# Realistic Expectations for Deep Ground Penetrating Radar Performance

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## SUMMARY

Ground penetrating radar (GPR) is unique amongst geophysical tools in terms of its imaging resolution and the diversity of its applications. Since its commercialisation four decades ago, GPR has also been distinguished because of the prevalence of some of its purveyors to oversell the method's capabilities, relying largely on the end users' lack of understanding of the underlying physics. Early adopters in the 1980s and 90s were dismayed to find that environments suitable for its purported ubiquitous deep penetration capabilities were rare and that it required resistivities well into the 1000s of Ohm m. Regardless of the advances made in electronics and antenna design in the intervening decades, the fundamental limitations have not changed.

Misconceptions, "specsmanship" and hype have continued to abound in the GPR marketplace, particularly in recent years. Systems purporting to penetrate hundreds of metres using "megawatt" transmitters from the former Eastern Bloc have been promoted for mineral exploration, particularly in Australia and Africa. Other pseudo-radar concepts, such as the use of beam forming to achieve kilometres of penetration with centimetre accuracy, or THz laser scanners which can detect individual diamonds deep underground, have generally targeted junior exploration groups who lack in-house geophysical guidance.

This work provides an overview of the fundamentals of non-dispersive EM wave propagation in the ground and an examination of the recent published performance claims of some GPR and pseudo-GPR systems within the context of accepted EM theory. The accepted methods for potentially increasing GPR performance, given the emerging technologies such as novel transmitter and receiver designs and new GPR antennas, are also discussed.

**Key words:** ground penetrating radar, megawatt transmitter.

## INTRODUCTION

The term *ground penetrating radar* (GPR) is often predicated by superlatives; some of them can be true, but many of them are exaggerations. A common adjective is to describe GPR as the "newest" geophysical tool, when indeed the concept of propagating electromagnetic waves through the ground has been considered since the 1800s. The first patent was secured in the 1920s. By extensive experimentation in the 1950s and 60s, and through commercialisation in the early 1970s, the technique is now mature and well understood (Morey, 1974). The fundamental principles of EM propagation established over a century ago remain unchanged.

Another superlative often associated with GPR is "highest resolution", which can be correct in some environments. The early adopters of GPR technology in the 1970s and 80s were encouraged by the impressive penetration and resolution of radar energy into ice caps and permafrost, and they expanded experimentation to more temperate environments, where disappointing performance was encountered due to the presence of conductive clays and phreatic water (Annan and Chua, 1992). GPR can indeed offer the highest resolution imaging of the subsurface, but only when applied to specific suitable environments, which are generally characterised by a high electrical resistivity and low moisture.

Perhaps most damaging to the reputation of GPR as an accepted geophysical method, particularly in the mining and geotechnical sectors, is marketing hyperbole regarding the depth of penetration and overall performance in challenging environments. Radar has a long history of aggrandisement or misinformed claims dating nearly back to its invention. A year after the first patent was issued to Gotthelf Leimbach and Heinrich Löwy regarding the use of radio waves to map the subsurface, news reports suggested that the technique could be used between boreholes spaced at 50 km apart to map lead ore bodies (The Brisbane Courier, 1911). Many of these claims are rehashed today by either inexperienced promoters or long-term industry players who attempt to obfuscate exaggerated performance claims by concocting new technobabble terms to describe what are fundamentally GPR methods.

The liberal use of "specsmanship" in GPR marketing and product naming can be traced to the early 2000s, when major manufacturers sought to expand the market appeal of their most popular GPR products: those intended for civil infrastructure applications. During the 1990s, the commercial use of GPR for such applications (e.g. utilities detection) was limited to specialist geophysical contractors. By simplifying the acquisition, automating the processing to a certain degree and interpreting the data, manufacturers were able to market instruments denoted simply as "shallow" or "deep". Although aimed at less-technical users, this oversimplification led to these utilities detection units being promoted for other, often inappropriate, applications by owners who had purchased the single radar "tool." The terminology further exacerbated the issue, as the term "deep" implies different expectations for different applications.

Through the late 1990s and early 2000s, some early adopters of GPR systems attempted to gain performance (usually extended penetration) through modifying commercial systems or purposely employing incorrect settings (Annan, 1996; McCann, 1995; Stove and Addyman, 1989). In some cases, zealous proponents of their customised GPRs made claims of unusual performance in abundant press releases (Vance, 2000; Chisholm, 1998; Vance, 2004).

## CONCEPTS FUNDEMENTAL TO ALL GPRs

Every radar device is defined by having a control circuit, a radio transmitter, one or multiple antennas for transmission and reception, a radar receiver and a means of storing the returned reflections (often displaying them in the field on a monitor). Most systems also contain a method of determining position, such as a wheel odometer or a link to a GPS receiver.

The radar controller triggers the transmitter to emit a pulse (in the case of impulse radar) or a train of pulses (in the case of stepped frequency radar), which is fed into the transmitting antenna. The transmitting antenna emits these waveforms, a portion of which propagate into the ground. At appreciable variations in the dielectric permittivity (primarily a function of water content), electrical conductivity and/or magnetic permeability, a portion of the radar energy is reflected to the surface. If no variations occur or if these variations occur on a scale significantly smaller than the wavelength of the imparted energy, then no radar reflection will be returned. The amplitude of the reflected signal is a function of the degree of variations in these properties.

The reflected signals are detected by the receiving antenna, creating minute voltage fluctuations in its elements. These fluctuations are, in turn, measured and digitised by the radar receiver, to be subsequently displayed and stored for later post-processing. As a rule of thumb, GPR systems are capable of penetration to approximately 10–15 wavelengths in ideal ground conditions (i.e. dry, highly resistive). The factors which limit effective penetration include geometric spreading, ohmic losses and scattering. The best possible radar environment is described by one where loses from conduction (ohmic) and those from displacement currents (dielectric) are minimal, such as dry sand or ice. For radar to be effective, an adequate signal-to-noise ratio for the system, sufficient difference in dielectric permittivity of the target from the host media to cause a reflection, and the ability to discern the returned reflection from other clutter (Daniels and Utsi, 2013) are needed.

## CLAIMS OF UNUSUAL PERFORMANCE

In recent years, a common claim has been made by Eastern European manufacturers and their agents of extreme radar penetration through the use of so-called “megawatt” transmitters and low-frequency “RC” antennas. Claims of hundreds of metres of penetration through any media have been made (Terravision Radar Ltd, 2016). 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).

In a recent press release, the specifications of a high-powered radar system being marketed in Australia were disclosed (Revolution Metals Ltd, 2017):

- Tx power (10 & 20 kW)
- 200m, 100m and/or 50m depth
- 3 ns pulse width
- 50 Hz stacks
- 1–4 sec sample time (nominal 1m shot spacing)
- 512 channels

These specifications list metrics which are not typical of other manufacturers, but can nevertheless be evaluated on the basis of accepted physics.

Given an antenna impedance of 70 Ohms for typical resistive-capacitive antennas, a peak power of 20 kW suggests a peak transmitted impulse of 1,200 V. This value is not novel, with most low frequency radars being able to produce similar impulses since the 1980s (Annan A., 2002). Other proponents of such megawatt systems claim transmitter voltages of 5,000 V, which is also not novel, given that a major manufacturer sold such transmitters through the mid-2000s and ceased production partially due to safety concerns. Such voltage impulses can easily be generated by the use of avalanche transistors or gas discharge (spark gap) circuits, a method known for over a century (United States of America Patent No. US2002181 A, 1931).

Of interest is the claimed 3 ns pulse width, which (assuming the conventional definition of pulse width) suggests a transmitted frequency of 200 MHz. Denoting what can be assumed as “programmed” depth ranges is incongruous to how radar works. Simply, no radar image to 200 m, 100 m or even 50 m is possible in all possible environments. The customer is left to estimate that at a maximum of 10 wavelengths of penetration, the 200 m depth range would require an antenna on the order of 20 m wavelength, which equates to a half-wavelength dipole length of 10 m. The central frequency of a 10 m dipole would be approximately 10 MHz. Although antenna bandwidth is a subject of specsmanship between various manufacturers, a general rule of thumb is that the effective bandwidth ranges from $f/2 \rightarrow 2f$, suggesting that the antenna is effective over a range of 5 MHz–20 MHz. In this case, the amount of energy which is transmitted by a 10 MHz centre-frequency antenna using a 200 MHz pulse would be low.

The key parameter for radar system performance is mean power, not peak power (Daniels, 2005). Aside from safety concerns relating to high-voltage discharges and strong radio interference fields around other electronic equipment, such high-voltage pulses are not used in commercial radars because of their low pulse repetition frequencies. Spark gaps and gas discharge circuits require significantly more time to recharge than more conventional FET or avalanche designs, which can pulse 1000's of times faster. Thus, far greater system performance gains can be garnered by the averaging (stacking) of conventional GPRs using a much higher pulse rate. A typical GPR may pulse 400 V at 150 kHz, which gives an SNR improvement of

$$10 \log \frac{150000\ Hz}{50\ Hz} = 80\ dB.$$

The difference in peak powers is

$$10 \log \frac{1200\ V}{400\ V} = 32\ dB.$$

The example radar profiles advertised by proponents of high-powered radars invariably 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 the dynamic range limitations of the instrument (Gerlitz et al., 1993). Leaving this extreme 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, as shown in Figure 1.

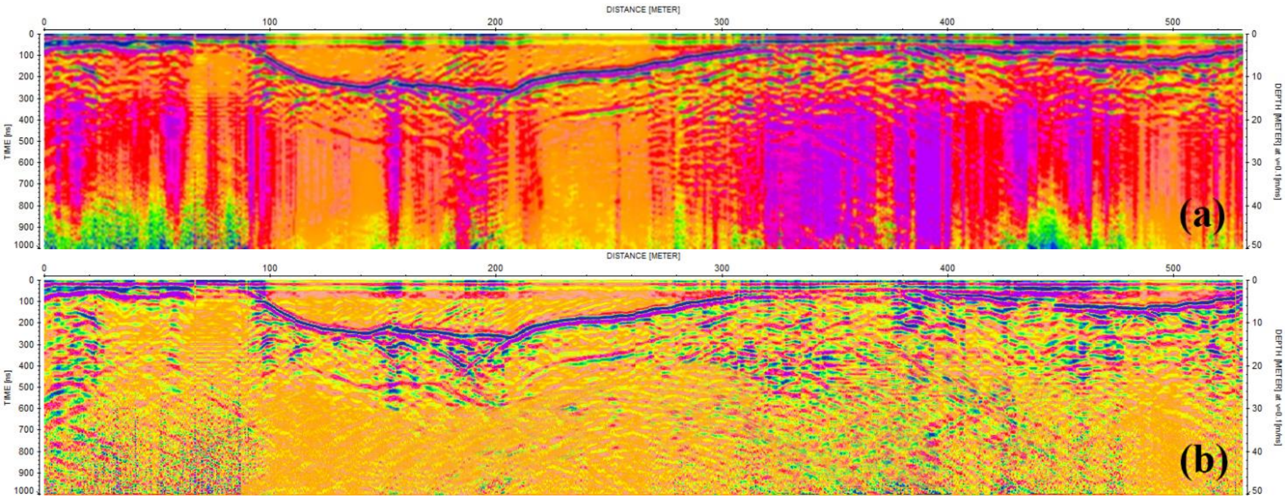


**Figure 1 – Raw GPR data appearing to show vertical geology to 50 m depth (a) prior to de-wowing. Filtered data (b) shows a realistic penetration to 25 m.**

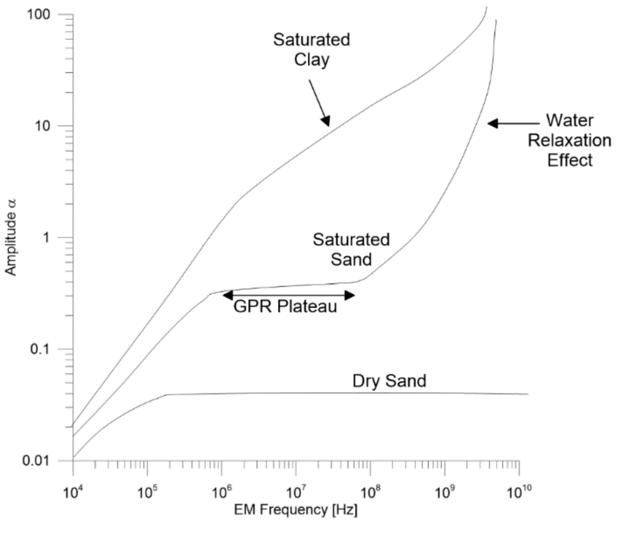


**Figure 2 – The GPR Plateau, below which EM fields are dispersive and above which microwave heating causes rapid attenuation.**

A common claim is that the resistive-capacitive (RC)-loaded dipole antennas can radiate more directional energy and have better ground coupling and a wider bandwidth than traditional resistive-loaded dipoles. The concept of combined capacitive and resistive loading is discussed at length in a number of publications (Lestari, Yarovoy, & Ligthart, 2004). Simple unloaded dipole antennas are relatively narrow band and produce late time ringing, which makes interpretation of reflections difficult. Resistive loading widens the bandwidth of a dipole and suppresses the strong multiple reflections between the antenna feed point and end, but at a cost of antenna efficiency (Shlager, Smith and Maloney, 1994). Capacitive loading has a similar effect of dampening ringing with less reduction in antenna efficiency, but has not been used in commercial GPR systems to date (Rao, Ferris and Zimmerian, 1969). The combination of resistive and capacitive loading is not novel and does not substantially increase antenna directivity, nor does such loading suggest that the antennas are "capacitively coupled" to the ground, as some proponents of deep radar instruments claim. What is realistic, however, is that RC antennas may produce wider bandwidths than standard resistively-loaded dipoles. Since this implies that lower frequencies are being emitted, proponents claim that extreme low-frequency energy (< 10 MHz) assists in achieving the substantial penetration shown in their marketing material. Often cited is a graph showing the relationship between frequency and attenuation (Figure 2).

Thus, there is indeed a relationship between attenuation and radar frequency, whereby lower frequencies 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 drops substantially, but the instrument is now in the EM domain of dispersive fields. With dispersive fields, both attenuation and propagation velocity 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. Annan (1996) discusses this phenomenon in detail, including a sample profile which closely resembles the "smeared" data produced by megawatt radars. Sample profiles provided in megawatt radar marketing materials do not appear to account for this and thus may show exaggerated depth scales.

In addition, a series of claims are made in the marketing material:

> DGPR is measuring IP (capacitance), conductivity, and porosity (density). We anticipate DGRP will make IP, EM and gravity obsolete in the top 150–200m where there is no saline groundwater. All three can be acquired together rapidly, without plugging in or levelling instruments and without ambiguity or need for modelling. The high resolution in x, y and z is also unparalleled especially for thin vein & fault systems. (Ultramag Geophysics, 2017)

Furthermore, it is claimed that "DGPR measures a combination of rock dielectric and conductivity. DGPR differs from conventional GPR in several key ways that will not be disclosed. Shots are very focused (i.e. can map 1m wide void @ 60m), unlike conventional GPR and EM. Note that conventional GPR can only shoot to ~10m in optimal conditions like granites and 1m in clays" (Ultramag Geophysics, 2017).

GPR responds to variations in dielectric permittivity, electrical conductivity and magnetic permeability, but does not directly measure any of these, nor does it measure density. Increased antenna directionality can be achieved by different antenna designs, with taper slot antennas offering excellent directivity of energy. Such directional antennas are required to be 3D in shape and to extend multiple wavelengths in height. Given the claimed low frequency of the promoted RC antennas, "focussing" or directionality would require antennas to be dozens of metres tall. RC dipoles are omnidirectional.

The claim of being able to detect a void of 1 m width at a depth of 60 m does not comply with accepted EM propagation. The accepted method of calculating the range resolution of a radar impulse is

$$R_v = \frac{T_{pulse} \times c}{2\sqrt{E_r}},$$

where $R_v$ is the vertical resolution, $T_{pulse}$ is the pulse width of the antenna, c is the speed of light, and $E_r$ is the dielectric permittivity of the ground. Assuming highly favourable ground conditions (dry) with an $E_r$ of 4 and a published $T_{pulse}$ of 3 ns, this suggests a vertical resolution of 2.3 m, not taking into account the low-pass filtering effect of the ground (even longer wavelengths) and exponential spreading losses.

Horizontal resolution can be described by

$$R_{h=} \frac{c}{4f\sqrt{E_r}} + \frac{D}{\sqrt{E_r + 1}},$$

where $R_h$ is the horizontal resolution, and D is the depth to target (Cabrera, 2011). At 60 m and assuming a 20 MHz centre frequency antenna, this equates to 28 m. An accepted rule of thumb with any GPR system is that a discrete target may be detectable if its diameter is on the order of $1/10^{th}$ of its depth (Jol, 2008).

Increasing penetration through attempted increases in antenna directionality is also a claim made by several other proponents of pseudo-radar technologies (United States Patent No. US20150153470A1, 2013). Atomic dielectric resonance (ADR), a technology patented by its inventors, in part claims to achieve vast penetration into the subsurface using what the inventors suggest as coherent RF waveforms, which essentially form very narrow beams, enabling the detection of narrow features at depths of hundreds of metres or kilometres. In the published literature, ADR is variously described as using lasers (generally considered in the THz range), masers (generally considered in the GHz range) and more conventional GPR frequencies. It is well accepted that lasers or any RF energy in the THz band will not penetrate through rock at an appreciable distance. An in-depth analysis of the ADR claims has been provided (Daniels and Utsi, 2013), although achieving coherent waves generally requires an antenna with an aperture in the range of 10 wavelengths. In the recent literature (Stove and van den Doel, 2015), the transmitted waveform of an ADR instrument is shown to range from 1 MHz to 70 MHz, suggesting that coherent waveforms could theoretically be achieved with an antenna several hundred metres in height, compared to the 1-m-long antennas described in the patent and shown in the marketing material.

Further claims of THz frequency lasers which can penetrate through earth media and detect small objects are made for technologies such as those promoted online and at trade shows which purport to be able to detect individual diamonds and oil molecules at up to 5000 m depth (Captial Consulting Corporation Ltd, 2016). As previously stated, it is generally accepted that EM energy in the THz (laser) range has minimal penetrative ability through opaque objects, such as soil and rocks.

## ACCEPTED METHODS OF INCREASING GPR PENETRATION

Whilst the fundamental governing physics are immutable, recent developments have proven effective at increasing penetration and instrument practicality by harnessing the latest improvements in antenna designs and micro-electronics. Perhaps the most effective improvement has been the approach to how the returned reflections are sampled and digitized in the receiver. Most commercial GPR systems use sequential sampling, whereby an analog-to-digital converter (ADC) captures a single time sample for each transmitted pulse. A timing source triggers both the transmitter (to emit the voltage pulse into the antennas) and the receiver (to commence listening). A radar trace consists of a series of time samples with intervals in the ns scale. For each transmitted pulse, a subsequent point on the trace is sampled until the entire trace is reconstructed. A trace of 512 time-sampled points requires 512 transmitted pulses. Although the energy travels through the ground at a fraction of the speed of light (0.03–0.15 m/ns), the requirement of 512 pulses to create a single trace effectively limits the signal-to-noise enhancing stacking to 32 or 64 times. At 64 stacks, such a trace requires the antennas to be stationary for approximately 1.5 s, which limits the survey speed when traces are recorded at 1 m intervals. Conversely, modern GPR receivers which use real-time sampling are able to digitize the entire 512 point waveform with a single transmitted pulse, allowing 16,000 stacks to be collected at the same survey speed as older systems that could collect 32 stacks. In theory, stacking 1,000 times alone could double the penetration in a scenario where the limit of penetration is the noise floor.

Another improvement with such full-waveform sampling systems is the significant increase in effective bandwidth by increasing the signal-to-noise ratio (SNR) (i.e. lowering the noise floor), as demonstrated in Figure 3.

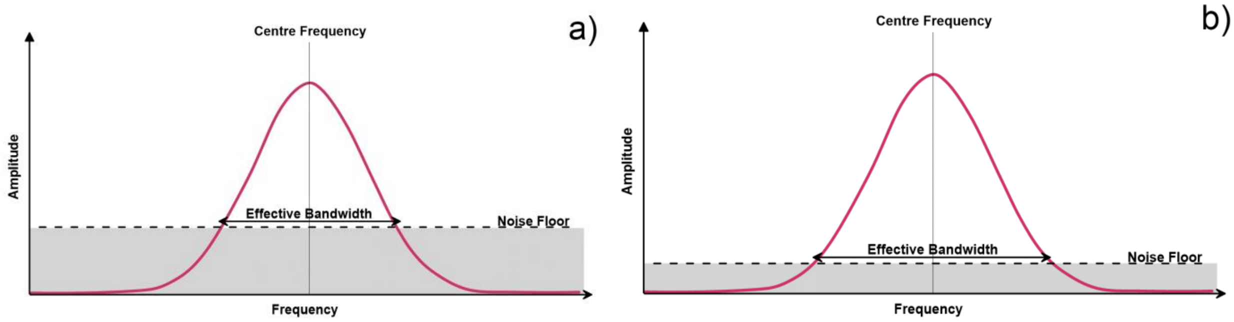


**Figure 3 – Sequential sampling receivers (a) exhibit higher noise floor and narrower bandwidth than full-waveform receivers (b).**

Penetration can also be increased through the use of novel transmission modulation schemes other than a simple impulse. Pseudo-random sequence or coded transmissions are correlated against the reflected waveforms to improve SNR (Utsi, 2007; Xia, et al., 2015; Reeves, 2014). Successful surveys to nearly 200 m have been achieved using Golay-coded waveforms through desert sands for seismic static corrections (Francke, 2016).

Although there is a limitation on lowering radar frequencies to a point where the energy no longer travel as waves and become dispersive fields, similar to EM surveying methods, low-frequency antennas (<20 MHz) can be used in some environments to increase penetration. The resultant data are relatively low resolution, with a minimum detectable horizon thickness on the range of 10 m; however this still compares favourably with other geophysical methods. The limiting factor with such antennas is their cumbersome size, even when arranged in a collinear fashion. New, fast RF switches have enabled the design of monostatic dipole antennas with minimal reductions in output power, reducing the system length by half. Folded dipoles and other experimental antenna designs hold potential of reducing antenna size even further (Lestari, Yarovoy, & Ligthart, 2004; Elsheakh & Abdallah, 2013; Guangyou & Pipan, 2004). Perhaps the most promising antennas have been magnetic designs which potentially could allow low-frequency radar units to be packaged within small loops (Leat, 2003). Rather than relying on RF excitation from voltage impulses, some researchers have considered current excitation as a promising option to substantially increase penetration (Sugak, Klochko and Koropets, 2007).

## CONCLUSIONS

Although a well-understood and accepted geophysical tool, GPR has a long history of exaggerated claims and marketing hype which abound today. The recent claims by various manufacturers of unusual performance, including extreme penetration through any earth material, the detection of small targets at substantial depths and the penetration of THz EM waves through thousands of metres of rock, may be examples of misunderstood fundamental physics and/or overzealous marketing. Any one of these claims, if validated, would represent a dramatic improvement to current technology and would force the re-examination of the currently accepted theories of EM wave propagation through the earth. In many cases, the fundamental concepts, be it increased peak transmission power or the use of novel antennas and beam focussing for the formation of coherent waves, have been well tested over decades. If these approaches to improving performance had shown significant promise, further research and publications would have been forthcoming. The lack of significant peer-reviewed publications on these technologies possibly suggests that the marketing claims do not necessarily meet the requirements of the scientific process. The issuance of patents to a particular technology does not indicate its scientific validity, for no working prototype must be produced or proven to work as claimed for a patent to be issued.

A commonality amongst these technologies is their proponents' claims of confidentiality and intellectual property when discussing their scientific merits, therefore suggesting that verification methods such as blind testing cannot be conducted. As noted by Hodges

(2011), the geophysical instrumentation sector is highly competitive, and any substantial improvement to an existing technology would be replicated by other manufacturers in short time, if the improvement showed scientific merit. Hodges suggests that many of the proponents of these extraordinary technologies may not be intentionally misleading clients, but are simply misguided scientists or inventors who genuinely believe in their technology's potential without fully understanding the underlying physics. As with any extraordinary claim not backed by extraordinary evidence, caveat emptor.

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