m (λ/8). A 10 MHz antenna may penetrate to 50 m, with antennas 10 m long and a spatial resolution of only 2 m. Lengthening the wavelength even further approaches a limit whereby the EM fields no longer travel as waves and become dispersive.

A second approach to increasing depth range is to increase the power of the transmitter. Unfortunately, the governing physics dictates that the mean power of the transmitter must be increased exponentially to increase penetration. In theory, an increase of 32 times is required to double penetration. For impulse radars, this poses technical, safety and legal issues. Typical impulse radar transmitters for mineral exploration operate with peak voltages of 400 V and pulse repetition frequencies of 100–150 kHz. With 25 MHz dipole antennas (70 Ohm impedance), this suggests a mean power of 0.01 mW. Increasing the mean power appreciably requires either increasing the PRF, which is limited due to the required receiver "listening" time window for deep soundings, or increasing the peak voltage significantly. The latter would require slowing the PRF to as little as 500 Hz or 1 kHz to allow the transmitter circuit to recharge, thereby offsetting the advantage of the increased peak power. In addition, such transmitters would be illegal in many jurisdictions, and certainly unsafe to operate in a non-controlled setting.

Other methods such as increasing the system's signal-to-noise ratio (SNR) by employing coded or pseudo-random coded transmit sequences have been employed successfully with appreciable increases in penetration (Utsi, 2007; Xia et al., 2015). The ability of modern radar receivers to capture complete waveforms instantaneously and thereby stack 64,000 times whilst moving the radar at surveying speed can double penetration over conventional radars where the limit of penetration is the noise floor. Experimental electrical antenna designs such as folded or rolled dipoles (Lestari et al., 2007) and novel Vivaldi designs (Elsheakh and Esmat, 2013) as well as magnetic loop antennas (Leat, 2003) hold potential for reducing the physical size of low frequency antennas.

EVALUATING GPR PERFORMANCE CLAIMS

From the first commercial GPR system in the 1970s until the mid-2000s, only a handful of GPR manufacturers existed. Since 2010, the number of manufacturers have burgeoned to include dozens, from large corporations to basement hobbyists. With this expanding market also comes inconsistencies in describing radar performances, with some manufacturers resorting to "specsmanship" to bolster radar performance claims.

Examples of claims of radar performance which do not adhere to accepted physics have a long history in GPR. An article in a Scottish newspaper from 1998 describes a radar-like technology which the publication purports to be able to image "miles" underground, and describes successful trials in South African gold mines with penetration to 10,000 feet (Chisholm, 1998). Another article in the same publication (Vance, 2000) describes a radar-like technology being used to detect sunken treasure off the coast of Cuba by the same Scottish company. Sea water is not suitable for the propagation of VHF and UHF waves, and penetration of any radar system in off-shore settings would be on the order of centimetres. That company, now renamed (Companies House, 2017), is the principal proponent of a technology known as atomic dielectric resonance (ADR).

To the author's knowledge at the time of writing, one academic journal article and six conference papers have focused on ADR for geological applications, each of which authored or co-authored by its inventors. In addition, ADR technology is subject to a pending patent application by its inventors (Stove et al., 2013). It is noted that a patent is not a peer-reviewed document, and the issuance of a patent does not require the demonstration of a working prototype. The published works and patent refer to somewhat varying descriptions of how the ADR instrument emits radio frequency (RF) energy, how that energy penetrates vast distances into the ground and returns to the surface, and how that energy is detected. The patent and some of the publications refer to the RF energy as lasers, which typically relate to frequencies in the THz range, and coherent wavefronts producing narrow beams. The literature also refers to photons being emitted by the ADR instrument's antennas, and that ADR is not depth constrained. It is well accepted that lasers, or any RF energy in the THz band will not penetrate through rock an appreciable distance. An in-depth analysis of the ADR claims is given in Daniels and Utsi (2013).

Recent publications describe ADR as typically operating within the 1 MHz – 70 MHz band, and show a ultra-wideband (UWB) spectrum of the instrument's transmitted waveform as having peaks near 3 MHz and 70 MHz (Stove and van den Doel, 2015).

One paper claims that the ADR instrument, which emits EM fields at these frequencies, could detect gold-bearing veins on the scale of decimetres in thickness to depths exceeding 800 m (Richards et al., 2015). With conventional radar, a layer is generally considered to be resolvable if its thickness is on the order of the incident EM wavelength. Although the publication does not mention a radar propagation velocity in the host rocks, for purposes of optimistic calculation v = 0.1 m/ns can be used. At 70 MHz, a wavelength of 1.42 m would be expected, not accounting for dispersion of lower frequencies with range, which would increase the wavelength further. The publication does not explain how a geologic layer less than 1/10th the thickness of the incident wavelength can be resolved by the reflection of EM energy.

In recent years, claims of impressive GPR penetration have been made by the promoters of a GPR instrument which employs "megawatt" transmitters (Terravision Radar Ltd, 2015). The specifications for these instruments are published in marketing materials, along with impressive depth sections showing apparent penetration to hundreds of metres in seemingly any ground condition. The technique has purportedly been successful in iron ore, coal, kimberlite, tin and alluvial exploration, amongst others, to depths of 400 m (Ultramag Geophysics, 2016).

The proponents of this instrument are understood to make the following claims:

a) Depth of penetration is increased dramatically due to a transmitter which has a peak power of 10 MW.
b) This transmitter is 100,000 times more powerful than a conventional GPR.
c) The low frequency of the antennas employed produces less attenuation in conductive soils.

Although a full technical analysis of these claims is beyond the scope of this report, it is important that these claims be briefly addressed herein.

Radar range or penetration is a function of mean power, not peak power (Utsi, 2007). The peak power of a radar system is calculated by:

$$P = \frac{V^2}{R}$$

where P is the peak power, V is the peak voltage of the transmitter, and R is the impedance of the antennas, measured in Ohms. The proponents of this instrument claim a peak voltage of 5,000 V, which should be noted is not novel and has been available commercially for nearly two decades from manufacturers such as Sensors and Software. Given that dipole antennas are used with an impedance of approximately 50 Ω, the equation above yields a peak power of 500,000 W, or 0.5 MW. This alone is 20 times less power than the proponents claim.

However, it is primarily the mean power that dictates penetration. Mean power is calculated by:

$$Pavg = \frac{(Pulse\ width) * (PRF) * (Peak\ Power)}{1{,}000{,}000}$$

where pulse width is in μs, the pulse repetition frequency (PRF) is in Hz, and the Peak Power is in Watts. The proponents state a pulse width of 40 ns (0.04 μs), and a PRF of 1000 Hz, yielding a mean power of 20 Watts (Volkomirskaya et al., 2012). As a comparison, a conventional GPR uses 400 V transmitters, 40 ns pulse widths (25 MHz) and a PRF of 150 kHz, resulting in a mean power of 19.2 Watts. Thus, the promoted "megawatt" radar transmitter has no technical ability to penetrate substantially deeper than an off-the-shelf GPR.

As previously shown, the peak power of the promoted instrument is 500 kW. A conventional GPR's peak power is 3.2 kW, a factor of 156, not 100,000. Secondly in terms of mean power, the values are almost the same. Put another way, significant gains can be made by averaging (stacking) of conventional GPR's much higher pulse rate, which gives a SNR improvement of

$$10 \log \frac{150000\ Hz}{500\ Hz} = 25\ dB$$

The difference in peak powers is

$$10 \log \frac{5000\ V}{400\ V} = 10\ dB$$

The sections provided in marketing material produced by the promoters of these "megawatt" radars appear to show data which have not been low-cut filtered, also known as de-wowing. This basic step used in nearly all GPR processing removes the low frequency components associated with inductive phenomena and instrument dynamic range limitations (Gerlitz et al., 1993). Leaving this very low frequency response on the radar sections produces "smeared" data profiles akin to those shown by promoters of "megawatt" radars. Such data could be reproduced by nearly any commercial GPR instrument.

There is indeed a relationship between attenuation and radar frequency, whereby lower frequencies will encounter less attenuation than higher radar frequencies, particularly in saturated conductive soils. However, this dependence is minimal in most soils at radar frequencies. For example, wet clays attenuate radar at a rate of approximately 4.1 dB/m at 400 MHz, but only 4.07 dB/m at 50 MHz. and 3 dB/m at 5 MHz. Below approximately 2 MHz, the attenuation in clays does drop substantially, but the instrument is now in the EM domain of dispersive fields.

Assuming the extreme claimed penetration was achieved by very low frequency antennas (< 10 MHz), dispersion becomes a controlling factor in propagation, meaning that propagation velocity and attenuation vary with frequency. This is manifested on a radar profile as a lengthening of wavelengths with depth, which appears to occur on nearly every sample radar profile produced by these megawatt radars. A detailed discussion of this phenomenon, including a sample profile which closely resembles the "smeared" data produced by megawatt radars is given in Annan (1996). It is important to note that once in the domain of diffusion, EM propagation velocity lowers substantially. Sample profiles provided in megawatt radar marketing materials do not appear to account for this, and thus may show exaggerated depth scales.

CONCLUSIONS

GPR has been subject to exaggerated claims and over-interpretation of data since its commercialization some four decades ago. From the pareidolia effects of interpreting Noah’s Ark on early radargrams from Turkey’s Mt. Ararat to modern claims of being able to discern centimetre and decimetre-thick horizons at depths approaching 1,000 m, promoters rely on the ignorance of the customer to general EM principles to promulgate their claims.

As with any extraordinary claim in science, there must be extraordinary supporting evidence to support it, which, in the case of GPR, would generally be the placement of a posteriori boreholes for verifications of results. In nearly every case of exaggerated claims made in recent years, the data shown in marketing material appears to have been correlated to ground truthing information provided a priori. Peer-reviewed publications in reputable journals, not authored by a technique’s promoters, provide substantial credibility to spectacular claims. As stated by Hodges (2011), “Physics isn't magic—the same principles apply to everyone”.

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