The Past, Present and Future of GPR

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ABSTRACT

Nearly a century since its first field use, GPR has become an accepted geophysical method for near-surface imaging, particularly in the civil infrastructure market. Unique amongst geophysical methods for its high resolution and unrivaled diversity of applications, GPR instrumentation has seen little significant development over the past decade, due, in part, to market demand, legislative restrictions, and adherence to existing designs. Nevertheless, recent published works have shown significant improvements on the main components of GPR instruments: the transmitter, antennas, and the receiver. In addition, new systems are being introduced commercially which are a fraction of the cost of previous systems and offer similar, or better, performance. This work will examine the history, state-of-the-art, and future of GPR instrumentation and applications and will demonstrate that the natural progression may be a low-cost open source technology.

INTRODUCTION

Perhaps one of the least understood and thus oversold geophysical methods, ground penetrating radar (GPR) instrumentation has seen significant technological development since its commercialization in the early 1970s, particularly in the last decade. Many of these advancements have been commensurate with the near-exponential improvements in consumer digital electronics over the past three decades.

The concept of employing MHz-frequency EM waves to penetrate the subsurface is ostensibly simple. A GPR transmitter generally consists of a DC voltage source (12V battery) connected to a pulse generator followed by a pulse shaper to produce an impulse or monocycle waveform with minimal ringing. The pulse width is generally twice the inverse of the center frequency, measured at half peak amplitude. Thus, for a 100 MHz center-frequency GPR system, the pulse width would be 5 ns.

These pulses are fed into either resistively-loaded dipole antennas (< 100 MHz) or bow-tie antennas (> 100 MHz), which radiate the energy into the ground as well as into the air. For bow-tie antennas greater than 100 MHz, EM shielding and suppression can be used to minimize the air-bound energy, thereby increasing the SNR of the energy entering the ground. Lower-frequency antennas cannot practically be shielded due to the required size of the EM cage.

The energy radiated into the ground propagates downwards to reflect and refract off discrete targets or surfaces with varying dielectric permittivities, conductivities or magnetic properties. Generally, reflections from dielectric variations are due to changes in the moisture content of soils and rocks. Reflected energy returns to the surface to energize a matched receiving antenna.

The radar receiver is simply a fast digital sampling oscilloscope. Timing and synchronization to the transmitted pulse is of critical importance, as fast analogue to digital converters (ADC) are used to capture the voltage fluctuations in the receiving antennas (on the scale of mV) into discrete digital samples at time intervals ranging from picoseconds to nanoseconds. A series of digitized values are then concatenated in time to create a voltage vs time series, known as a radar trace. The entire apparatus is then moved at a set step size and the process is repeated to create a radar profile. Figure 1 shows a typical radar profile acquired over a series of buried metallic pipes, each appearing as an inverted hyperbola at a depth of 1.6 m.

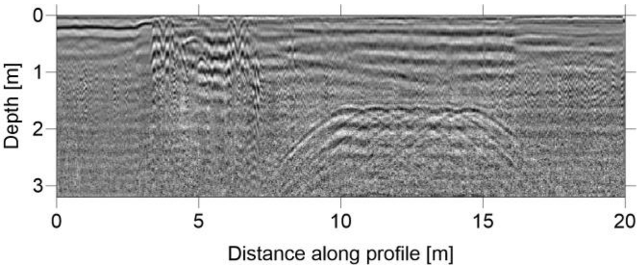

Figure 1: Example data showing 500 MHz radar response from six buried pipes.

Radar penetration is a function of a number of factors, including moisture, the degree of heterogeneity in the subsurface geology and most critically the electrical conductivity of the ground. As a general guideline, most radar systems are able to image approximately ten wavelengths in a good radar environment. The corollary to this is that the longer the radar wavelength, the deeper the maximum penetration. Since GPR antennas are generally half a wavelength long, deep surveying requires longer antennas.

Today, there are tens of thousands of GPR instruments in use commercially worldwide, with four major manufacturers and over a dozen smaller producers. The vast majority of systems are employed for shallow civil infrastructure applications, such as buried utilities detection, pavement analysis, rebar imaging in concrete walls, etc. A small percentage of units are used for deeper imaging applications, such as glaciology, geotechnical and mineral exploration surveys.

HISTORY OF GPR

The concept of using pulsed EM energy to image the subsurface is not new. The background research can be attributed to Christian Hülsmeyer in 1904 (Hülsmeyer, 1904), who first patented the concept detecting distant objects with continuous radio waves. In 1912, a patent was issued to Gotthelf Leimbach and Heinrich Löwy to use radio waves to located buried objects using surface antennas an a continuous-wave transmitter (Leimbach, et al., 1912). By 1926, Hülsmeyer had patented the impulse radar system which is commonly used today, thereby improving temporal resolution of the returned signal.

The first published work on the use of radar to image the subsurface was a work by Walter Stern in 1929 wherein a radio imaging device was used to measure the depth of a glacier in Austria. Minimal technological development on radar was achieved until World War II forced rapid innovations in military radars by both sides of the conflict. Miniaturization for aircraft-mounted systems, high-frequency impulses to improve target resolution and lower power requirements were all necessitated, leading to experiments with more practical subsurface radar instruments following the war. The Scott Polar Research Institute at Cambridge University were amongst the first to experiment with surplus military radars for glacier mapping in the early 1960s (Annan, 2002).

The 1960s saw further developments in subsurface radars due to the Apollo Space Program. Launched in 1972, Apollo 17 carried the Apollo Lunar Sounder Experiment (ALSE), a chirp radar system with two dipoles and one Yagi antenna, centered at 5 MHz, 15 MHz and 150 MHz, mapped the lunar subsurface from the orbiting spacecraft to depths of 1600 m beneath Mare Crisium, Mare Serenitatis, Oceanus Procellarum, and other areas. Such penetration was possible due to the extreme aridity of the lunar surface and subsurface (i.e. low dielectric permittivity). Surface electrical properties were measured with instruments mounted on the lunar rover.

Researchers who had worked on the ALSE instrumentation went on to found a commercial GPR company in 1973 (Geophysical Survey Systems Incorporated). During the 1970s, the first commercial radar systems were used what are today considered low frequency antennas (50 MHz – 150 MHz), which were generally simple dipoles, to map glaciers and shallow geology (Morey, 1974). The US Military were users of these early systems to monitor potential subsurface incursions along the 38th Parallel separating South and North Korea. Some of the most successful early commercial surveys were performed to map ice and muskeg thickness along the proposed Mackenzie Valley Pipeline in the late 1970s (Annan, et al., 1976). These early systems employed large electronic components which were susceptible to temperature fluctuations and required a large truck for transportation, thereby limiting their practicality.

Figure 2: Early GPR system being used to map subsurface conditions along proposed pipeline route.

With the availability of smaller and more stable components in the late 1970s and early 1980s, additional manufacturers were formed in Canada, Sweden and Japan. These improvements in components allowed higher frequency systems to be developed (i.e. faster sampling ADCs) for applications such as utilities detection and archeology. These civil infrastructure applications immediately gained acceptance for near-surface engineering and were concurrent with the installation of new fiber optic lines in urban areas worldwide. These early systems were still cumbersome, had no ability to digitally store recorded data, and relied on electrostatic plotters and CRT oscilloscopes to display the received EM waveforms, negating the ability to post-process the recorded data.

By the mid-1990s, GPR instrumentation had been miniaturized sufficiently to enable systems which were small enough to be carried in a backpack, with dipole antennas for low frequency studies (< 100 MHz) and bow-tie antennas for shallower investigations (> 100 MHz). Dramatic market uptake was made possible with the ubiquitous availability of laptop computers, which could digitally store recorded data for later processing. Software packages become available which harnessed 1D and 2D seismic processing methods, such as FFT filtering, background removal and migration.

Whilst many of the developments made in the 1990s remain today, the 2000s saw significant interest in multi-channel radars, wherein an array of antennas are arranged in a row to enable wide swaths of ground to be covered in a single pass. When coupled with an accurate means of position, such as a RTK-DGPS or robotic theodolite, the hitherto impossible data density which arrays systems allowed produced 3D representations of the near-surface with exquisite detail. Malå GeoScience AB, a spin-off from the Swedish Geological Survey's development of borehole radar for nuclear waste disposal in the 1980s, produced the first commercial multi-channel GPR system, which was employed to map buried utilities around the Ground Zero site around the World Trade Center in New York after September 11, 2001.

An array system commercialized from the University of Trondheim, known as 3D Radar employed 32 or 64 bow-tie antennas with a stepped frequency transmitter was released in 2004. By 2010, each major radar manufacturer had produced a commercial multi-channel GPR system, with antennas numbering from 2 to 64, all marketed towards shallow utility investigations and archeology.

GPR TODAY

With few exceptions, all commercial GPR instruments today operate on the same principle. An impulse is created in a transmitter and dumped into either a dipole or bow-tie antennas to radiate into the air and ground. The received signals use a matched antenna and a sequential sampling circuit to capture the recorded waveforms. The digitized signals are then stored on a tablet or laptop computer, generally running Windows or a custom build of Linux for subsequent data processing on a Windows PC. Increasingly, manufacturers are packaging systems as complete turn-key solutions for specific markets, with parameters and processing pre-set to minimize the operator's experience level required. Such devices are designed for ski slopes to map snow thickness, ice road construction to map ice thickness, police forces to locate buried forensic evidence and utilities crews to demark underground pipes and cables prior to excavation. In general, single channel GPR systems from a major manufacturer are presently priced in the range of $13,000 - $18,000 USD. Multi-channel systems are considerably more complex, require specialized processing software and expertise, and generally cost in the range of $80,000 -$150,000 USD.

Despite marketing claims and the liberal use of "specsmanship" whereby GPR performance is overstated either intentionally or due to un-established industry standards, the vast majority of GPR systems available all use the same general methods of pulse generation, antenna designs, and receiver digitization.

The pulse generator can be one of several options for high voltage generation, as listed below (Utsi, 2014).

Impulse generator	Common output voltage [V]
Gas-discharge tubes	5,000
Field-effect transistors (FET)	500
Avalanche transistors	100
Step recovery diodes (SRD)	50
Bipolar RF transistors	10
Gallium arsenide field-effect transistors (GaAsFETs)	5

Commercial GPR transmitters commonly employ avalanche transistors, outputting between 50 V and 400 V. Two manufacturers state that SRD transmitters are used, with pulse voltages as high as 800 V (Prokhorenko, et al., 2000). Regardless of the type of pulse generation and voltage output, of relevance to performance and radar penetration is the average power output from a transmitter, suggesting that the pulse repetition frequency (PRF) is of greater importance. Most commercial radar systems employ transmitters with PRFs in the range of 150 kHz – 400 kHz. Generally, the greater pulse amplitude, the slower the PRF, thereby offsetting the benefits of high voltages (Utsi, 2007). In the 1990s, Sensors and Software produced 1000 V and 5000 V impulse transmitters, for specialized applications. Their PRFs were significantly slowed as compared to their standard 400 V transmitter, resulting in modest gains in penetration due to the similar average power outputs (Francke, et al., 2009).

Antenna designs for all manufacturers are strikingly similar, despite claims of uniqueness. All common systems employ some variation of bow-tie antennas for high frequencies (>100 MHz) and dipoles for lower frequencies (<100 MHz) (Daneils, 2009). These were the same designs which were employed in the first commercial GPR systems in the 1970s and 80s with little improvement on designs.

With few exceptions, the technology employed in GPR receivers has improved, yet remained fundamentally unchanged since the 1990s. At the time, ADC chips were reliable for field use at relatively slow speeds without significant drafting due to temperature and other variations. As such, receivers were designed as sequential samplers, whereby a single time sample is captured for each transmitted pulse. Thus, to construct a full trace of 512 points, a transmitter would need to be pulsed 512 times. This would produce a single trace, or a single stack. An issue with GPR in most settings is that the received signals are often superimposed with spurious random noise from the internal components of the radar itself, cultural interference from TV and radio broadcasts, and cosmic radio interference. A trace of a single stack of radar data is often useless in defining a discrete reflection from a target or geological horizon due to this noise (Figure 3). Multiple stacks of data with the antennas held stationary are collected in order to improve the SNR of the final recorded trace. Although the radar energy is travelling at a fraction of the speed of light, and trace lengths are on the scale of tens or hundreds of nanoseconds, electronics and computing overhead can, in practice, limit the number of stacks to 32 or 64 times.

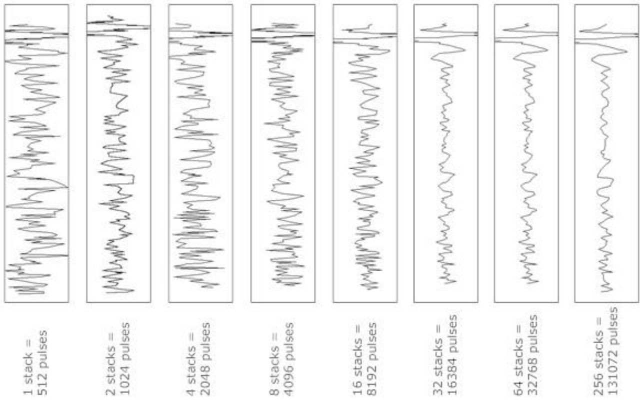

Figure 3: The improvement in SNR through stacking illustrated in a real-world example with 500 MHz antennas in an urban setting.

FUTURE DESIGNS

Despite manufacturer marketing claims to the contrary, the fundamental design of commercial GPR systems have remained stagnant for at least the last decade. Radar instruments are packaged with updated mechanics, and processing software has improved to incorporate voxel processing and 3D interpretations, but the source data are generated by circuits and antennas which are very similar to those used in the 1990s. There are several reasons for this, which may include the cost and complexity of re-designing existing technology for marginal performance improvements, legislative restrictions which limit commercial radar systems in major jurisdictions to shielded, low-powered units suitable mainly for civil infrastructure and archeology applications, the market acceptance of a specific GPR form factor, and a lack of market demand.

However, these rationales for the limited development in commercial radar instruments over the last decade do not mean that other approaches to their design would not yield significant improvements. On the contrary, the field of existing research detailing experimentation with improved transmitters, antennas and receivers is ever-expanding. With rare exception, few of these demonstrated improvements have been commercialized to date.

Improvements to Transmitters

Rather than the ubiquitous use of impulse or monocycle transmitted waveforms, a possible improvement may be gained by moving to a frequency-domain radar system, such as swept-frequency or stepped-frequency GPRs. Such instruments were experimented with in the 1970s and 1980, and an attempt was made in the late 1990s to commercialize a system, but to date, only the 3D Radar array GPR from Norway is designed to operate in the frequency domain. Such systems offer significant advantages over time-domain systems, such as controlled transmission frequencies, lower power requirements, and the ability to use lower cost ADCs, as well as the ability to capture real and imaginary portions of the returned signals, thereby allowing complex processing and the use of SAR algorithms (Koppenjan, 2009). Conversely, the requirement for on-board digital signal processing requires complex electronic design and computationally-intensive IFFT in order to view data in the time domain. Comparisons of frequency-domain to traditional time-domain systems are few, but published works have demonstrated marginal performance improvements in real-world scenarios (Leckebusch, 2011).

A simpler approach to improve signal to noise ratio would be employ a coded transmitted pulsed waveform. Such systems were discussed in the early 1990s (Nicollin, et al., 1992) and have been commercialized in a road pavement scanning arrayed radar system from Australia (Reeves, 2014). Coded transmitters require precise synchronization to the radar receiver, generally through a fiber optic connection or wireless trigger. The SNR of the system is improved by correlating the received signals with the known transmitted code.

An additional advantage is the increase in mean power from the transmitter. Radar penetration is a function of mean power, not peak power, and increasing the peak power of an impulse radar generally results in the lowering of the PRF, and thus mean power. Coded sequences allow a longer pulse width (and thus greater mean power) without the decrease in time resolution. Although researchers have published initial results, only Radar Portal Pty of Australia produces a pseudo-random transmitter GPR for high-speed road surveys and Utsi Electronics of the UK produces a Golay-coded transmitter GPR for deep geological surveys.

Figure 4: Noise-modulated GPR used for pavement analysis and utilities detection in Australia (Radar Portal Surveys Pty).

Improvements to Antennas

All commercial radar systems employ bow-tie or dipole antennas for energy transmission and reception. The requirements for a practical GPR antenna is to be as wide-band and directional as possible whilst maintaining a practical size and shape for moving the antenna across the ground. The first GPR systems employed resistively-loaded dipoles, which are still used today. These are single wires or a series of parallel wires with resistors at spaced intervals dictated by an accepted relation between distance from antenna feed point and resistance (Daniels, 1989). Such antennas are easy and cheap to manufacture and are reasonable portable when used in their optimal perpendicular orientation. For deeper surveys in dense vegetation, such antennas require wide cut-lines of up to 12 m (Figure 5).

Figure 5: 12.5 MHz dipole antennas

Recent low-frequency systems have employed dipole antennas in a collinear orientation, allowing the entire radar system to be designed as a “snake”, thereby enabling much faster surveying in difficult terrain (Figure 6). The drawback of this orientation is that the dipole radiation patterns of the transmit and receive antennas do not overlap well, resulting in much higher “end-fire” interference patterns than with traditional dipole antenna orientations. This drawback can sometimes be mitigated by advanced FFT processing in the spatial domain to subdue the characteristic “X” end-fire patterns from above-ground reflections.

Figure 6: 25 MHz dipole antennas in collinear orientation

For higher frequency systems from 100 MHz – 4 GHz, bow-tie antennas are ubiquitously used. These antennas are relatively directional (thereby reducing end-fire issues), and are small enough to be shielded using a metal cage, often filled with radar-absorbent foam. The shielding of radar antennas is somewhat of an art, as improper shielding or absorbency can result in ringing of the radar energy within the antenna, thereby creating far more interference than would an unshielded antenna.

In both the case of dipole or bowtie antennas, the functional bandwidth is approximately 50%, whereby, for example, an antenna centered at 100 MHz has a functional bandwidth from 50 MHz to 150 MHz. In order for a survey to achieve both depth penetration and high-resolution for shallower depth, multiple antennas, usually requiring subsequent surveys, are required. An alternative approach may be to use antennas with much wider bandwidths, such as Vivaldi antennas (Figure 7). A number of works have discussed the use of alternative UWB antenna designs for GPR applications in recent years (Sato, et al., 2004) although only one company in Russia currently produces a GPR with Vivaldi antennas for ice profiling.

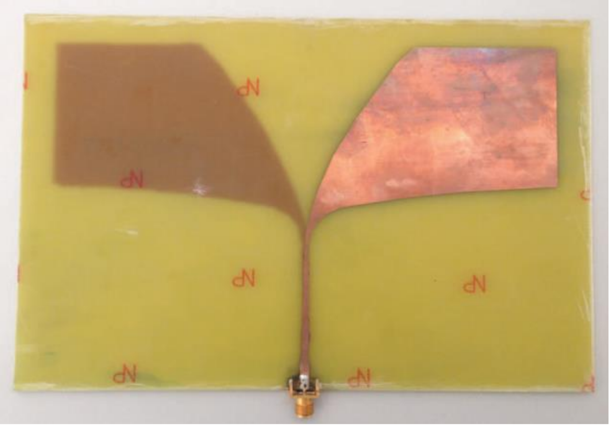

Figure 7: Vivaldi antennas used to increase bandwidth and directionality of GPRs (from Al Takach, et al., 2016)

One drawback to Vivaldi or tapered slot designs is the requirement for the width at their base to be ½ of the wavelength of the radar frequency. Thus, for systems lower than 200 MHz, their size may be impractical, regardless of their ability to span wider bandwidths. Some recent works have shown promising results from more exotic variations of such antennas, reducing their size dramatically to allow frequencies as low as 50 MHz from practical-sized antennas (Elsheakh, et al., 2014).

Likewise, variations of traditional dipole antennas shown in recent works hold promise for increasing antenna directionality for low-frequency systems whilst maintaining a physically small and portable instrument size (Howlader, et al., 2016).

Improvements to Receivers

Unlike transmitter designs, which could seek to increase mean power or increase SNR through coded transmissions, or antennas, which could improve signal clarity and reduce instrument size, improvements to receivers are limited to improvements to SNR. The front end of receivers generally incorporate a low-noise amplifier and an ADC with as many sampling bits as practical and affordable. The latest GPR systems employ 16-bit and higher samplers. However, with the dramatic lowering of costs for ADC chips over the last decade, it is now possible to purchase ADC chips with sufficiently fast capture rates to digitize the full radar waveform for a few hundred dollars. Such real-time sampling receivers are not significantly difficult to design or expensive to build, but can significantly improve radar SNR through stacking alone (Francke, et al., 2009).

In theory, where the limitation of radar performance is a function of the noise floor and not, for example, a lossy layer, radar penetration can be doubled by stacking 1000 times. Stacking that many times would require too much time per station to be practical with commercial radar systems, but a real-time sampling system could stack 1000's of times and still be pulled at high speed. An additional advantage of real-time sampling is that the noise floor is lowered, thereby increasing the bandwidth of the radar system itself, as demonstrated in Figure 8.

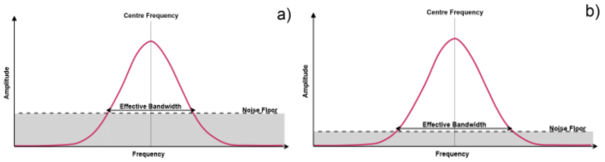

Figure 8: Sequential sampling receivers (a) exhibit higher noise floor and narrower bandwidth than full-waveform receivers (b)

The improvement made possible by modern real-time sampling ADC receivers is illustrated in Figure 9, a sample radar profile acquired over an aeolian sand dune on Stradbroke Island, Australia. The profile at top shows data acquired with a sequential sampling 50 MHz GPR system with collinear antennas, whereas the profile at bottom shows the same profile acquired with a real-time sampling receiver. In both cases, the transmitters were of similar design and mean power, the antennas were both collinear resistively-loaded dipoles, and the processing steps the same.

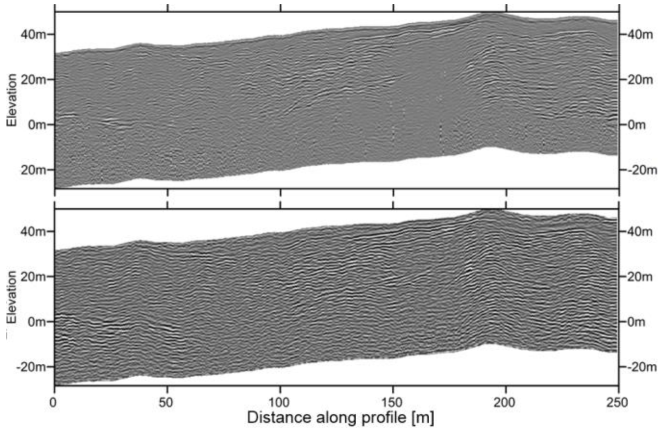

Figure 9: Comparison of commercial 50 MHz radar (top) with real-time sampling 50 MHz radar (below) showing improved bandwidth and penetration through sand dune

Improvements to Portability

Ground geophysical equipment, in general, has a reputation of being overbuilt. Designs of magnetometers, EM meters, resistivity units dating from the 1980s are still in production today, with housing machined from solid blocks of aluminum, or steel plates in some cases. The typical environment these instruments are used in necessitates such extreme protection, although modern manufacturing techniques can drastically reduce the overall weight of the instruments without compromising durability. Furthermore, commensurate with the miniaturization of consumer electronics over the past two decades has been the ability to shrink the size and complexity of the circuits and components within these instruments. Technologies such as surface mounted devices and miniature microprocessors can shrink the size of a radar control board to a fraction of what was required a decade ago. Smaller components and smaller boards tend to require less input power and are easier to maintain physically stable.

Whereas the majority of commercial radar systems still rely on separate, large, units for the radar transmitter, receiver and controller, and a laptop or tablet to record and view the data, it is now possible to combine most of these items into a single, small, circuit board. Figure 10 shows a functional GPR receiver design which draws 260 mAmps at 12 V, can sample full waveforms with real-time sampling using parallel 125 MSPS ADC chips, has an on-board GPS for tracking as well as on-board SD memory card data storage. The data can also be sent via Bluetooth or WiFi to an app running on an Android or iOS phone for monitoring and secondary recording. This board measures only 40 mm x 100 mm, and has a production cost in the range of hundreds of US dollars. The transmitter for this system employs a board of similar size, although it is possible to design a single circuit board with both the transmitter and receiver on board to create a monostatic radar, whereby a single antenna is used for both transmission and reception of the radar energy.

Figure 10: Single-board GPR receiver, control unit and data logger with on-board GPS.

Reducing the size and complexity of the receiver and transmitter electronics, and eliminating the need for a controller unit raises the possibility of manufacturing more complex array radar systems at low cost. For example, a 64-channel GPR system operating at 500 MHz could be manufactured at a cost of less than $10,000 USD. Furthermore, for low-frequency applications, the possibility of multi-fold GPR becomes a practicality.

Figure 11 shows an UltraGPR system which harnesses many of these technological advances for deep radar surveys. The instrument employs a real-time sampling receiver, on-board GPS and datalogging, connected wirelessly to an Android or iOS app. The entire system weighs less than 4 kg, is submersible, and, given its collinear antenna arrangement, can be used in the most rugged of environments. With settings self-calibrating and pre-set, such designs allow extensive radar surveys to be conducted using existing tracks in dense vegetation at low cost using local unskilled labor. Data may then be uploaded to a server and processed offsite by experienced geophysicists.

Figure 11: 30 MHz UltraGPR with collinear antennas for rapid surveying in difficult terrain.

Improvements to Cost

Radar systems have remained at a similar price point since their initial market release decades ago. Units with single antennas average $18,000 USD, whereas multichannel array systems can cost well over $100,000 USD. Such prices are not dissimilar to those of the 1990’s, despite a significant drop in component costs and the availability of streamlined offshore manufacturing for small production runs. Even systems manufactured in China for the domestic market are priced similarly to those from Europe and North America, despite lower manufacturing costs.

Whilst the research and development cost of a GPR system can often not be defined, but can easily account for the majority of the final product cost, the technology is now mature and the integral components are well published in the public domain. The actual component cost of a single channel radar system is less than $1,000 USD, with the mechanics adding perhaps an additional $1,000 USD. Whilst geophysical equipment manufacturers are well within their rights to set pricing as the market will bear, such a disparity between manufacturing cost and sale price leaves the market open to smaller players who may seek to exploit this opportunity.

In recent years, GPR systems have been designed and built by individuals who may be described as hobbyists, often for treasure hunting purposes. Many of these “backyard tinkerers” publicize their developments on-line, whilst others have sold their GPR instruments. Some clearly are not radars and are more aptly described as metal detectors, whilst others are indeed functional GPR systems. One such device is marketed for less than $4,000 USD, and employs an 800V SRD transmitter, bow-tie antennas at 500 MHz center frequency, and a sequential sampling receiver. As an experiment, this device was purchased on-line and tested over a known test site. The results using a 500 MHz commercial radar system are shown above in Figure 1, whilst the results from the homemade system are shown in Figure 12. Although the six buried pipes are not as well defined, the results are certainly comparable. In addition, the surveys were conducted over different times of the year, with the commercial system being used during more favorable dry conditions. Nevertheless, the experiment demonstrates that GPR instruments do not require such high costs to be effective.

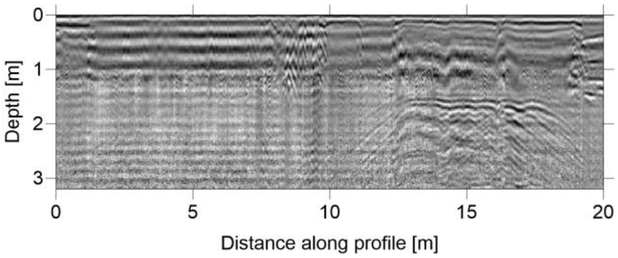

Figure 12: Low-cost 500 MHz GPR acquired over same targets as shown in Figure 1.

There would be few barriers for an experienced manufacturer to take the simple concepts used in the example $4,000 USD system and produce a more capable system *en masse* at a very low cost. Survey positioning, which is often the bane of civil infrastructure surveys as it required experience RTK DGPS systems or robotic theodolites, can now be incorporated into the GPR instrument itself. RTK DGPS chips are now available with accuracies which rival $50,000 USD systems for less than $500 USD (Stempfhuber, et al., 2011). Other positioning technologies which have seen very recent market releases may also be incorporated into new, low-cost, GPR designs, such as UWB RTS positioning or motion capture technologies commonly used in film production to track radar antennas in indoor settings (Campbell, et al., 2015).

Another rarely-published concept for high frequency radar is the concept of phased array radar systems (Das, et al., 2003). Such systems, potentially employing small spatial footprint antennas such as Vivaldi-designs, could be used for shallow scanning of the subsurface with extreme detail, by beamforming and beam-steering using an antenna array.

Improvements to Depth Penetration

The laws governing EM propagation limit the practical penetration of radar energy in lossy environments. As stated, a general rule-of-thumb is that a radar system can reach approximate ten wavelengths in a good radar environment (i.e. low dielectric permittivity and low electrical conductivity). Penetration can be significantly increased by simply increasing the transmitter voltage, as this is usually accompanied by a lowering of the PRF, and thus average power.

The use of real time sampling receivers and bow-tie antennas may somewhat increase radar range, although 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. The most common type of antennas used for GPR systems below 100 MHz are resistively-loaded electric dipoles. In the case of a 25 MHz centre-frequency system each antenna is 3.7 m long. Radar systems below 10 MHz have been constructed for glacier profiling where large open spaces enable very long dipoles to be towed by snowmobiles (Zamora, et al., 2009). However, in most other environments, such low frequency electric dipole antennas would be impractical.

Beyond the size limitation, another limit on low frequency GPR is defined by what is known as the GPR plateau, as shown in Figure 13. GPR fields propagate through media as non-dispersive waves, being reflected or scattered by changes in electrical impedance, which, in turn, create reflections similar to the transmitted waveform. Therefore, signal recognition is simple since the returned waves are similar to the emitted waves. The propagation velocity and attenuation rates of EM fields along the plateau are independent of frequency. Above the plateau, signal absorption due to microwave heating severely limits penetration. Below the plateau, EM fields are diffusive and dispersive in character, which is the real of electromagnetic induction surveying (EMI).

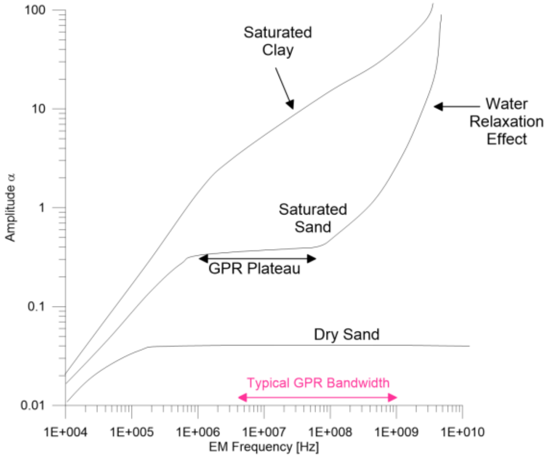

Figure 13: The GPR plateau.

A recent research project seeks to harness the high resolution of GPR and the deep penetration of EMI in a single, hybrid EMI-GPR instrument (AMIRA, 2017). The goal of the project is to create a new instrument which transmits waveforms in the range of 300 kHz to 30 MHz. Although electronically an easy task to accomplish, the fundamental goal of the research project is to design an antenna or series of antennas, which are electrically large yet physically small and portable. Possible designs could employ magnetic loop and other current antennas. Given that wavelengths in the 300 kHz range would be on the order of 300 m, penetration depths may be as deep as kilometers with such a hybrid concept.

Expanding Applications

The miniaturization of radar electronics and the availability of lightweight power sources have broadened the potential fields of application for GPR instruments in recent years. New borehole radars have been developed which are less than 25 mm in diameter and are housed in titanium enclosures and mounted on the end of drill rods (Zhou & van de Werken, 2015). Such systems are used in gold and platinum mines worldwide, particularly in South Africa, to map reef contacts and geotechnical hazards ahead of an active mining face (Figure 14).

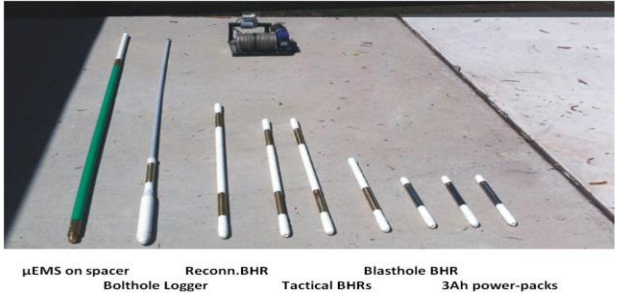

Figure 14: Monostatic slimline borehole GPRs

Miniature GPR instruments have also been designed for mounting on a UAV. Due to the size of the antennas, frequencies are limited to 500 MHz – 1.5 GHz. The potential applications are unexploded ordinance surveys, mapping ice thickness along ice roads and runways, as well as locating avalanche victims. A more challenging application of such UAV-based systems would be to remotely monitor collapsed buildings after earthquakes for human movement, without the need for rescuers to place instruments atop unstable rubble piles themselves. The use of such UAV-based GPR systems may be limited both by legislation, which dictates in Europe, Canada and the US that the GPR antennas must be less than 1 m above the ground, and by physics, wherein a large amount of energy will be lost at the air-ground interface.

Legislation Considerations

Perhaps the most limited factor in the development of commercial radar systems over the last 15 years has been the restrictions placed upon the sale and use of GPR systems in major markets, such as Europe, Canada and the US. In these jurisdictions, low-frequency unshielded antennas are essentially unusable, and shielded systems must undergo rigorous and costly testing and certification to ensure that they do not radiate excessive spurious EM energy, which may disrupt other radio communications infrastructure. Such certification requires low transmitter output power (and thus limited penetration), and careful design of shielding. The use of coded transmitters may be an approach to legally achieve greater average power output in these jurisdictions.

Conclusions

Nearly a century since its first practical use, GPR is now a mature and accepted geophysical tool, used extensively worldwide. Aside from offering the highest resolution of any geophysical method, it also undeniably has the widest fields of application, ranging from imaging rebar in concrete to mapping the base of glaciers kilometers deep.

GPR instrumentation designed two decades ago still form the basis of instrumentation sold today by a handful of major and dozens of smaller manufacturers. However, the depth of research on improved transmitter, antenna and receiver designs, along with the availability of small and more specialized components in recent years has bred an emerging series of “next-gen” GPR instruments. These instruments have the ability to image the subsurface in greater clarity, at high speeds, at greater depths, and as importantly, at lower costs than previously possible.

The design and manufacture of GPR instrumentation is potentially moving away from the domain of large manufactures with production lines and into the realm of backyard hobbyists, with resulting systems which rival the best commercial units. It is quite conceivable that a successful crowd-funded campaign to design and construct an open-source GPR instrument may be possible in the near future. Such a venture would lower costs and potentially increase functionality even further.

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