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GPR Principles and Applications

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GPR Principles and Applications

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70.1 Introduction

Ground-penetrating radar, also known as surface-penetrating radar, geo-radar, or more commonly by
the abbreviation GPR, has seen significantly increased acceptance as a viable near-surface geophysical
technique in recent years. The practice of employing radio waves to image the subsurface dates to work
conducted on glaciers in the Austrian Alps in the 1920s (Stern, 1929). Research on the ice-penetrating
capabilities of radio waves languished until the late 1950s, when it was noted that newly installed radar
altimeters on aircraft could penetrate through the Greenland icecap and display the aircraft’s height
above the underlying bedrock, which led to a number of mishaps (Waite and Schmidt, 1961). Although
the ability to penetrate ice was a limitation for the reliance on radar altimetry for low-altitude flying in
Polar regions, agencies such as NASA took an interest in the ability of radar to penetrate the ground in
suitable environments. A rudimentary GPR system was launched onboard Apollo 17 in an attempt to
determine surface conditions prior to a manned mission to the moon (Simmons et al., 1972).

Stemming from NASA’s requirements for instrument portability and miniaturization and research
conducted by the Atomic Energy Commission, the technology was commercialized in the mid-1970s,
initially for archaeological investigations (Morey, 1974). However, GPR’s potential to locate discrete
targets in the ground, such as buried pipes, cables, tunnels, or land mines, was quickly realized. It was also
found that low-frequency radar waves (10–100 MHz) could image geological contacts in some
environments to depths of dozens of meters (Clough, 1976; Tierbach, 1974). Sedimentologists, geologists,
groundwater hydrologists, and the mineral exploration sector all experimented with the technology in
various environments. This research was assisted by work conducted to better understand the
electrical properties of geological materials at radio frequencies as well as the relationship between electrical conductivity and dielectric polarization of such media (Olhoeft, 1975, 1987).

By the late 1980s, the major restrictions on the further use of GPR as a geophysical tool were the bulkiness and power requirements of the instrumentation. Furthermore, data were generally recorded on electrostatic plotters, limiting the geophysicist’s ability to employ advanced seismic processing techniques, which were keeping pace with the rapidly developing power of desktop computing.

The advent of portable computing and fast A/D microchips in the late 1980s led to a significant reduction in power requirements, more portable instrumentation, and the ability to digitally capture radar data for subsequent processing.

Since the early 1990s, the possible applications for GPR have burgeoned to include the mapping of pavement thickness and cracks at highway speeds (Saarenketo and Scullion, 2000; Spagnolini and Rampa, 1999), network-wide mapping of utilities in full 3D imaging (Eide and Hjelmstad, 2002), and the detection of movement in collapsed buildings (Sachs et al., 2008; Zaikov et al., 2008). GPR has also led to the development of subtechnologies such as wall-penetrating radar (Nag et al., 2001), which is used for the detection of live targets through nonmetallic walls by law enforcement of military personnel, and pipe-penetrating radar (Ariaratnum et al., 2005), which is employed within pipes to detect variations in wall thickness and adjacent voids.

Regardless of the application, all penetrating-radar technologies rely on electromagnetic (EM) fields to probe lossy dielectric materials to image variations in material properties. In most geological material, as well as manmade media such as concrete and asphalt, EM fields will penetrate some distance before being attenuated. The depth could range from many kilometers through Antarctic ice sheets to a few centimeters in some concretes.

### 70.2 Radar Wave Propagation in the Subsurface

Radar signals are emitted by a transmitter and penetrate into the subsurface as nondispersive waves. When the signals encounter a variation in the subsurface material’s impedance, the signals are scattered or reflected, with some of the energy returning back to the surface, where it is captured and digitized by a receiver. Due to the nondispersive nature of radar, the returned reflections are similar to the transmitted signal, making signal recognition and interpretations simple. The frequency range of GPR signals is generally between 1 MHz and 2 GHz. Below the MHz range, the EM fields become dispersive, whereas higher frequencies are limited in their practical application because several factors increase attenuation to a degree where penetration would be limited to a few millimeters.

Maxwell’s equations mathematically describe the physics of the EM theory and thus GPR energy propagation as a 3D polarized vector field. In geological media, the waves travel at velocities lower than the speed of light and are scattered by variations in the electrical and magnetic properties of the subsurface. The subsurface media through which GPR energy must penetrate are referred to as semiconductors, or dielectrics, and are characterized by three EM properties: electrical conductivity, electrical permittivity, and magnetic permeability.

Electrical conductivity, $\sigma$, is the measure of a material’s ability to transmit a direct current, which results in energy dissipation through the conversion of electrical energy to heat. Dielectric permittivity, $\varepsilon$, refers to the degree to which a geological medium resists the flow of electrical charge divided by the degree to which free spaces resists the same charge. The dielectric permittivity is thus defined as the ratio of the electric displacement to the electric field strength and is an important quantity for GPR.

Most of $\varepsilon_0$, the terms relative permittivity or dielectric constant are used, which may be defined as the ratio of $\varepsilon / \varepsilon_0$, where $\varepsilon_0$ is the permittivity of a vacuum. The velocity of an EM wave propagating through a medium is the reciprocal of the square root of the dielectric permittivity.

Magnetic permeability, $\mu$, is the result of electron spin and motion in atomic orbits and also results in energy loss and storage. In most GPR applications, the effect of magnetic permeability is negligible and is often excluded from calculations.
GPR Principles and Applications

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GPR is most effective in environments with low electrical loss media. If the media through which GPR is imaging has \( \sigma = 0 \), the radar system would be able to image great depths, limited only by the power of the radar transmitter and the sensitivity of the receiver. However, neither geological material nor manmade media are perfect insulators, and their semiconductive nature is highly variable and often unpredictable.

One of the greatest determinant factors of the GPR range in most media is the concentration of both pore and bound water. Generally, bulk minerals are good GPR targets with low pore water content and thus exhibit low dielectric permittivities. Conversely, sands and soils have pore spaces filled with air, water, and other minerals. Furthermore, the water within the pores can contain ions from dissolved minerals, with the ionic mobility within the water being the dominant contributor to bulk electrical conductivity.

A number of factors control the maximum range of a radar system. As a radar wave field encounters a discontinuity in impedance, a portion of the energy is returned, while the remainder continues on to greater depths. In an environment with a large number of impedance changes with depth, there is a decrease in the portion of the original imparted energy that is still available to continue deeper. Since the radar energy path is generally two-way, these losses, known as reflection losses, are doubled due to the return journey to the surface. Although this describes a simple layered model, the effects on penetration of which may be modeled easily, most GPR environments also include scattering effects from unwanted targets such as gravels and boulders. Scattering losses cause the incident radar energy to reflect in multiple directions, with only a portion aimed back toward the receiving antenna.

The electrical conductivity of the media being propagated through leads to material losses, which have a significant effect on the maximum range of a GPR system. With increasing conductivity, the radar energy is attenuated more quickly, thereby restricting the effective penetration depths.

The fundamental type of loss is due to the geometric spreading of the radar energy. Although generally difficult to quantify in real-world complex geologies, these losses are exponentially proportional to the range being imaged. The maximum range of a GPR system can be generally estimated by summing these losses along with the losses encountered within the instrument itself.

### 70.3 GPR Instrumentation

A generalized radar block diagram is shown in Figure 70.1. The transmitted energy may be a waveform modulated in frequency, amplitude, or phase, as well as random noise. The amount of power, the pulse rate, and the bandwidth will depend on the lossiness of the subsurface media and the target dimensions. The transmitting and receiving antennas are usually matched and are also designed with target dimensions and signal polarization taken into account, as well as practical size and weight limitations. The receiver must be designed to capture the returned signals quickly and at a sufficient dynamic range to overcome the losses encountered by the radar signals on their two-way journey from the surface to the target and back to the surface.

Of the possible modulation techniques, amplitude modulation, commonly referred to as impulse radar, is most commonly employed for GPR instrumentation. Presently, there are over a dozen manufacturers of commercial GPR systems worldwide, with all but two employing impulse transmitters. In such systems, a train of impulses are applied to a transmitting antenna. The impulse sequence may have amplitudes ranging from 20 to 400 V, a width of a few nanoseconds, and a pulse repetition frequency (PRF) in the range of 100–800 MHz. The signals returned from the ground are applied to a flash A/D converter or, more commonly, to a sequential-sampling receiver with a high-speed sample-and-hold circuit. The requirement for ultrafast sampling generally restricts impulse radars to the range of 10 MHz to 1 GHz.

For radar frequencies greater than 1 GHz, frequency-modulated continuous wave (FM CW) radar architectures become more suitable. Thus, such systems are generally employed for shallow,
high-resolution applications such as pavement analysis and landmine detection. In an FM CW system, a continuously changing carrier frequency is repeatedly transmitted using a voltage-controlled oscillator over a range of frequencies. The returned signal is combined with a sample of the original transmitted waveform, which produces a difference frequency related to the phase of the received signal and thereby a different time delay and range in relation to the target reflector. To produce a radar signal similar in the time domain, the difference frequency must be derived from an I/Q mixer pair (Daniels, 2004).

### 70.4 Commercial Radar Systems

As of 2012, it is estimated that there are between 10,000 and 20,000 GPR systems in existence worldwide. Although the majority of these are used on rare occasion for research purposes, many thousand systems are employed regularly for commercial surveys. The first commercial manufacturer of GPR systems, Geophysical Survey Systems, Inc., of Salem, N.H., United States ([www.geophysical.com]), remains the world leader in terms of sales volumes, followed closely by Sensors and Software, Inc., of Mississauga, ON, Canada ([www.sensof.ca]), and Malå Geoscience of Malå, Sweden ([www.malags.se]). In addition, over the last decade, Inggrernia dei Sistemi SpA of Pisa, Italy, has become known for their multichannel GPR systems. More recently, researchers from the former Eastern Bloc countries and from China and South Korea have also begun to commercialize GPR systems.

Each of these manufacturers tends to focus on the lucrative civil infrastructure market, which includes rebar detection in concrete, road, and railbed analysis, utility mapping, and void identification. Although the instrumentation is packaged differently and the robustness and flexibility of the design vary greatly, all systems generally employ impulse transmitters with shielded bowtie antennas and sequential-sampling receivers. Figure 70.2 shows a typical commercial cart-mounted GPR system employed for utilities detection.

For low-frequency radar applications (10–200 MHz), manufacturers rely on resistively loaded dipoles for the transmitter and receiver antennas, as depicted in Figure 70.3. Such antennas can be unwieldy in difficult terrain, such as in forests, where cut lines up to 4 m wide are required. Alternatively, dipole antennas may be placed collinearly, allowing the radar system to be housed within a long “snake” and towed easily along a trail. Malå Geoscience’s RTA system and the UltraGPR from Groundradar, Inc., in Vancouver, Canada ([www.groundradar.com]), both employ such a design with real-time radar receivers for long-range imaging of mineral deposits (Figure 70.4). Such a collinear orientation of
radar antennas often produce clutter patterns on the received radar profiles due to the end fire from the antennas reflecting off of aboveground targets such as trees.

In recent years, the availability of large array radar systems for 3D mapping of wide swaths has grown significantly (Figure 70.5). One of the pioneers in the field, 3D-Radar AS of Trondheim, Norway (www.3d-radar.com), has commercialized large radar arrays for pavement and utility mapping using FMCW radar architecture. Radar Portal, Pty., of Brisbane, Australia (www.radarportal.com.au), specializes in integrating large radar arrays using noise-modulated FMCW radars with complementary sensors such as high-speed falling weight deflectometers, panoptic cameras, and laser profilers to comprehensively map road surfaces and structures at highway speeds.

FIGURE 70.2 Typical cart-mounted utility-detection GPR.

FIGURE 70.3 Low-frequency dipole antennas.
Environmental

70.5 Typical Commercial Applications

A review of GPR manufacturers’ websites would suggest that GPR is a panacea to all near-surface imaging problems. What are often neglected or downplayed are the inherent limitations of GPR in many, if not most, environments. These limitations are governed by the laws of physics, and no degree of advanced radar design, virtual-reality 3D software, or high instrument price can circumvent them. Listed in the following text are the most common applications for GPR technology for commercial surveying. A myriad of other applications are possible, ranging from tree root imaging and the detection of wood rot and landmine detection.

70.5.1 Utilities Detection

Perhaps the first substantial commercial application of GPR technology was the mapping of buried utilities. With many urban areas, “as-planned” maps are often unrelated to “as-is” conditions underground. The severing of a sewer or natural gas line can have disastrous consequences. Traditional methods such
as radiodetection can yield ambiguous depths or inaccurate results in clustered pipes. While disruptive trenching has given way to trenchless technology such as horizontal directional drilling, which enables far more rapid installations in urban settings, engineers still rely on a degree of chance to avoid collateral damage to preexisting plants. As existing plants age and cities expand, the need for a tool to rapidly and accurately map existing utilities has become critical.

Although seemingly an ideal solution, particularly for metal pipes and cables, GPR suffers from some limitations. The most common is due to signal attenuation in the subsurface. Many cities built along floodplains or in coastal zones are situated atop clay units, which significantly restrict radar suitability to as shallow as a few decimeters. It has been estimated that in the United Kingdom, only 60%–70% of the total land area may be suitable for GPR surveying (Daniels, 2004). A further limitation is that in a situation where radiodetection is ambiguous and GPR is most useful, such as clusters of pipes and cables, radar is generally ineffective without extreme care in sensor positioning and complete high-density 3D imaging by surveying the region in perpendicular directions. Such surveys are time-consuming with single antennas, often require positioning accuracies not practical in urban settings, and generally still produce data volumes subject to ambiguous interpretations.

Nevertheless, a significant portion of the commercial GPR market is aimed at utilities detection. In many environments, such as parking lots and open fields with uncluttered pipe layouts, GPR can be a highly effective tool at mapping utilities. Figure 70.6 shows a typical radar cross section of a series of utilities, each shown a characteristic hyperbolic reflection signature.

### 70.5.2 Pavement and Railbed Analysis

Traditionally, the health of a road or highway has been measured using methods such as falling weight deflectometers to determine dynamic moduli and coring to measure the thickness of various construction layers. Together with other sensors such as surface roughness, profilometers, and data on traffic flow, estimates of the residual life of the road can be determined. These approaches are time-consuming and costly and also interrupt traffic flow during surveys. Furthermore, coring disturbs the road surface and provides information only at disparate points.
70.5.3 Concrete and NDT

The advent of high sampling rate A/D converters for high-frequency radar receivers and the further miniaturization of electronics have led to the proliferation of relatively low-cost concrete radar systems. Radar now forms an important role in the nondestructive testing (NDT) of in situ concrete. In many jurisdictions, standard practices for GPR use in concrete NDT have been published (American Concrete Institute, 1998; Concrete Society, 1997; Texas Transportation Institute, 2001). Products such as the Hilti PS 1000 X-Scan (www.hilti.com) have moved concrete GPR from the exclusive realm of geophysics to a consumer product on par with inspection cameras. The acquisition of accurate 3D grids for rebar mapping is now a trivial task using adhesive templates (Figure 70.7). Applications for these systems include the location of rebar and posttensioning cables as well as metal and plastic conduits and voids, with the former being the most common. The optimization of antenna orientation to maximize the effect of signal polarization is important for both the imaging of rebar and for attempting to image through them to deeper targets (Annan et al., 2002).

Recent research in this field has focused on determining the size and shape of voids (Pollock et al., 2008), the location of honeycombing and cracking (Beutel et al., 2008), and the estimation of rebar size and corrosion (Lai et al., 2010). Each of these subjects has been studied extensively through numerical modeling and laboratory measurements, although practical applications have remained elusive.
70.5.4 Snow and Ice

The original applications of GPR, snow and ice, provide the ideal environment for radar penetration. Extremely low conductivity, low dielectric permittivity, and no magnetic relaxation processes combine to permit penetration to many kilometers. Spurred by an interest in climate change, ground-based, as well as increasingly airborne, GPR surveys are being regularly conducted by researchers over glaciers with impressive results (Arcone, 1996; Arcone et al., 2000; M aijala at al., 1998). Such data are of use in the examination of ice structures and paleoclimatic studies.

Common commercial applications include the delineation of ice thickness for ice roads and runways as well as the creation of snow thickness maps on ski slopes. Recent discoveries of major oil and diamond resources in the Arctic have created the need for an extensive network of seasonal ice roads and runways. Ice thickness is traditionally controlled by manual auger coring, a process that is both slow and inherently inferential due to practical limitations on hole spacing. Furthermore, as weather conditions change, it is critical the ice roads and runways be monitored regularly in order to ensure that minimum ice thicknesses are maintained. High-frequency antennas (500 MHz-1 GHz) are of en used for this application. Water lenses in the ice may cause significant distortion in the radar profiles or inhibit further radar penetration altogether (Galley et al., 2009). The ideal radar velocity of ice is approximately 0.17 m/ns, while water has a velocity of 0.03 m/ns. Not compensating for this significant variation in velocity will lead to inaccurate depth maps.

Recent developments have included the use of multichannel radar systems designed for roadbed surveys to automatically collect radar velocity information. While allowing for more precise ice depth maps, the dielectric permittivity variations, calculated from the radar velocities, may also yield information on the load-bearing characteristics of the ice (Proskin et al., 2011).

GPR is now a common tool used for monitoring snow depth at ski resorts (Heilig, 2008). The optimal distribution of natural snow and the creation of manmade snow are reliant on accurate and dense snow depth data, which have been traditionally measured by probing. GPR systems fitted with GPS can be easily mounted on hand-towed sleds to rapidly provide snow maps with 3D depth. When mounted on groomers, GPR can provide a real-time display of snow thickness, allowing the operator to redistribute the snow evenly over a run. Such radar systems eliminate the need for an expert interpretation of a GPR profile by automatically interpreting the depth of snow and storing only these depths and GPS locations for subsequent mapping.
70.5.5 Archaeology and Forensics

Archaeologists were among the first to realize the potential benefits of the rapid subsurface imaging that GPR made possible in the 1970s. Early surveys were conducted to search for buried foundations and stone walls (Bevan and Kenyon, 1975). In addition, extensive surveys were conducted during the 1980s in Japan for burial mounds and ancient pit dwellings (Imai et al., 1987).

Although hundreds of successful surveys have been performed and the technique has been well established as a viable tool for both archaeology and forensics, these surveys are ofen conducted by untrained users in environments unsuitable for GPR. As the intended targets for such GPR investigations are ofen discrete objects buried among other radar reflections from geological features, the results of a “radar search” ofen produce ambiguous anomalies. Prior to the ability to integrate high-precision GPS positioning to track the radar antennas, surveys only relied on widely spaced 2D cross sections to map targets. Modern GPR systems with integrated RTK-DGPS allow the user to traverse a search site rapidly in a random semigrid pattern, ofen with lines spaced decimeters apart (Nuzzo, 2002). These data may then be input into a gridding algorithm to produce a 3D voxel cube, which may subsequently be sliced both vertically and horizontally to discriminate a potential investigation dig site from background clutter.

Regardless of these advancements in the 3D visualization of archaeological GPR data, the inherent ambiguity of the technique in all but the most ideal environments suggests that GPR is best considered in tandem with another sensing tool such as magnetics and/or EMs.

70.5.6 Tunnel Detection

Concurrent with the development of radar for lunar exploration and monitoring nuclear test explosions, the US military experimented with early radar systems to detect tunnels beneath the DMZ along the 38th parallel (Kim and Ra, 1993). Tunnel detection, whether for security or geotechnical applications, has always been an important application of GPR.

While manufacturers ofen display images of clear radar profles across large highway tunnels through solid bedrock, the most practical applications for tunnel detection are situated in areas of significant subsurface and aboveground clutter and involve relatively small tunnels at significant depths. Research on the use of GPR to monitor tunneling beneath sensitive borders such as the US-Mexico frontier and the West Bank and the Gaza Strip has yielded moderate results due to the generally conductive nature of the soils in these locations (Cechak, 2007; Matter and List, 1995). Furthermore, due to the ambiguous nature of radar targets, security personnel are ofen reluctant to rely solely on the technique due to the costly implications of false anomalies (Pappalardo, 2009).

Similarly, in the geotechnical community, GPR has found mixed success at locating abandoned mine workings (Duf, 1983; Fenner, 1995; Leggo and Leech, 1983). Perhaps the most crucial need for the remote sensing of tunnels is that of abandoned coal mines. Ofen, urbanization has encroached on historical mining areas, raising the risk of ground subsidence or collapse. Such applications generally require shielded antennas to minimize the effects of interference from aboveground reflectors and other EM signal sources. Due to size limitations, the lowest frequency shielded antenna commercially available is 100 MHz, which restricts the practical search depths to less than 8 m in most environments. Recently, a partially shielded 40 MHz system has become commercially available for tunnel detection (Francke, 2012).

70.5.7 Sedimentary Geology

Geologists have long employed radar imaging to past depositional environments and the nature of sedimentary processes in a variety of settings, particularly in describing unconsolidated recent and Quaternary fluvial deposits both above and below the water table. Numerous studies dating to the early 1990s provide excellent examples of fluvial stratiforms (Jol and Smith, 1991, 1992; Vandenberghhe and van Overmeeren, 1999).
An associated commercial application of sedimentary geology studies is the mapping of paleochannels for alluvial gold and diamond exploration. A complete understanding of the paleof luvial environment is critical to resource exploration and project economics. Exploration is normally conducted using drill holes and trenching, with seismic or EM geophysical surveying occasionally employed. GPR is increasingly being trialled in suitable environments where the in-filled sediments consist of course-grained sands and gravels in order to map the ore-rich basal gravels. Figure 70.8 shows an example of a radar-imaged paleochannel from an alluvial project in Guyana.

Given the low electrical conductivity and dry nature of the environment, desert sand dunes are of an ideal radar settings. Studies of the internal structure of dunes are useful for studying desertification and climate change processes as well as for constructing petroleum reservoir analogies. While studies of sand dunes with GPR have been conducted over the last two decades (Bristow and Jol, 2003; Bristow et al., 1996, 2000), recent advances in rapid long-range radar have enabled the deep profiling and 3D surveying of sand dunes (Tatum and Francke, 2012). The example shown in Figure 70.9 demonstrates the suitability of radar in mapping the complex sedimentary bedding features of large duneforms.

70.5.8 Tropical Weathering Environments

One of the most common applications for GPR technology in mineral exploration is in tropical weathering environments with residual enrichments of either nickel (nickel laterites) or aluminum oxide (bauxites) (Francke, 2012). Both environments pose particularly challenging problems for traditional resource definitions that use drill holes alone, due to the extreme lateral variability in weathering thicknesses. Radar penetration depths of up to 70 m have been recorded in these weathering environments, with many tropical types of clay exhibiting unexpectedly low electrical resistivities. Although the clay-rich limonite and saprolite contain high bound water and thus are characterized by relatively slow radar
velocities, the lateritization process, with its repeated seasonal groundwater fluctuation, effectively leaches most of the conductive mineralogy from the profile.

The primary objective of nickel laterite and bauxite exploration is the mapping of the contact between weathered materials with the underlying bedrock, which commonly defines the limit of mining. Radar reflections from this interface are due to the dramatic change in water saturation between the moist weathered zone and the dry solid parent rock beneath. Similarly, the boundary between weathered soil and the interstitial rocky saprolite is well imaged with radar as a region of superimposed hyperbolic reflections. Figure 70.10 shows an example of GPR data acquired over a nickel laterite deposit.

In some lateritic bauxite deposits, particular challenges are faced due to the thin ore zone and the undulating nature of the underlying ferricrete. Seasonal fluctuations in the water table result in regions of diffuse bauxite to ironstone transitional zones, whereas a static water table produces a more abrupt transition. Resource exploitation consists of a large earth-moving operation, wherein the avoidance of bauxite ore contamination by the silica in the underlying ferricrete is critical while still maximizing the tonnage of extracted bauxite. GPR has been used to accurately map the depth of bauxite and the texture of the underlying horizon with high accuracy, with the intention of eventually using a GPR-generated digital surface model to form a "mine-to" surface for semi-automated excavators (Francke and Yelf, 2003).

70.6 Future Advancements in GPR

70.6.1 Depth Range

With the ongoing development of faster processors and A/D converters, the future of long-range radar is seemingly limitless. However, both the laws of physics and practical limitations will significantly inhibit deeper radar systems in the future. In the realm of impulse radars, to double the penetration of an existing GPR transmitter in a given geological environment, an increase of 30 dB in system performance would be required, which in turn requires an increase in peak transmitter voltage of 1000 times. Generating hundreds of kilovolts in a portable instrument is not practical. Furthermore, the PRF of the transmitter would need to be lowered substantially to avoid saturation of the components.

An alternative approach to increasing penetration in environments where the radar range is limited by the noise floor is through stacking or averaging of radar signals at colocated positions, thereby increasing the signal-to-noise ratio. Stacking 1000 times would theoretically double the penetration over a single-stack system. The sequential sampling used in most radar systems limits the practical number of stacks to approximately 32. Technologies such as UltraGPR employ real-time sampling to effectively stack 32,000 times in the same amount of time that it takes a sequentially sampled system to stack 32 times. In addition, the latest GPR systems employ completely wireless designs and use PDAs or mobile phones as data acquisition computers.

Even further depth penetration may be achieved by using pulse compression techniques, which refer to the wave-shaping process that is produced as a propagating waveform is modified by the properties...
of the transmission system (Uttsi, 2007). Pulse compression combines the high energy of a long pulse width with the high resolution of a short pulse width. Since each part of the pulse has a unique frequency, the resultant returns can be completely separated. A GPR system developed for extreme penetration in suitable radar environments using pulse compression has imaged to 200 m through Libyan sand dunes. T is penetration through dunes demonstrates the possible applicability of radar techniques to seismic static correction problems in deserts. A thorough understanding of the variations in the shallow low seismic velocity (LVL) zones in these environments is critical for seismic processing.

Accepted approaches of up-hole surveys and drilling are costly and time-consuming and provide only point data over a large concession. GPR is showing promise of being able to penetrate to sufficient depths to image the base of the LVL.

70.6.2 Rapid 3D Surveys

The proliferation of multichannel array radar systems over the past 5 years foretells the future of GPR surveying for shallow civil infrastructure surveys through the use of instruments that can survey wide swaths of ground at once and of en at high speeds. These systems are linked to RTK-DGPS or robotic theodolites to provide accurate positions for each of the antennas. The latest radar processing software, Ref ex (www.sandmeier-geo.de) and GPR-Slice (www.gpr-survey.com), are capable of importing and manipulating these large data volumes to visualize buried targets. However, such systems are an order of magnitude more costly than single-channel radar units, suggesting that most future GPR surveys will be conducted by large companies capable of the required capital investment.

70.7 Conclusion

Four decades after commercialization, GPR has gained acceptance as a mature geophysical method. While the rapid growth in the number of manufacturers has yet to lower equipment prices, the increased competition in commercial systems appears to have split the market into two approaches to instrumentation. Systems intended for small-scale utilities detection, pavement studies, and concrete NDT are no longer designed as high-level geophysical instrumentation but as standard job site tools to be used by untrained workers. Conversely, large-scale surveys conducted by multichannel radar arrays and long-range GPR systems designed for mineral exploration have become increasingly expensive and complex, relegating their use to the largest and most experienced service providers. This bifurcation of the radar instrumentation market is likely to continue for the foreseeable future, with more manufacturers being spun off from university research laboratories. Eventually, competition should drive down the cost of single-channel units.

Although new uses for GPR appear in the literature each year, they are generally ancillary to those that have been well established over the past decades. What appears to be the future is the incorporation of GPR as a complementary tool in a suite of sensors, such as those used for roadbed analysis. EM sensors, magnetometers, precision positioning and guidance sensors, and LIDAR (light detection and ranging) all have applicability when fused with subsurface radar for use in many different scenarios.

Partial List of GPR Manufacturers and Suppliers

Geoscaners AB, Sweden
http://geoscaners.com
Ingegneria Dei Sistemi, Italy
http://www.idcompany.it
International Groundradar Consulting, Inc., Canada
http://www.groundradar.com
Koden Electronics Co., Ltd., Japan  
http://www.koden-electronics.co.jp/eng/
Mala Geoscience, Sweden  
http://www.malags.com
Non-Intrusive Inspection Technology, Inc., United States  
http://www.niitek.com
PipeHawk, Plc., United Kingdom  
http://www.pipehawk.com/
Radar Systems, Inc., Latvia  
http://www.radsys.lv
3D-Radar, Norway  
http://www.3d-radar.com
Geophysical Survey Systems, Inc., United States  
http://www.geophysical.com
Radarteam Sweden AB, Sweden  
http://www.radarteam.se
Sensors and Software, Inc., Canada  
http://www.sensof.ca/
Subsurface Imaging Systems, United States  
http://www.usradar.com/
Transient Technologies Company, Ukraine  
http://viy.com.ua/e
UTSI Electronics, Ltd., United Kingdom  
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