A Theory Primer And Field Guide For Archaeological, Cemetery, And Forensic Surveys With Ground-Penetrating Radar

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A THEORY PRIMER AND FIELD GUIDE FOR ARCHAEOLOGICAL, CEMETERY, AND FORENSIC SURVEYS WITH GROUND-PENETRATING RADAR

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1 INTRODUCTION

This GSSI Handbook was specifically designed for archaeological surveys, cemetery investigations, and forensic searches (herein abbreviated ACF). These GPR applications have many similarities and there is considerable overlap in pertinent theoretical considerations and recommended field techniques. The main goal of this Handbook is to provide an overview of relevant GPR theory and to inform new and experienced operators in recommended GPR field procedures for various project settings. There are many excellent scholarly articles and books (see Chapter 8) that cover GPR theory and data interpretation, but there are very few (if any) that actually describe ***how to do GPR surveys***. Therefore this Handbook is an attempt to fill the conspicuous literature gap, and is based on the author's experiences learning GPR over the past 15 years, multiple years of teaching GPR classes at GSSI, and from the many questions asked by GSSI customers on best practices for ACF data acquisition. The major hardware focus is SIR3000 and later control units and 350MHz to 900MHz antennas. A future version of this Handbook will include recommendations for StructureScan MiniXT data collection and for the GS Series' 200HS antenna. The methods discussed herein focus on 3D data collection within geophysical grids but also provide recommendations for profile-based surveys. Gridded datasets are critical for ACF projects because they ensure predictable data density, prevent gaps in coverage, and provide time slices to illuminate the geometry of buried targets and features. This 3D focus should not be misinterpreted as a lack of interest in 2D profiles. On the contrary, during post-processing and data interpretation the interpretive power of 2D profiles is equal to, if not greater than, 3D time slices. The 2D and 3D data should always be used in concert to provide a data-based interpretation of a dataset.

ACF projects have two critical and inseparable components: fieldwork and computer-based post-processing. Each of these elements is intimately tied to the other. To get the most out of your GPR data you have to understand what is required for assembling, processing, and interpreting GPR data, and this directly affects the decisions made during data collection. This document is a companion to GSSI's RADAN 7 for Archaeology, Cemeteries, and Forensics Handbook and the field methods covered are heavily focused on interoperability with RADAN 7. You must know what your software requires so you can make the best decisions in the field. Field mistakes can sometimes be corrected in post-processing, but usually an extra few minutes spent in the field can save hours of software frustration. If you do not know what your software needs, how can you collect effective data?

GPR is not an ideal "real-time" technique for ACF surveys. The discussion below will illuminate the reasons for this. In a nutshell, GPR field data are noisy and inherit external interference and soil-related issues. These problems can mask important targets in real-time and reduce data interpretability. On the other hand, after data have been collected, processed, and interpreted GPR can be quite useful to relocate features and to fine-tune excavation locations.

There are numerous geophysical devices used for ACF projects, including electrical resistance, magnetometry, and GPR. These instruments measure different physics properties of subsurface materials and can be quite complimentary when used in concert. Each instrument class has a different method for deploying the equipment and acquiring the data, with associated limitations based on surface cover and environmental factors. GPR is one of the only methods that provides accurate depth information, and as such it is ideal for evaluating soil layers and targets in complex depositional settings. Rather than a plan-view composite of everything within the sensor range, GPR creates a true three-dimensional dataset with vertical profiles and plan-view time slices at different depths. This functionality is excellent for ACF – it provides cross-sections for evaluating stratigraphic relationships while time slices reveal the geometry of anomalies and show their vertical and horizontal spatial relationships.

GPR has never been easier to use thanks to recent and on-going engineering developments. This means that the learning curve is shallower and that better data can be acquired earlier in the learning process. An added benefit is that the GPR form factor has decreased, facilitating easier transportation and deployment of the equipment. Combine these advancements with an archaeological GPR specialist at GSSI and you have the perfect recipe for successful GPR projects.

1.1.1 Recommended field equipment

Having the right field equipment makes everything easier. This includes GPR accessories and extra batteries, but also tape measures, tent stakes, graph paper and other items. Here's a checklist of essential non-GPR equipment that should always be on hand.

- **Surveyor's tape measures –** minimum of three. If surveying in feet consider buying tape measures in engineered feet (10ths of feet); this will make it easier to lay out grids.
    - Two 100m/300ft tapes
    - Two 50m/ 150ft tapes
- **Road cones –** I use these while collecting gridded GPR datasets. They serve as targets that help me walk straight lines. The use of cones during gridded surveys is discussed later in the handbook (see Section 4.1.10). There are many varieties out there. Small running cones are easily blown away by wind. Standard road cones are too large to carry into remote field locations. A good compromise is to use collapsible automotive road cones. They are heavy enough to resist the wind and collapse down into a low-profile square.
    - 4 road cones
- **Metal tent stakes** – these are indispensable for laying out grids and securing tape measures. I prefer the simple hooked tent stakes sold at Walmart or other similar stores. If you are also conducting a magnetometer/gradiometer survey you should purchase aluminum tent stakes.
    - >20 aluminum or steel tent stakes
- **Zipper bag/ bankers bag –** useful for storing tent stakes.
- **Plastic tent stakes** – I usually have 10 yellow plastic tent stakes (6") on hand. When a survey is completed I will hammer the plastic stakes into significant grid nodes to facilitate relocation of the grid and assist with ground-truthing efforts. Plastic stakes are preferable to metal because they will not affect lawnmowers, hay bailers, or other machines.
    - 10 yellow plastic tent stakes
- **GPS** – useful for georectification of GPR grids. Higher accuracy (<50cm) is preferred.
- **Notebook –** weatherproof notebooks (like Rite-in-the-Rain) are preferable
- **Graph paper** – I recommend 10 squares/inch
- Pencils and Sharpie or other indelible markers
- Small ruler
- Bug spray, sunscreen, and wide-brimmed hat (fedora recommended but not required)

2 GPR THEORY OVERVIEW

There are many excellent resources for learning GPR theory (see Chapter 8) and this document is not intended as a complete treatment. Instead, herein I will summarize the most relevant theoretical information and provide an overview that compliments the field practices discussed later.

Ground-penetrating radar [GPR] is an active geophysical technique that uses wide-band electromagnetic [EM] pulses to non-invasively assess subsurface conditions. The GPR energy is safe to use as it outputs approximately 1% of the emissions of a cellular phone. GPR energy propagates into the ground as an expanding wavefront often referred to as a cone of penetration. The farther the wavefront travels from the antenna the wider its footprint becomes. Think of this like a flashlight. If you are close to a wall the illuminated area is small; the farther you walk away from the wall the larger the illuminated area. This spreading-with-depth effect is important conceptually because it can distort deeply-buried targets and reflections. On the other hand, it is this property that generates ubiquitous hyperbolic targets from point source objects (see Section 2.1.6). In air the cone of penetration spreads at an approximate 90-degree angle from the front to the back of the antenna, and eventually stretches beyond the footprint of the antenna. There is an approximate 45-degree spread from side-to-side, or perpendicular to normal antenna orientation, and this creates side-lobes to the wave propagation. In concrete inspection fieldworkers capitalize on this principle to cross-polarize antennas (90 degrees to normal orientation) and reduce the width of hyperbolic tails. Cross-polarization is not common in ACF surveys because hyperbolic tails are important for data interpretation, and hyperbola-based migration requires normally-polarized data.

Reflections from subsurface materials occur when the GPR energy changes its speed at the interface between layers or objects. Velocity changes occur when there are contrasting chemical and electrical properties between materials. A common misconception is that GPR simply measures density contrasts; density is an important variable for water retention but is not the driving force behind energy reflection. At an interface with a velocity change a portion of the total available energy is reflected and travels back to the antenna, while the remaining energy travels deeper until it encounters another interface. This process continues until all available energy is depleted. The magnitude of the velocity change controls the amplitude of the reflection; larger changes create brighter, higher amplitudes. Phase/polarity information reveals whether the velocity increased at an interface (negative-positive-negative) or decreased (positive-negative-positive). In the absence of velocity changes there will be no reflections regardless of any visual stratigraphic indicators, such as those derived from translocation of iron and aluminum sesquioxides (from illuviation) or textural deviations. For these and other reasons GPR profiles are not a literal representation of subsurface stratigraphy. Profiles represent vertical amplitude and phase changes measured across subsequent scans. Spreading effects and related distortion from a wide cone of penetration, hyperbolic targets, and other data artifacts are common and they create complex and imprecise datasets. Combined with other variables, like external EM interference and soil-related noise, novice GPR operators may initially find the data difficult to read and comprehend, but it is the GPR interpreter’s responsibility to understand the behavior of GPR and be able to recognize all of the data artifacts that can be present.

2.1.1 The anatomy of a GPR profile

A basic understanding of GPR data begins with GPR profiles and their characteristics (**Figure 2-1**). This includes identifying the direct wave and time zero position, phase/polarity and amplitude information, and the presence of layers and discrete targets. When a new project is started on a UtilityScan Pro system (SIR4000-based or SIR3000-based) the data window displays scrolling data that manifest as long horizontal lines. There will also be an O-Scope window; this reveals what the GPR system "sees" beneath the antenna in the form of a reflection trace. Often referred to as a scan or an A-Scan, the O-Scope shows the combined samples (typically 512 samples) collected across the current vertical time range. There is a 0.0 line down the center, and peaks of various sizes to the right (positive phase/polarity) and to the left (negative phase/polarity) of the 0.0 line. The O-Scope will be fairly stable when the antenna is stationary, though external interference may cause periodic data spikes. With increasing time range the bottom of the O-Scope might become unstable, and when a depth limit has been reached it will appear chaotic. The top of the profile should show consistent high-amplitude and flat-lying reflections, arranged as black-white-black. These reflections make up the Direct Wave, and are generated by the GPR energy traveling from transmitter to receiver inside the antenna. Since the geometry of the antenna does not change these are constant reflections with little to no deviation.

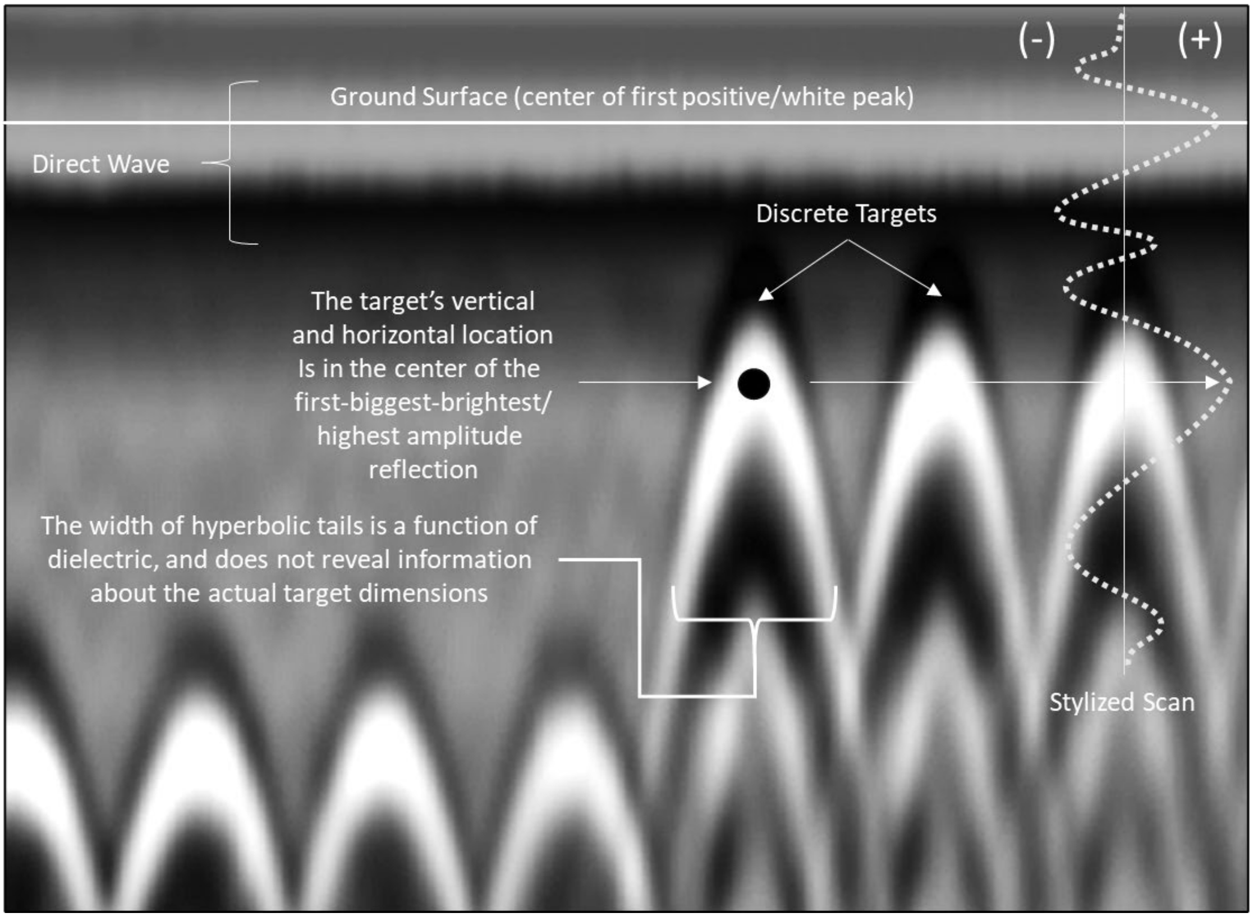


Figure 2-1 Anatomy of a simple GPR profile

The Time Zero position is calculated as nanoseconds of displacement from the 0.0 amplitude point between the first low amplitude negative peak and the first high amplitude positive peak. This is a stable and repeatable measurement and is therefore an important reference point. The ground surface, in general usage, is considered to be in the center of the first high-amplitude positive peak. A more conservative estimate might place the ground surface at 90% of the first positive peak. The Direct Wave is an important piece of information and must be located at the top of the profile. If it is not visible, the Position (or potentially Surface Percentage) should be adjusted on the control unit. Just remember that some forms of real-time processing, like a background removal or the UtilityScan's band filter, can suppress or remove the Direct Wave.

2.1.2 Conductivity/ resistivity and magnetics

As an EM device GPR is susceptible to environmental conditions that could disrupt either the electrical or the magnetic components. If one component (electrical or magnetic) is adversely affected then the other is as well. GPR operates best in resistive conditions. Conductivity (the inverse of resistivity) has the greatest negative effect on GPR propagation; if conductivity levels are high the GPR wave enters the ground, is dissipated, and the energy does not return to the antenna. Conductivity can be increased by anthropogenic salt pollution or natural salt content (when dissolved in water), nitrates (from fertilizer), and the cation exchange capacity of soils. Other factors include inherent conductivity of certain clay types (see Section 3.1.5) where their conductivity increases with increasing water content. The magnetic component can be affected when soils and sediments have high magnetic susceptibility or high iron content. This can occur in ancient highly-weathered soils (laterites) or in soils derived from highly-magnetic bedrock (some basalts or iron-rich sandstones). The magnetic component can typically be ignored unless surface materials are iron-rich (Cassidy 2009). The effects of conductivity and magnetic-induced issues increase with frequencies above 500MHz (Cassidy 2009), and this is referred to as frequency dependence (Bradford 2007).

2.1.3 GPR velocity/dielectric and reflections

GPR energy does not travel at a constant speed through all materials. It travels the fastest through air and the slowest through fresh water. Velocity is related to the square root of the dielectric (Goodman and Piro 2013), or the ability of a material to store and transmit an applied EM field (Conyers 2013, Goodman and Piro 2013). Low dielectric materials result in faster velocity, and higher dielectrics reduce wave velocity. This is because higher dielectric materials store the EM charge for a longer time and thus it takes longer for the GPR wave to travel through them. Metallic objects do not allow the transmission of GPR energy and as such they violate the dielectric scale (velocity of 0.0 at the boundary with metal). GPR reflections occur whenever the transmitted wave changes its velocity due to contrasts in chemical and physical properties (dielectric changes) at layer or target boundaries. Generally this is directly related to the amount of pore water available and sediment texture/grain size. At such boundaries some of the transmitted wave is reflected back to the antenna and the rest travels through to the next boundary. Larger changes in velocity/dielectric create higher amplitude/stronger reflections (higher reflection coefficient) and reflect more of the total available energy. The reflection coefficient, or the amplitude/strength of a reflection at an interface, can be determined by calculating the "difference between the square roots of the dielectric between the materials" (Goodman and Piro 2013). The formula for reflection coefficient [R] is:

$$R = \frac{(\sqrt{e}_1 - \sqrt{e}_2)}{(\sqrt{e}_1 + \sqrt{e}_2)}$$

R = Reflection Coefficient
e_1 = Dielectric Constant for Layer 1
e_2 = Dielectric Constant for Layer 2

At some point there is not enough energy to travel back to the antenna and the depth limit is reached. Dielectric/velocity will change seasonally, and can change overnight with large rainstorms. Dielectric must be as accurate as possible because we use it to convert two-way travel time to depth. Modern GPR control units provide a real-time hyperbolic matching feature for this calculation, though in some case targets of known depth can be used to enter a ground-truth value.

2.1.4 Calibrating the depth scale and dielectric

Dielectric (or Relative Dielectric Permeability [RDP]) is a stand-in for velocity and is conceptualized on a scale from 1-81. Air (dielectric = 1) exhibits the fastest radar velocity (0.3 m/ns) and freshwater (dielectric = 80/81) exhibits the slowest velocity (0.03 m/ns) (**Table 1**). Almost all natural and human-made materials have a laboratory-established dielectric. Metallic objects are assigned a dielectric of infinity (∞), or the highest possible dielectric and the slowest possible velocity (0.0 m/ns), because the GPR energy cannot pass through them and this leads to 99.999% energy reflection. It is important to determine dielectric because it converts the GPR time scale (in nanoseconds [ns] of two-way travel time) to depth. More accurate dielectric value means a more accurate depth scale. In the early days of GPR dielectric/velocity was either estimated based on assumptions about subsurface conditions (from a lookup table) or from a common midpoint [CMP] evaluation. Modern GPR systems can now determine dielectric from hyperbolic matching in real-time, and this provides an estimate of dielectric with an approximately 10% error in homogenous media. The error increases with soil complexity and differential moisture content. In general, dielectric increases as more water is added to a material. Soil texture is critical, as fine-textured materials like silt and clay can hold more water than sand or gravel. As dielectric increases the expanding wavefront becomes more focused, narrowing the cone of penetration. This focusing effect results in narrower hyperbolic targets, likely reduction of depth penetration, and a possible increase in soil-related noise.

To calculate depth GPR operates much like radar systems used for airplane detection. The radar operator wants to know the airplane's distance from the airport. Using the equation D=ST (distance = speed x time) the unknown distance to the airplane can be derived if the speed and elapsed travel time of the radar wave can be determined (if you know two variables you can solve for the third). Air has a well-established dielectric of 1 (one) and a radar wave traveling through air moves at a velocity of 0.3m/ns. The two-way travel time [TWTT], or the time it takes for the radar wave to leave the antenna, reflect off an object/layer, and return to the receiver, can be accurately measured by the radar system (let's say 1000000ns). Modifying D=ST to D=ST/2, because TWTT must be halved, we now know that the airplane is 150,000 meters away (93.2 miles). The typical depth calculation for GPR uses the same principle: we want to know the depth of a target or layer, so we need to determine velocity and time. The GPR system measures TWTT very precisely, so we always know the elapsed time. We want to know depth to target/layer, so we need to constrain dielectric/velocity. This is the tricky part; in most near-surface Earth materials the dielectric is not constant and varies with depth, subsurface material type, water content, and other variables. We could use a lookup table to estimate the dielectric from observed soil characteristics but this would not be accurate. GPR can provide a relatively accurate depth calibration but the dielectric (or at least the average dielectric) must be constrained to do so. During fieldwork the most common method is to use hyperbolic matching to derive an average dielectric. A less common method is to ground-truth by using a target of known depth. In this case we could rearrange the equation to S=(D)/(T/2) (Speed = Distance divided by half of the TWTT), and if we somehow already knew the depth of a target we'd use depth and two-way travel time to calculate speed (and thus dielectric).

Air	1	Frozen Soil/Permafrost	6
Snow Firn	1.5	Dry Salt	6
Dry Loamy/Clayey Soils	2.5	Syenite Porphyry	6
PVC	3	Wet Granite	6.5
Asphalt	3 - 5	Travertine	8
Glacial Ice	3.6	Wet Limestone	8
Dry Clay	4	Basalt	8 – 9
Dry Sands	4	Wet Basalt	8.5
Dry Granite	5	Tills	11
Limestone	4 – 8	Wet Concrete	12.5
Concrete	4 – 11	Volcanic Ash	13
Soils & sediments	4 – 30	Wet Sands	15
Coal	4.5	Saturated sand (20% porosity)	19 – 24
Frozen Sand & Gravel	5	Wet Sandy Soils	23.5
Shale	5 – 15	Dry Bauxite	25
Dry Concrete	5.5	Saturated Sands	25
Dry Limestone	5.5	Wet Clay	27
Dry Sand & Gravel	5.5	Peats (saturated)	61.5
Potash Ore	5.5	Organic Soils (saturated)	64
Sandstone	6	Sea Water	81
Dry Mineral/Sandy Soils	6	**Water**	81

Table 1 Relative Dielectric Permeability (RDP) for selected surface and subsurface materials.

2.1.5 GPR reflections: layers and targets

GPR creates two distinct reflection types: layers and targets. Layers manifest as continuous reflectors much like stratigraphic layers in the wall of a backhoe trench. For stratigraphic sequences layer reflections only occur when there is sufficient dielectric contrast; if the dielectric of successive layers is the same there will be no reflection regardless of any changes in texture or visual characteristics. For ACF surveys layers are quite useful because any vertical ground disturbance (pits, trenches, graves, etc.) that cuts through them will be apparent on GPR profiles. The presence of a relatively shallow marker bed, or distinct stratigraphic reflector present across a survey area, is especially useful for ACF surveys because any ground disturbance will have to cut through it. Subsurface objects with a defined cross-sectional area appear as hyperbolic targets much like fish on a fishfinder. Targets are ideally profiled when crossed perpendicular to their long axis. As they are crossed at more acute or oblique angles hyperbolic tails can be distorted and artificially elongated/shortened relative to their perpendicular expression. Examples of hyperbola-generating targets include tree roots, rocks, animal burrows, bricks or other materials in historical fill units, and coffins/burial vaults. In forensic and cemetery contexts we are interested in targets associated with breaks in overlying layer reflections; this suggests the target was buried. If the human remains and burial container are completely decayed an obvious target may not be present but the associated stratigraphic breaks should still be visible. On historical or precontact sites pits and trenches will also cut through natural soil layers. Note that the actual size of objects cannot be derived from hyperbolic reflectors, and that the width of hyperbolic tails is more closely related to the local dielectric and the depth of the target.

2.1.6 Hyperbola formation

Hyperbolic targets are ubiquitous components of GPR records. Due to the width of the propagating wavefront (approximately 90 degrees front-to-back, and 45 degrees side-to-side in air) point sources (discrete objects) in front of or behind the antenna can reflect energy and be recorded in the profile (**Figure 2-2**). The GPR places the reflection directly below and at the corresponding time (in ns). Since the object is not directly below the antenna, but instead it is ahead or behind, in the profile the tails are deeper than the actual target. As the antenna approaches the true target location the tails become shallower, and as it passes over and beyond the tails get longer. The tails manifest as continuous, sloping reflections because the antenna images them with every subsequent scan. The result is that the GPR reads them as continuous reflections instead of individual point sources. When the antenna is directly over the target the leading tail reaches the apex, and once past the target the trailing tail begins to appear.

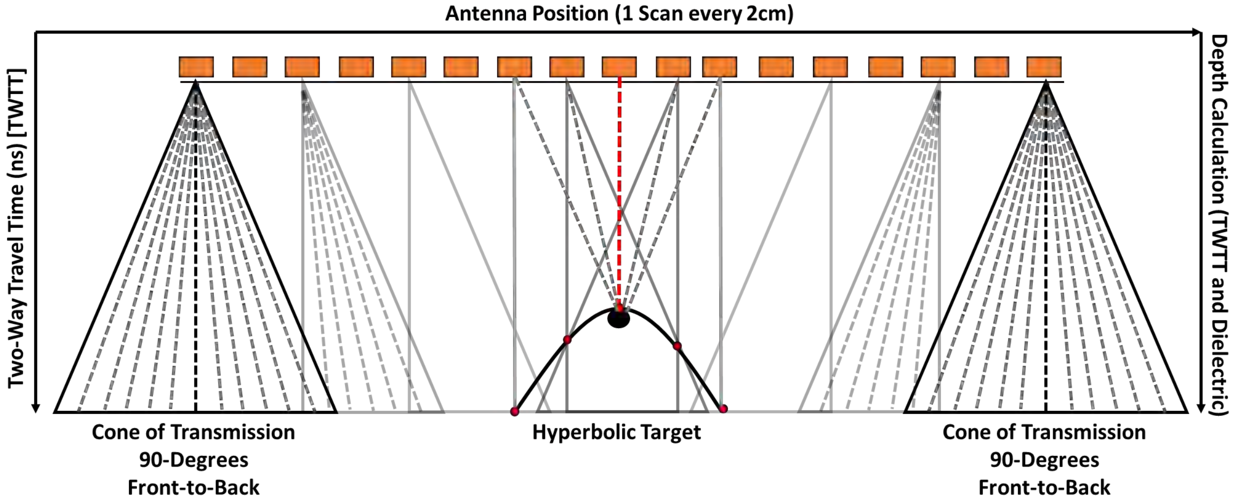


Figure 2-2 The formation of a hyperbolic reflection from a point source.

Full hyperbolic reflections are generated by discrete objects whose shape reflects energy back to the antenna. Irregularly shaped objects with vertical flat sides or other characteristics could scatter the energy and only generate single or partial hyperbolic tails (**Figure 2-3**). In the case of trenches, pits, and other vertical anomalies single hyperbolic tails are often generated on the lips/shoulders of the trench and can cross in the center of the feature. This is because the lips/shoulders of the trench have the correct geometry to reflect GPR energy from one direction and this generates single tails on the interior of the feature (**Figure 2-3**). This is not always the case, but when present these single crossing tails strongly suggest a pit, trench, air void, or similar feature.

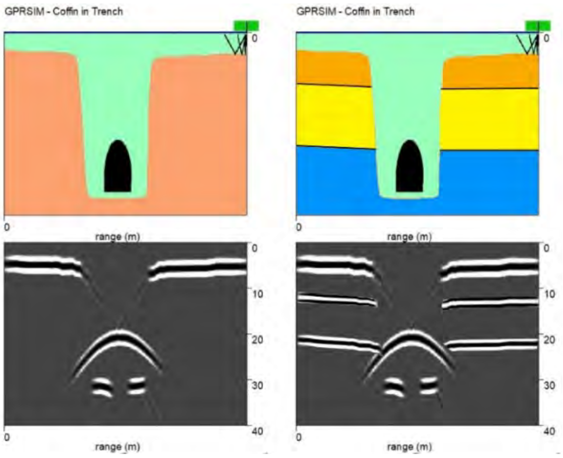


Figure 2-3 Scattering of GPR energy from vertical walls, single hyperbolic tails on the shoulders of the trench, and stratigraphic breaks from trench.

The dielectric/velocity of the surrounding media directly effects the width of the hyperbolic tails. In low dielectrics hyperbolic tails are wider; in high dielectrics the tail width is more narrow. Other factors contribute to tail width, including depth (in general, deeper targets generate wider hyperbolas) and angle of approach (90 degree approach creates 'normal' tails; other angles widen or restrict tail width and distort the tails or scatter energy). For ACF projects it is useful to characterize hyperbolic targets as simple and complex. Simple hyperbolas are smooth and uninterrupted reflections that may represent objects with small cross-sectional areas like pipes, tree roots, and individual rocks. Complex hyperbolas are often wide, with potential breaks or other inconsistencies and may exhibit an association of two or more stacked and irregular hyperbolas. These complex targets can be generated by objects with large cross-sectional areas, those that have an upper and lower boundary (like coffins or vaults), or in cases where the surfaces are irregular and many larger or smaller hyperbolas may coalesce into one larger and more complex target. These usually suggest ACF targets but there are always exceptions.

2.1.7 GPR phase/polarity and reflections

GPR reflections always manifest as a series of three bands (called a wavelet) of alternating polarity/phase. The wavelet will either be negative-positive-negative, or positive-negative-positive. Using the standard GPR color scale (negative = black; positive = white) the phase pattern will be either black-white-black or white-black-white (**Figure 2-4**). The first, biggest/brightest peak (highest amplitude) is the reference point for assessing phase change information. Some targets and layers will exhibit a weak white or black phase as the first reflector, but it is important to use the GPR's O-Scope to compare the relative amplitudes for the first and second reflectors. If the velocity increases/dielectric decreases at a boundary the resulting phase/polarity pattern will be black-white-black. If the velocity decreases/dielectric increases at a boundary the resulting phase/polarity pattern will be white-black-white. Thus, the phase information for a reflection tells us what happened to the velocity/dielectric at a boundary. The resulting amplitude (strength) of a reflection tells us how much the velocity/dielectric changed. Larger dielectric changes create brighter reflections. As an example, consider a forensic survey where a clandestine burial is below a concrete slab. Decay of the body will eventually cause subsidence of the burial fill and this will create a localized air void under the concrete. Assuming a dielectric of 6 for concrete, and a dielectric of 1 for air, we can predict that the air void will manifest with a polarity of black-white-black (negative phase when dielectric decreases at a boundary). This principle can also be applied to tombs or other subsurface structures to determine structural integrity where an air void could suggest that the structure has not collapsed.

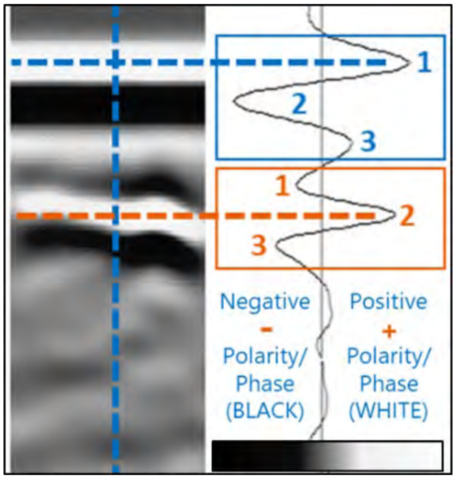


Figure 2-4 GPR reflection as a wavelet where negative polarity is reflected as black and positive polarity is reflected as white. A wavelet will reflect as either negative-positive-negative (black -white -black), or positive -negative -positive (white-black-white).

2.1.8 Focusing and scattering of GPR energy

Layers, targets, and other subsurface phenomena can focus or scatter GPR energy based on their configuration and the angle of approach. The simplest examples are a concave-up bowl and a convex-up bowl. The concave-up configuration focuses energy and reflects it back to the antenna. The convex-up feature scatters energy and it does not reflect back to the antenna. This is an example of Snell's Law, where in general terms the angle of radar incidence is the angle of reflectance. A more complex but accurate description is that the angle of incidence changes based on the dielectric/velocity contrast between layers (Goodman and Piro 2013). This means that straight-sided shaft walls are themselves not visible in GPR data though the stratigraphic breaks associated with the shaft are visible. Often there are single hyperbolic tails generated by the lips/shoulders of the trench and potentially on the edges of broken stratigraphic units. The same general concept applies to vertical stone or brick walls, though individual rocks and bricks in walls could generate their own hyperbolic targets. More common is the generation of single hyperbolic tails where ideally-shaped/oriented wall elements reflect energy. Steeply dipping stratigraphic layers may scatter GPR energy and not be visible, and irregularly shaped objects may not generate hyperbolic targets because of the same principle (**Figure 2-5**).

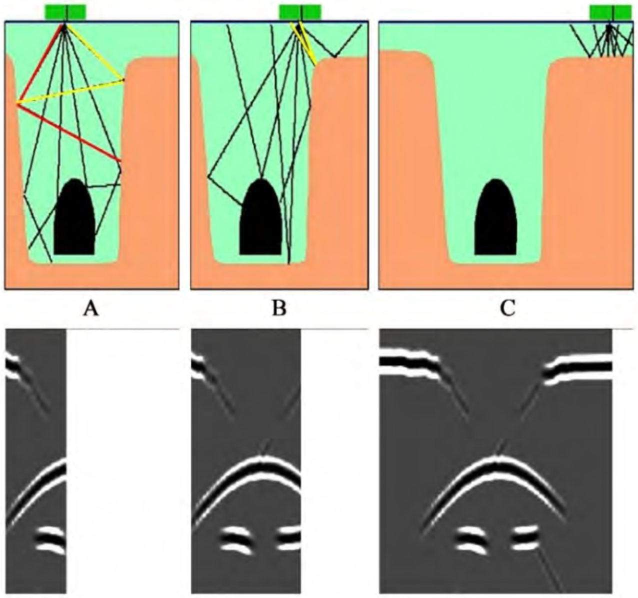


Figure 2-5 Scattering of GPR energy and the formation of single hyperbolic tails on trench shoulders

Consider a coffin in a grave shaft cut through massive (non-stratified) sand. The grave shaft will be very difficult to image with GPR because of scattering effects on the shaft walls and the lack of stratigraphic breaks to indicate a disturbance. The coffin may be visible if it hasn't completely decayed, though ground water fluctuations and other environmental factors may enhance or reduce the coffin's preservation potential. The nature of the backfill may be sufficient to generate dielectric contrast, or perhaps the grave shaft and fill have a different moisture content than the surrounding matrix. In these cases the grave may appear but likely it will be a low-amplitude and easily-overlooked feature. In weakly stratified sand the likelihood of imaging the grave shaft will improve due to truncated stratigraphic layers and potential single hyperbolic tails on the stratigraphic breaks. A well-stratified sand matrix would be the ideal situation.

As a cautionary tale it should be noted that historical brick vaults may exhibit vertical walls and a domed roof and these elements may scatter energy. This is also the case with some modern concrete/synthetic burial vaults that have domed lids. The brick or concrete vault may have a strong dielectric contrast with the surrounding and overlying sediment but will not be visible to GPR if the energy is scattered away from the receiver. In these cases stratigraphic breaks and single hyperbolic tails will aid in the interpretation process.

GPR energy can scatter from the ground surface in some conditions. These include cobble pavements, paving stones with large gaps, brick walkways, gravel driveways, and others. Aside from attenuation from differential moisture content between the surface covering and underlying sediment, coarse materials and those with gaps between paving elements can scatter the GPR wave and vastly reduce the amount of energy that returns to the antenna. This will also reduce the total amount of energy that can penetrate the subsurface and will ultimately reduce penetration. This scattering is enhanced by coupling issues, where irregular surfaces may prevent adequate antenna coupling and further reduce the amount of energy that enters the subsurface.

2.1.9 Multiples and reflections from metal, surfaces, and interfaces

GPR profiles can exhibit multiples much like seismic reflection data. A multiple reflection can occur when the radar wave reflects off a very large dielectric change or a piece of metal, goes back to the surface and is reflected from the air/sediment interface, goes down and reflects off the source of the multiple, and keeps bouncing until it runs out of energy. This results in repeated layers below the multiple-generating reflector, and they are often nearly identical except there may be some oversteepening of the multiples with longer elapsed TWTT. The first of the multiple reflections occurs twice as deep as the source layer because the reflection will have twice the TWTT of the original reflection. Additional multiples will share the same vertical spacing.

Metal targets can create multiples (**Figure 2-6**, top) because the GPR energy cannot pass through them and the reflection is so strong that it bounces back and forth between the air/sediment interface and the target itself. The resulting multiples will only be present below the metallic object; all overlying data will not be affected. If crossed by the GPR antenna small and shallowly-buried pieces of metal, like bolts, horseshoes, and small parts from farm machinery, may create a thin, vertical high-amplitude reflection that continues to the bottom of the profile. This may look similar to cell phone data spikes but these usually originate at the base of the profile and do not reach the surface. If small objects are deeper in the profile (>1m) they may not create vertical data spikes. Larger pieces of relatively shallowly-buried metal, like vehicle parts and manhole covers, will generate very high amplitude multiple reflections that are roughly the same width as the target. The larger the metal object the more likely the multiple reflections will completely and irreversibly obscure any data below. Data may still be visible below relatively small metallic targets due to the spreading of the GPR wavefront with depth.

Surface water, whether as puddles on asphalt or concrete or perched water on the ground, is a common source of multiples (**Figure 2-6**, bottom). Wet surfaces that do not have standing water are not usually a source of multiple reflections. Standing water affects GPR propagation by creating large dielectric contrasts at the antenna/water interface and at the water/surface boundary. It might seem that the water under the antenna is too thin to be resolved by a mid-range antenna frequency (see Section 3.1.1). However, the GPR energy will decelerate in the water and result in a shorter wavelength with a higher effective frequency (see Section 3.1.1). This will increase the vertical resolution, and thinner interfaces will generate reflections. Given the high reflection coefficient at the water interface, a large portion of the GPR wave will reflect and bounce between the interface and the antenna. Much like a metal target this can create stacked multiples. Multiples can be generated at soil boundaries as well (**Figure 2-7**, top), with the likelihood increasing with larger dielectric changes between bounding layers. These multiples are often much stronger below asphalt or concrete when the underlying sediments have been compacted or their dielectric contrasts sharply with the overlying material (**Figure 2-7**, bottom).

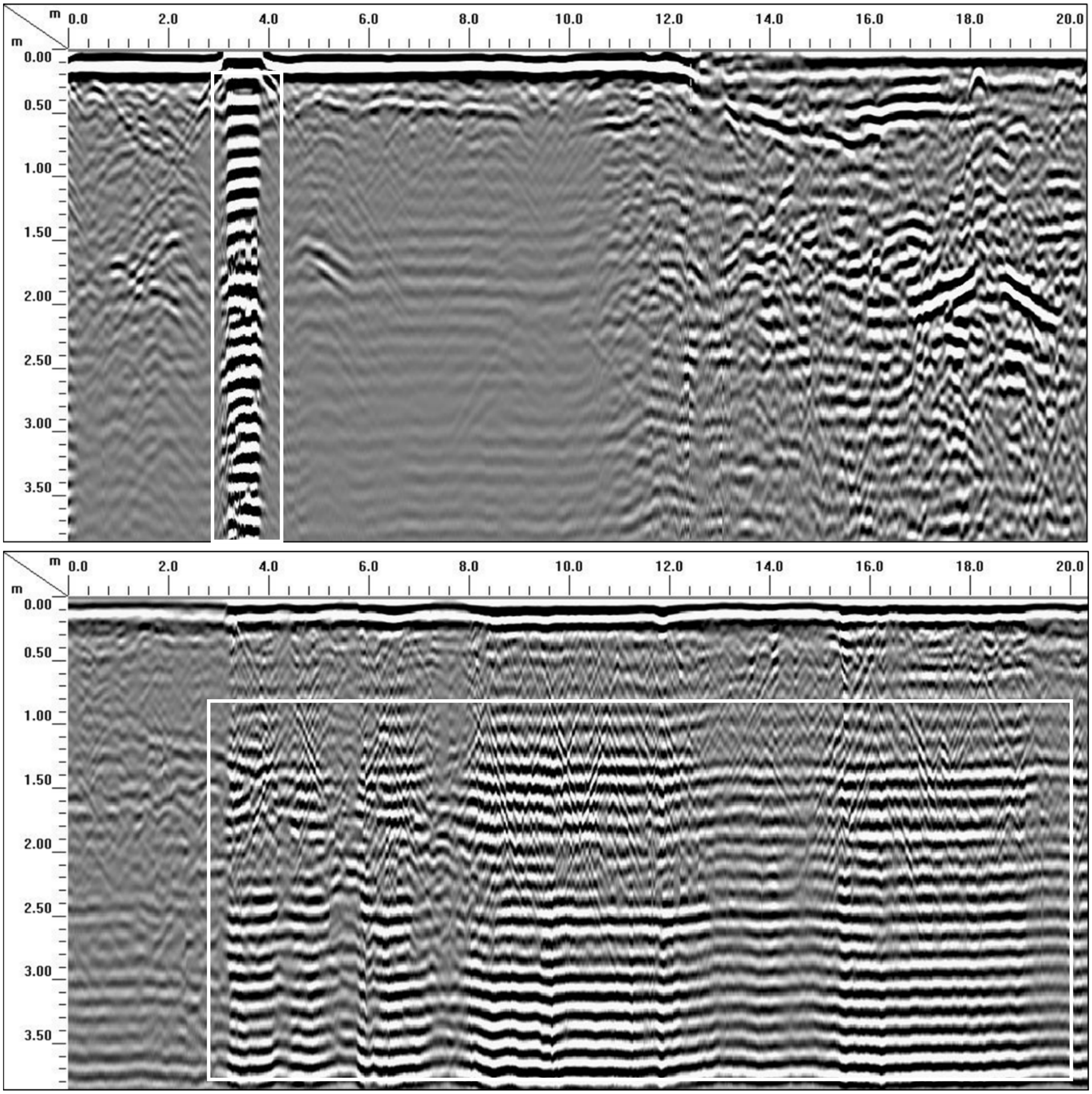


Figure 2-6 Top: high amplitude multiples from surface metal and attenuation from salt in groundwater. Bottom: multiple refelctions from standing water on road surface

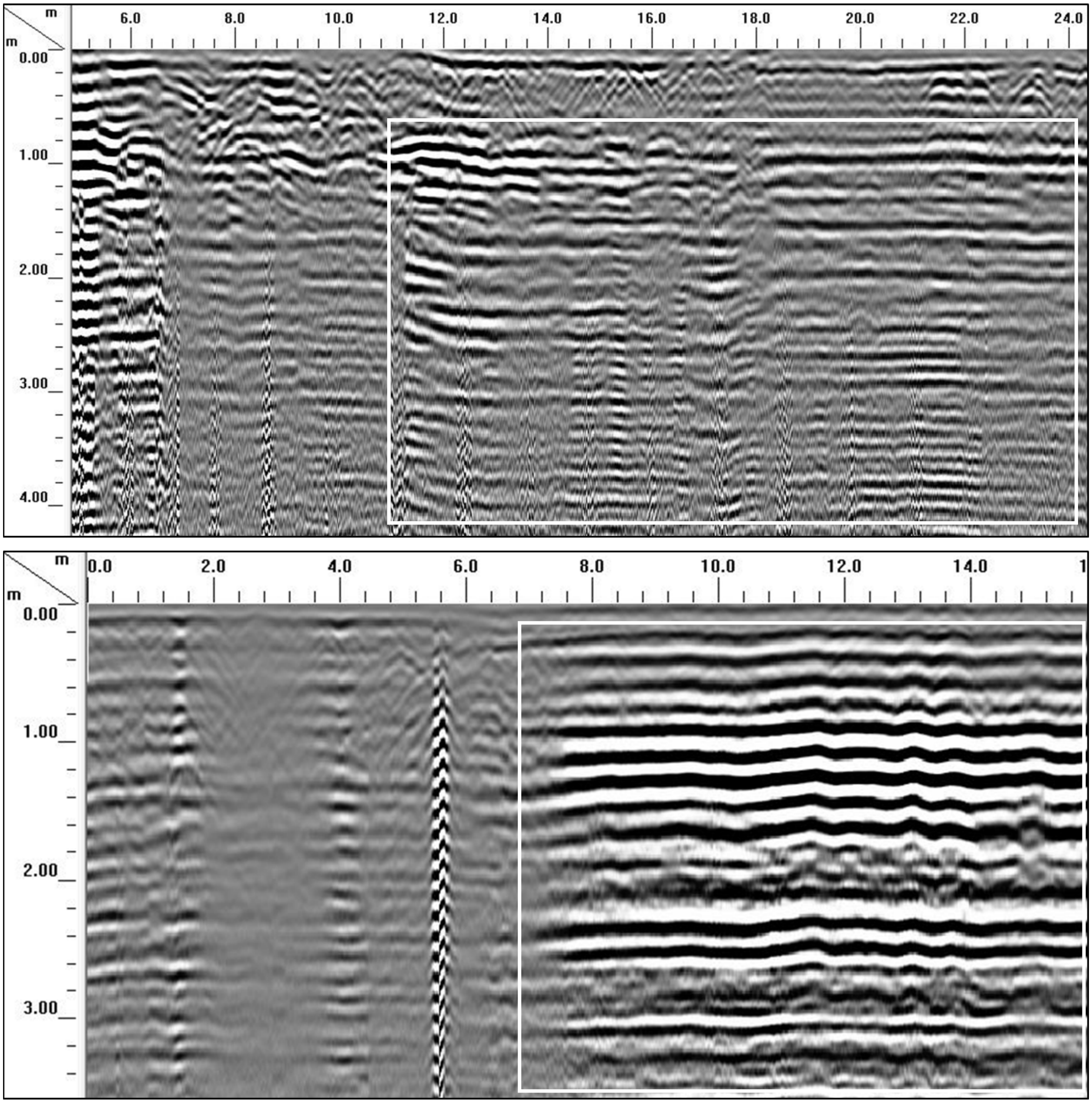


Figure 2-7 Top: multiple reflections generated from dielectric boundaries with high reflection coefficients. Bottom: example of extreme multiples from a large change in near-surface dielectric.

3 GPR HARDWARE, USER INTERFACE, AND FIELD PROCESSING

3.1.1 Choosing the correct GPR antenna

The choice of GPR antenna directly affects the depth and resolution of the resulting data. The stated frequency of an antenna, such as 400MHz, is the antenna's central frequency. The central frequency is what the antenna is optimized for, and this includes the separation distance of transmitter and receiver, as well as the overall antenna height and size of antenna elements. As a rule of thumb GPR antennas transmit and receive usable data at ¼ to 2x their central frequency (**Figure 3-1**). For example, a 400MHz antenna has an effective bandwidth from 100MHz to 800MHz and this bandwidth can be conceptualized as a generalized bell curve. The central frequency is in the center of the bell curve and the usability of frequencies decreases with standard deviations from the mean. This is also directly related to the engineering of the antenna, and all monostatic (transmitter and receiver in same antenna) antenna models are designed with a specific bistatic offset (separation distance between transmitter and receiver). Lower frequency antenna elements are larger and farther apart, while high frequency antennas have smaller elements spaced closer together. As a result, a 400MHz antenna can transmit and receive 100MHz data but not as efficiently as a 100MHz central frequency antenna.

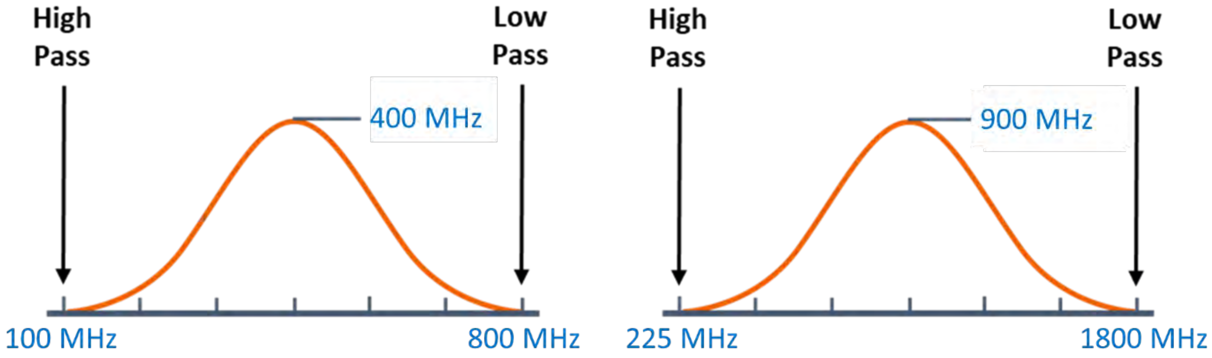


Figure 3-1 Generalized frequency spectrum for 400MHz and 900MHz antennas. The usable spectrum for any antenna is approximately ¼ to 2x the central frequency

Lower frequency antennas (100MHz to 400MHz) can penetrate deeper but they sacrifice resolution. Higher frequency antennas (900MHz to 2700MHz) provide excellent resolution but cannot penetrate as deep. Depth penetration is a function of wavelength and local dielectric and conductivity. Longer wavelengths (lower frequencies) travel farther and shorter wavelengths (higher frequencies) are more rapidly attenuated and scattered and do not travel as far. Antenna resolution is related to the wavelength of any given antenna frequency, whereby an antenna's general resolution can be derived from 25% to 40% of the wavelength. Most GPR practitioners use 40% as it is more conservative. Resolution for GPR has two related components: vertical resolution and target resolution. Vertical resolution is expressed as how small of an interface can be imaged by any given antenna. This is especially important for stratigraphic sequences where multiple horizons are present across a relatively short vertical distance. The lower the antenna frequency the less likely all the layers will be visible and the more likely that they will be expressed as one single reflector (composite of all layers). **Figure 3-2** demonstrates this concept by comparing a 900MHz and a 400MHz profile collected along the same transect. The central feature and stratigraphy are visible in each, but the 900MHz profile reveals more stratigraphic information and the feature is not as obvious due to added clutter. Target resolution refers to the smallest discrete object that can be imaged. A general rule of thumb for 400/350Mhz antennas is that for every 30cm (1ft) of depth an object's size must increase by 2.5cm (1in) to be visible. This is due to the spreading of the GPR wavefront as it travels through the ground; greater distances from the antenna result in a wider pattern and more distortion.

The concept of downloading is an interesting but rarely discussed component of GPR antenna resolution (Conyers 2013). As GPR energy travels through materials of higher and higher dielectric the wave decelerates. This compresses the wave, reduces its wavelength and increases its effective frequency, and ultimately increases the resolution (**Figure 3-3**). As a consequence GPR penetration in some settings can suffer since shorter wavelengths are more easily attenuated. As an example, in air (dielectric = 1) a 400MHz antenna has a wavelength of 75cm and a resolution of 30cm (at 40% wavelength). In a soil with a dielectric of 10 the 400MHz wavelength downloads to 23.7cm and the resolution is 9.5cm (at 40% wavelength). In freshwater (dielectric = 80/81) the 400MHz wavelength is 8.4cm and the resolution is 3.4cm (at 40% wavelength). It is worth noting that higher resolution allows separation of closely-spaced stratigraphic layers and detection of

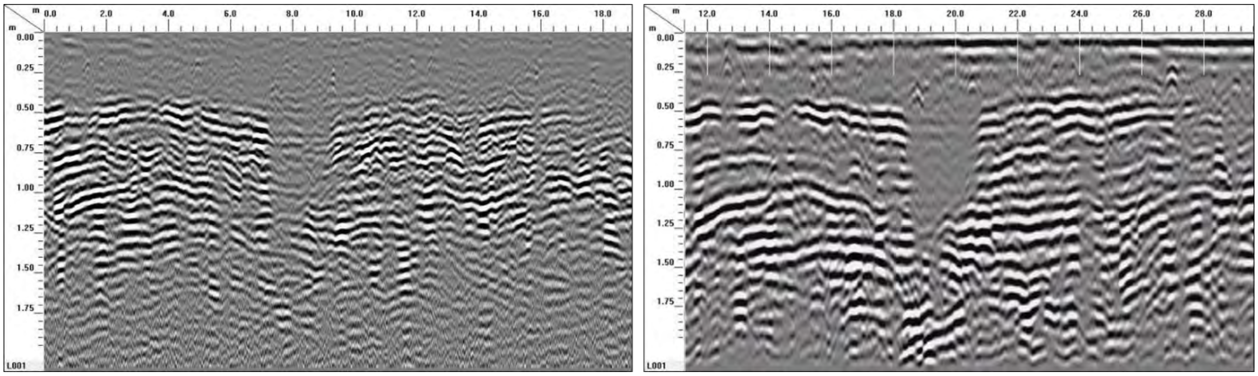


Figure 3-2 Comparison of a historical pit feature and stratigraphy with a 900MHz antenna (left) and a 400MHz antenna (right). Note relatively uniform data, suggesting plow zone, from surface to 40cm deep.

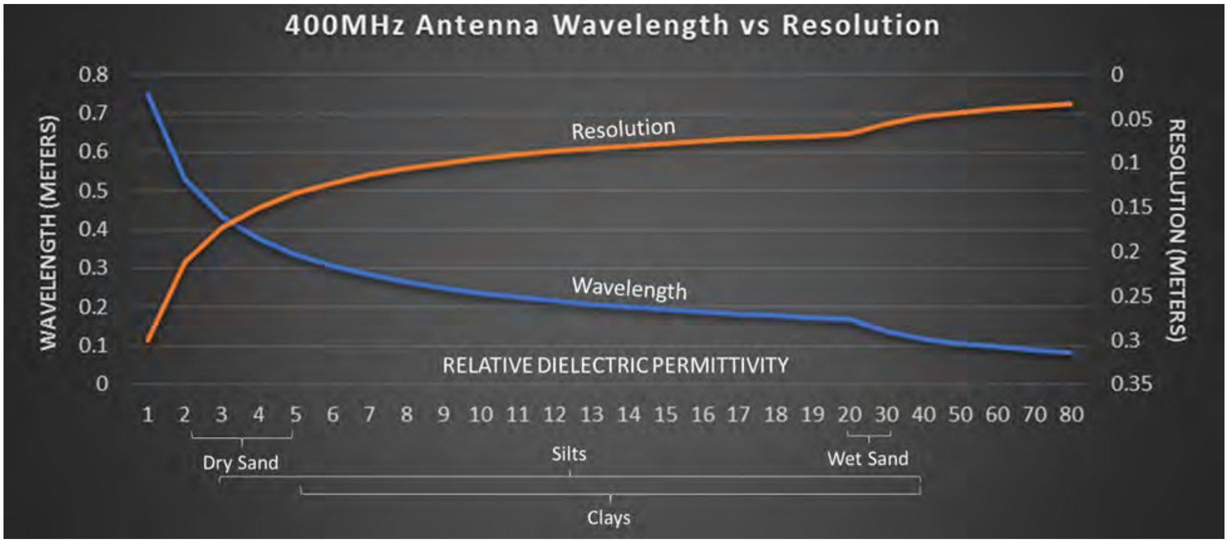
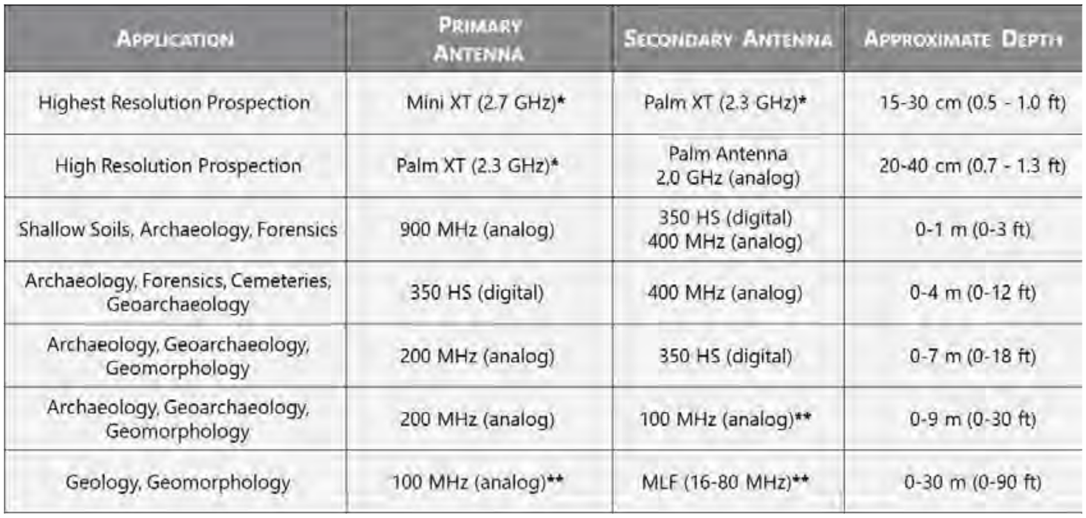


Figure 3-3 Relationship of 400MHz antenna wavelength and resolution with increasing dielectric

smaller targets, but this also enhances soil ‘clutter’ and adds unwanted detail to profiles that could obscure targets and layers of interest. Another impact of downloading is the focusing of the GPR wavefront with increasing dielectric. The wavefront generally spreads wider with depth, but as dielectric increases the cone of penetration is narrower than it would be in a lower dielectric. This results in less distortion with depth but significantly narrows the width of hyperbolic tails (making them harder to see). This is important for locating targets in wet clay, silt, and other high-dielectric media as the targets will be less obvious.

Antenna choice is critical in ACF surveys because of the concepts described above. **Table 2** lists various antenna models and antenna suggestions for different applications. For typical ACF surveys a 350MHz or 400MHz antenna offers the best interplay of depth penetration and resolution. A 350/400MHz antenna will penetrate 2-3meters (6-10ft) in normal soil conditions, and much more in perfect conditions (glacial ice) or much less in less-than-ideal conditions (wet clay). The resolution is sufficient to image most near-surface and deeper targets and to characterize stratigraphic relationships. If the shallow subsurface is the only area of interest, a 900MHz antenna is a good choice. The 900MHz provides more than 2X the resolution of a 400MHz but in normal conditions only penetrates to 1m (3ft). Very high frequency antennas (1600MHz, 2000MHz, 2300MHz, and 2700MHz) can generate amazing resolution for small targets and layer interfaces and can be used during archaeological or forensic excavations. However, due to their high frequency these antennas will usually penetrate to only 20cm or 30cm. While higher resolution can be beneficial (despite depth restrictions) the consequences of using higher frequencies include frequency-dependent soil issues and the unwanted “clutter”, like gravel and other coarse clasts, that obscure targets and layers of interest.



APPLICATION	PRIMARY ANTENNA	SECONDARY ANTENNA	APPROXIMATE DEPTH
Highest Resolution Prospection	Mini XT (2.7 GHz)*	Palm XT (2.3 GHz)*	15-30 cm (0.5 - 1.0 ft)
High Resolution Prospection	Palm XT (2.3 GHz)*	Palm Antenna 2.0 GHz (analog)	20-40 cm (0.7 - 1.3 ft)
Shallow Soils, Archaeology, Forensics	900 MHz (analog)	350 HS (digital) 400 MHz (analog)	0-1 m (0-3 ft)
Archaeology, Forensics, Cemeteries, Geoarchaeology	350 HS (digital)	400 MHz (analog)	0-4 m (0-12 ft)
Archaeology, Geoarchaeology, Geomorphology	200 MHz (analog)	350 HS (digital)	0-7 m (0-18 ft)
Archaeology, Geoarchaeology, Geomorphology	200 MHz (analog)	100 MHz (analog)**	0-9 m (0-30 ft)
Geology, Geomorphology	100 MHz (analog)**	MLF (16-80 MHz)**	0-30 m (0-90 ft)

* Not for use with SIR 4000 ** Not sold in USA

Table 2 GSSI antenna models and suggested applications

3.1.2 GPR antenna sampling

The majority of GPR systems acquire data through incremental sampling. GSSI systems use two variations: Equivalent Time Sampling (ETS) and HyperStacking. The ETS method sends an initial transmit pulse at a specific time interval and records the reflected information. A second pulse captures reflections at the next time interval, and the process continues until the entire scan/trace is recorded. These transmit pulses are always at the same time interval and occur in a linear progression. This means that external EM interference, especially continuous signals, can easily overprint on the GPR signal and manifest as noise. In GSSI control units the number of samples used to create a scan (seen on control units as the O-Scope) is referred to as samples/scan, and a typical value for ACF surveys is 512 samples/scan. This means that for any given time range (in nanoseconds of TWTT) 512 incremental transmit pulses are sent and received to build the scan. A nanosecond equals one billionth of a second, so GPR systems must measure the elapsed time with extreme accuracy and all of this must happen before the system moves to the next scan location. If an inadequate number of samples/scan are recorded the data will be aliased; there are not enough data points to accurately capture the subsurface reflections and the peaks on the O-Scope will appear pixelated/saw-toothed.

As an example, consider a simple mapping exercise where you are using a total station or GPS to map a semi-circular driveway (**Figure 3-4**). If you collect three points, and then digitize a polyline representing the driveway, there will be insufficient resolution to accurately map the true shape. This is an example of aliasing; the resulting linework does not fully capture the phenomenon of interest. Collecting an adequate number of points will faithfully represent the feature of interest. Oversampling will also capture the shape of the driveway but it would take longer and result in more data; this is an example of the diminishing returns in collecting too much data. The ETS GPR sampling occurs in much the same way. Under-sampling (too few samples/scan) will alias the data and produce a lower resolution reflection trace; oversampling will generate a non-aliased trace but it will take longer to acquire (reducing movement speed) and increase the GPR file size. It is important to choose a samples/scan value that will produce non-aliased data but not oversample. This is generally a function of the total time range set during data collection. Refer to **Table 3** for common values applied to various antenna models and the recommended time range at which the samples/scan should be increased.

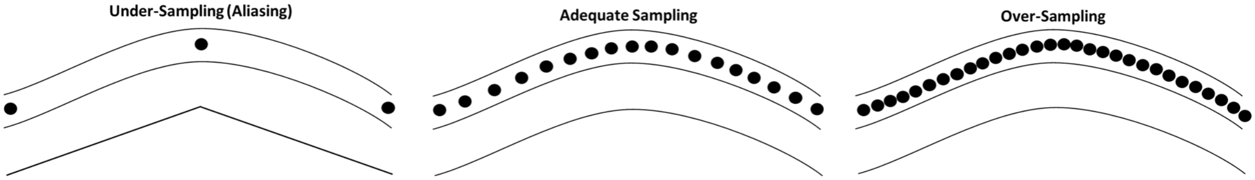
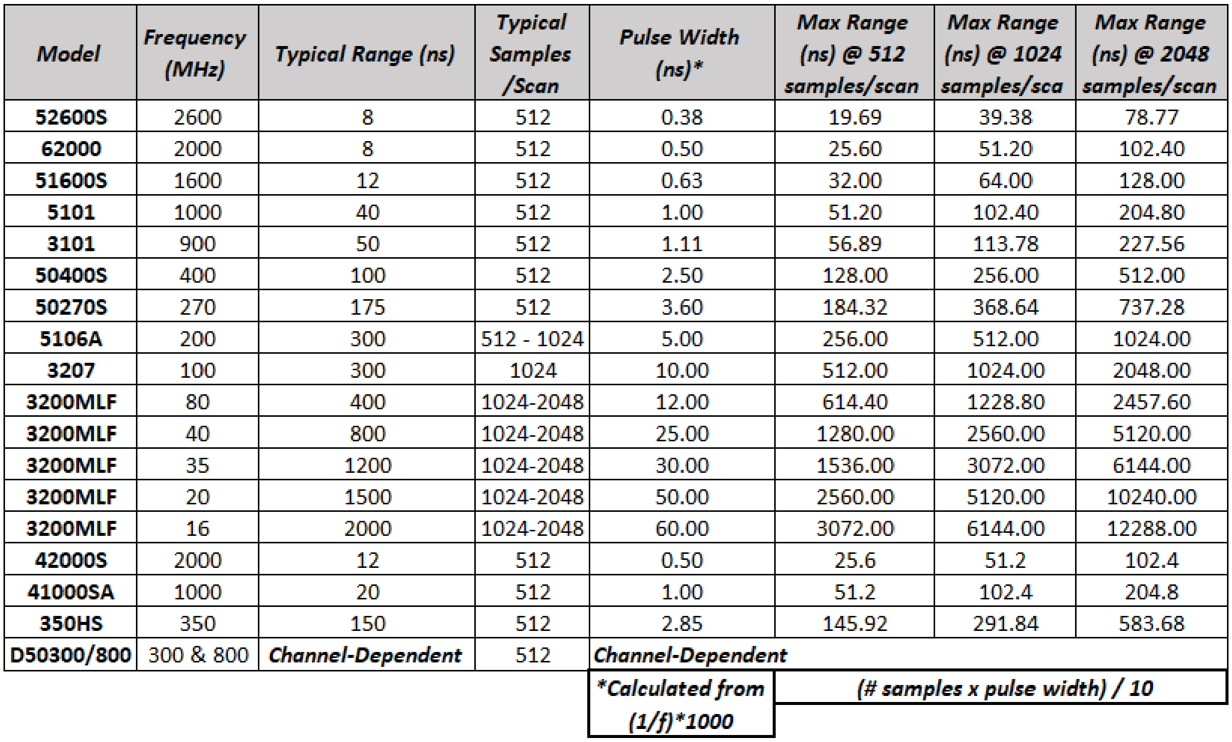


Figure 3-4 Aliasing of data through under-sampling

HyperStacking (patented by GSSI) is a variant of ETS that capitalizes on the efficiency of digital acquisition hardware to vastly increase the speed of sampling. A HyperStacking antenna operates hundreds of times faster than a typical ETS system (Feigin and Cist 2016) and averages scans together during sampling. An ETS system using 512 samples/scan must send and receive 512 transmit pulses to construct the scan. A HyperStacking system can collect data much faster, and as such ¼ of the total samples are acquired with each transmit pulse. This leaves more time for the antenna to collect additional scans (in the same location) and stack/average them together. An added benefit is that HyperStacking samples 'pseudo-randomly', whereas a conventional ETS system samples linearly. Pseudo-random sampling, and the averaging of scans, is an effective technique for downplaying the impact of external EM interference. Since external noise (especially continuous forms) is a linear or cyclic phenomenon the use of non-linear sampling limits the amount of external interference that can overprint on the signal. Furthermore, the averaging of scans can improve the depth penetration of GPR antennas by averaging out the effects of attenuation. The result is that HyperStacking antennas perform better in interference-rich urban environments and can improve data quality and depth penetration in nearly all environments, including less-than-ideal soil conditions.



Model	Frequency (MHz)	Typical Range (ns)	Typical Samples /Scan	Pulse Width (ns)*	Max Range (ns) @ 512 samples/scan	Max Range (ns) @ 1024 samples/sca	Max Range (ns) @ 2048 samples/scan
52600S	2600	8	512	0.38	19.69	39.38	78.77
62000	2000	8	512	0.50	25.60	51.20	102.40
51600S	1600	12	512	0.63	32.00	64.00	128.00
5101	1000	40	512	1.00	51.20	102.40	204.80
3101	900	50	512	1.11	56.89	113.78	227.56
50400S	400	100	512	2.50	128.00	256.00	512.00
50270S	270	175	512	3.60	184.32	368.64	737.28
5106A	200	300	512 - 1024	5.00	256.00	512.00	1024.00
3207	100	300	1024	10.00	512.00	1024.00	2048.00
3200MLF	80	400	1024-2048	12.00	614.40	1228.80	2457.60
3200MLF	40	800	1024-2048	25.00	1280.00	2560.00	5120.00
3200MLF	35	1200	1024-2048	30.00	1536.00	3072.00	6144.00
3200MLF	20	1500	1024-2048	50.00	2560.00	5120.00	10240.00
3200MLF	16	2000	1024-2048	60.00	3072.00	6144.00	12288.00
42000S	2000	12	512	0.50	25.6	51.2	102.4
41000SA	1000	20	512	1.00	51.2	102.4	204.8
350HS	350	150	512	2.85	145.92	291.84	583.68
D50300/800	300 & 800	*Channel-Dependent*	512	*Channel-Dependent*			
				***Calculated from (1/f)*1000**	***(# samples x pulse width) / 10**		

Table 3 GSSI antenna models, pulse width and suggested samples/scan for various time ranges

Regardless of the sampling technique, a GPR operator must be familiar with the samples/scan principles and adjust acquisition parameters accordingly. **Table 3** provides guidance for various antenna models by indicating optimal samples/scan settings for different time ranges. Note that these are mathematically-derived values and may not be ideal for all survey areas. In general, the goal should be the avoidance of data aliasing and when in doubt it is prudent to use the next higher samples/scan value. Some caution is advised for higher samples/scan values because these will reduce survey speed. A recommended strategy is to use an appropriate samples/scan value, and avoid oversampling when possible.

3.1.3 External EM noise interference

Ground-penetrating radar antennas transmit and receive radio frequencies in the MHz and GHz range. As such they are susceptible to external radio transmissions that overlap with their bandwidth despite antenna shielding. This should not be confused with soil-related noise (see Section 3.1.5). The impact of external interference is inversely proportional to the distance from the broadcasting source and proportional to the transmitter strength. The closer and stronger the source, the more impactful the interference. For example, a 400MHz antenna has an effective bandwidth of 100MHz to 800MHz. Your favorite FM classic rock station has a frequency of 104.7 MHz and is continuously broadcasting. Some portion of that continuous radio transmission can be received by a 400MHz antenna, and the antenna is unable to distinguish between classic rock and its own 104.7MHz signals. This would generate horizontal noise bands in your data which would be more obvious if you were close to the radio tower. In GPR profiles continuous low frequency noise will manifest as long, flat horizontal bands, while sporadic/pulsed low frequency noise (like a two-way radio broadcast) usually appears as a discrete area of high amplitudes.

On the other end of the spectrum is higher frequency periodic/sporadic noise. For most ACF surveys (350MHz/400MHz antenna) the source of high frequency noise is cellular communication, either from the phone in your pocket or nearby cell towers. A discontinuous cellular signal from a cell tower will produce a hazy/snowy overprint on your data, much like an old television where the rabbit ears were not oriented properly. Discrete and nearby cellular signals, like when your cell phone sends/receives a call, text, or email, appear as narrow vertical, high-amplitude data spikes. A real-time kinematic [RTK] GPS base station, depending on the radio modem frequency, can also create vertical noise stripes and these are usually regularly spaced during continuous antenna movement (**Figure 3-5**).

External interference is more obvious in the deeper profile sections because GPR signal strength becomes weaker with distance from the antenna. The deeper portions of the profile have lower amplitudes and signal strength, thus the interference overpowers the GPR data and is more apparent. In shallower profile sections noise is not as apparent because of high GPR signal strength. External noise is also more obvious in less-than-ideal soil conditions (due to overall lower signal strength) and in attenuated data zones. As an analogy, you are standing next to a radio (signal of interest, close to source) and people are talking (external noise). You can still hear the radio if people are talking normally (low power transmission) but if they are talking loud (high power transmission, close proximity) their conversation will overpower the radio. If you are 20ft away from the radio you can't hear it as well (weaker signal with distance), and if people are talking they might completely drown out the radio (noise stronger than signal). You could always turn up

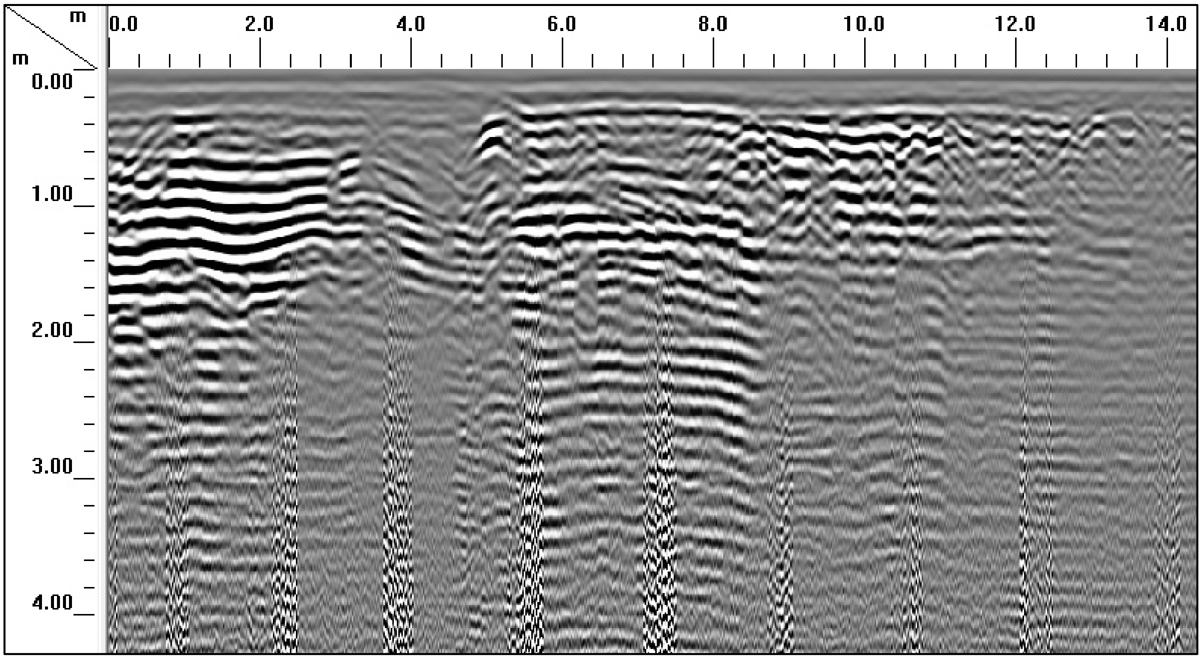


Figure 3-5 Periodic interference from a RTK GPS base station

the radio (range gain) but if people talk louder to compensate they will still drown out your favorite Bob Dylan song.

The manifestation of external noise interference has more to do with the nature of the broadcasted signal than it does with shielded antenna design. Continuous broadcasts (radio, television) appear in GPR profiles because the timing of the signal coincides with the GPR system's sampling interval. Continuous noise appears as horizontal bands (**Figure 3-6**) because it is a constant phenomenon (i.e. it is present every time we sample). Periodic/sporadic broadcasts (like cellular communication) occur at high frequencies and though they may seem to be continuous phenomena (due to the high frequency) they are not regular enough to coincide with every sample. This results in a static "overprint" from randomized but continuous interference (**Figure 3-6**; **Figure 3-7)**. An important factor is the strength of the transmitter. Radio and television broadcasts use moderate to high powered transmitting elements to ensure long-range transmission and reception. The stronger the transmitter the more impact it will have with decreasing distance. This is an important consideration for sources of EM interference you might have brought to the site, like a two-way or CB radio (**Figure 3-8**). If you broadcast with the radio it will appear on the GPR profile as a high-amplitude, vertical static band. The amplitude of the static band will be proportional to the transmitter power and its proximity to the antenna. Conversely, if someone sends out a broadcast from 10 miles away when you receive it on your radio you won't see as large of an impact (if at all) on your data.

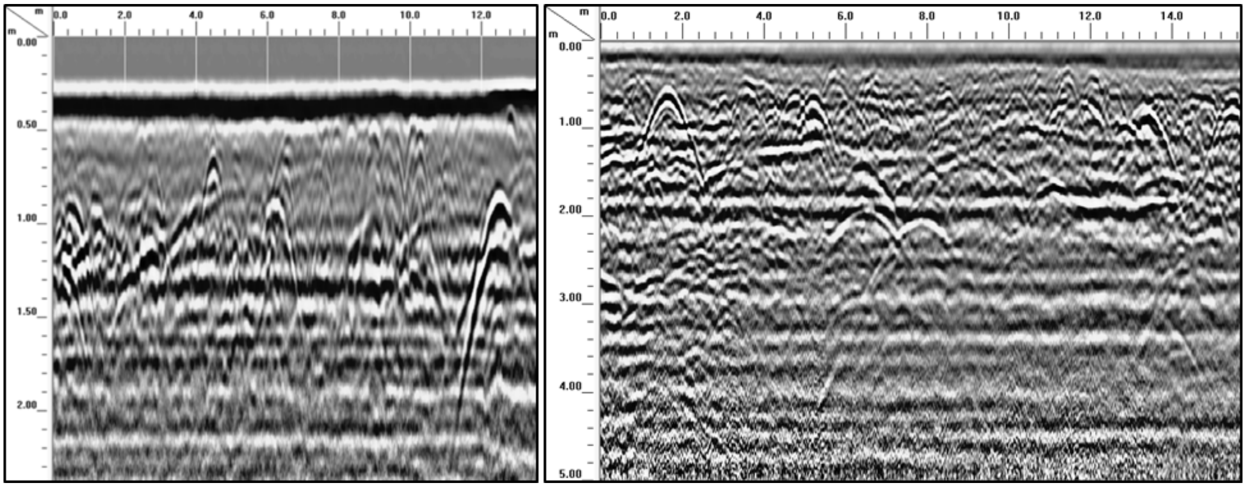


Figure 3-6 Left: horizonal bands from continuous interference and "snowy" overprint from periodic interference. Right: similar interference to example on left, but showing attenuation with depth

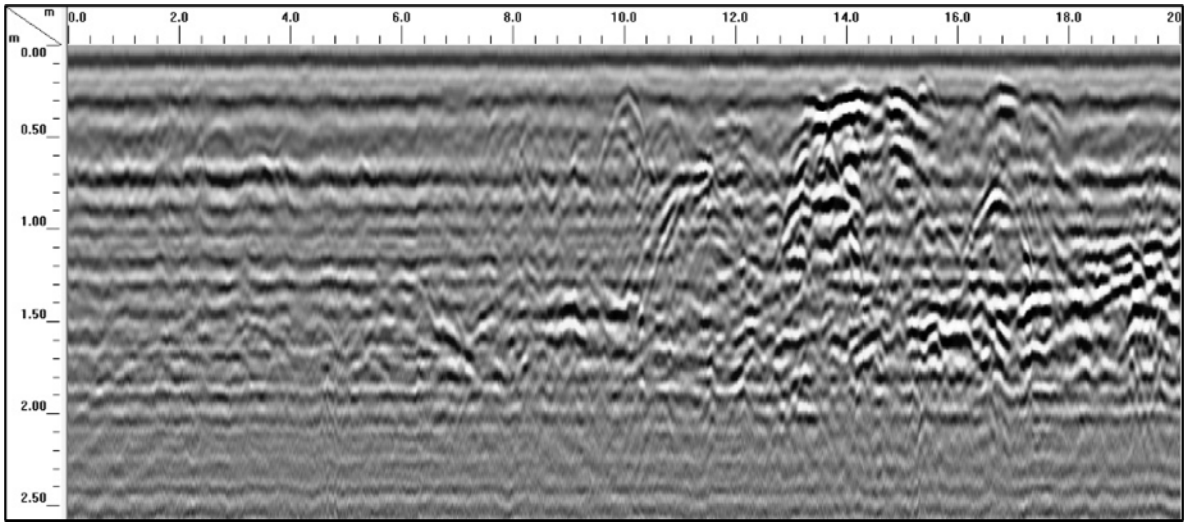


Figure 3-7 Horizontal interference bands from continuous broadcast (probably radio or television)

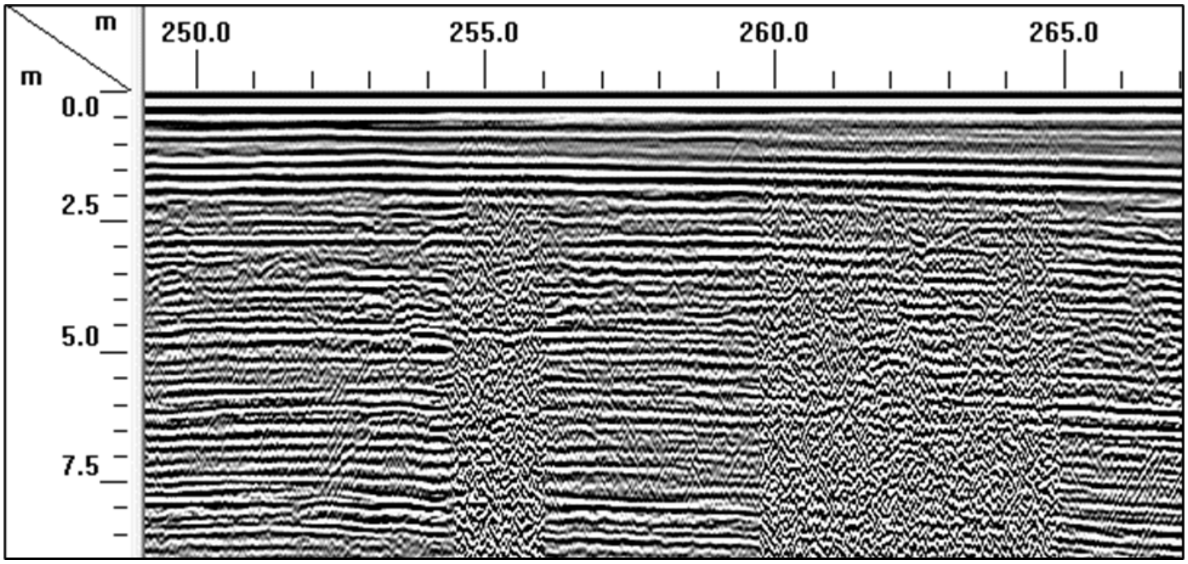


Figure 3-8 Example of radio interference from a nearby two-way radio transmission

3.1.4 Sources of external EM interference (USA only)

For your convenience I have compiled the major sources of EM interference in the USA from the Federal Communications Commission's [FCC] website (https://www.fcc.gov/). Become familiar with the central frequency and bandwidth of your antenna(s), and look around your project area for potential sources of external interference. Expect interference if you can see cell towers, radio dishes, or radio or television broadcasting towers from your survey area or if construction crews are using two-way radios. Make sure that everyone's cell phones are in airplane mode (yes, even yours) or in a vehicle. You should also know the frequency of any nearby Real-Time Kinematic (RTK) GPS base stations and/or radio modem(s) and understand how they will contribute to the local noise spectrum.

- VHF band (Low Band: 49 – 108 MHz; High Band: 169 – 216 MHz)
    - FM Radio band (87.5 – 108 MHz): ***Continuous***

    - Land Mobile Band/ two-way radio communication (138 – 174 MHz): ***Periodic/Sporadic***

- UHF band (300 MHz – 1000 MHz [1.0GHz])
    - DoD/Military Land Radio band: 380 – 399.9 MHz: ***Periodic/Sporadic***
    - Land Mobile Bands: 406.1 – 420 MHz, 450 – 512 MHz: ***Periodic/Sporadic***
    - Television Broadcasting (470 – 608 MHz): ***Continuous***
    - 600MHz Band (614 – 698 MHz): former TV, soon to be wireless/broadband: ***Periodic/Sporadic***
    - 700MHz Cellular Service (698 – 806 MHz): Cellular: ***Periodic/Sporadic***
    - Public Safety (re-allocated D-Block): 758 – 763 MHz / 788 – 793 MHz: ***Periodic/Sporadic***
    - Public Safety: 763 – 769 MHz/793 – 799 MHz: ***Periodic/Sporadic***
    - 800MHz Cellular Service (824 – 849 MHz; 869 – 894 MHz): ***Periodic/Sporadic***

Typical RTK GPS base station frequencies (***periodic/sporadic, based on update rate***)

- Trimble (TDL450 radio)
  390 – 430 MHz
  430 – 470 MHz

- Trimble (SNB900 radio)
  902 – 928 MHz

- EMLID
  Reach RS/RS+: 863 – 928 MHz
  Reach RS2: 868/915 MHz

- EOS Arrow Series (100, 200, Gold)
  Depends on paired radio modem

- NovaTel
  403 – 473 MHz
  902 – 928 MHz

- Sokkia (R4S-BT Radio)
  403 – 473 MHz

3.1.5 Soil-related noise and other issues

Soil variability is an ever-present consideration for GPR surveys. Data quality in resistive media is usually quite high, though in most cases soils exhibit a wide variety of characteristics that can lead to reduced GPR performance. Soil conditions are a major contributor to data quality issues. Most environments will produce some degree of subsurface noise, but in others the soil conditions may be so problematic that all real data are masked. This is especially true for evaluation of real-time data, and there are general noise contributors such as matrix texture and amount of air-filled and water-filled pore space (Cassidy 2009). Other specific variables include pedogenic or anthropogenically-applied salt, fertilizer concentration, and the presence of certain clay varieties. In the USA the Natural Resources Conservation Service [NRCS] has approached soil-related issues by creating a soils-derived GPR suitability index based on clay content, organic matter, carbonates, sulfates, salinity, sodicity, and other soil properties (Doolittle et al. 2007; NRCS 2020; www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053622). These and other soil factors are considered, and landscapes are rated to predict GPR penetration and depth to attenuation. The resulting maps are low resolution due to widely-spaced soil survey measurements, but NRCS soil data can be downloaded for small project areas and viewed in GIS software for a more refined suitability index. One downside is that the NRCS maps do not account for seasonal water content (Doolittle et al. 2007), and therefore it is difficult to predict GPR suitability until you travel to a site and collect test profiles. As ACF practitioners we usually cannot choose our project areas, so the NRCS maps should be considered only as an initial evaluation. Regardless of expected less-than-ideal soil properties ACF practitioners still have to conduct surveys, and to this end an understanding of critical soil-related problems is essential.

Soil-related noise and lower data quality in less-than-ideal soil conditions are more relevant to soils and geologic prospection than ACF projects. Pedologists and geologists often attempt deeper penetration and therefore poor environmental conditions are not ideal. On the other hand, for ACF surveys less-than-ideal soil conditions can, and often do, generate improved GPR data. This may seem counterintuitive, but the concept is fairly straightforward. In poor soil conditions, such as wet clay, undisturbed areas may exhibit minor to non-existent dielectric changes. This is due to conductivity and water retention. In anthropogenically disturbed locations there can be a localized ‘window of penetration’ where digging and other activities have changed the nature of the matrix. Perhaps these areas hold less water (or more?), or the process of excavation has reduced conductivity/ increased resistivity. Other factors may include the incorporation of variable textural classes and coarser clasts to the feature fill, or there are more organics. Regardless of the mechanism, in less-than-ideal soil conditions ACF targets often sharply contrast with the general low amplitudes from undisturbed background levels (especially in time slices). These contrasts will greatly improve the likelihood of identifying features of interest, though any soil-related noise will require removal through post-processing.

Soil water is a critical variable for GPR performance in any environment. Perfectly dry soils are not ideal GPR media and in arid environments there are other issues related to salt and carbonate accumulation (Doolittle et al. 2007). Some pore water is required for GPR wave propagation, though too much water can be problematic. With increasing water content dielectric increases and velocity decreases. This is important for real-time evaluation of depth calibration, as well as inherited downloading effects. Resolution increases with higher dielectrics, but the effective bandwidth shifts toward higher frequencies and this can lead to more rapid attenuation and reduced depth penetration. In certain soil types there are abundant minerals that, when in dissolved in pore water, can increase local conductivity levels (see below). Additionally, there may be layers that restrict permeability and either hold more water or cause water pooling. The dielectric contrast between overlying strata could be quite high, and with a large reflection coefficient much of the total GPR energy will be reflected and little will remain to travel to deeper interfaces. This often leads to multiple reflections or horizontal banding that obscure deeper, low amplitude data. Water-related issues are more pronounced with higher frequencies (>500MHz) due to frequency-dependent losses. These losses are often a direct result of a molecular relaxation effect, whereby the EM wave spins water molecules and free ionic charges and is transferred to heat (like a microwave oven; Cassidy 2009; Doolittle and Butnor 2009).

Conductivity is a major factor in GPR attenuation. Salt, nitrates and other fertilizers, along with calcium carbonate and calcium sulfate (gypsum), originate from soil media or anthropogenic activities and when in solution they increase soil conductivity (Doolittle et al. 2007). These same materials are not as impactful to GPR data quality when dry, as evidenced by the excellent performance of GPR in salt mines (Gundelach et al. 2012). Highly conductive media dissipate GPR energy and greatly reduce penetration depth. The basic process is that through displacement and polarization the GPR energy is converted to heat during conduction (Cassidy 2009). The direct result of dissipation is that no energy returns to the antenna, thus all data within and below the conductive zone are attenuated. GPR is highly ineffective in seawater and in brackish conditions due to greatly enhanced salt-related conductivity. In salt marshes conductivity can also be a problem as GPR penetration will decrease, and attenuation will increase, with greater distance from higher high marsh (freshwater marsh) areas and proximity to tidal channels or the open coast. In northern climates, where road salt is applied in the winter, conductivity can be quite high on and below asphalt and concrete surfaces. Plow trucks, vehicles, and rain can move excess salt off these surfaces where it can accumulate in nearby soil profiles and enhance conductivity.

Clay content is problematic for GPR due to clay's ability to store water across a large surface area and the potential for increased conductivity levels (Doolittle et al. 2007). Pore water is not in-and-of-itself problematic for GPR, but increased water content does reduce propagation velocity/ increase dielectric and will enhance downloading effects (higher frequency/resolution but potential for reduced penetration). There are many varieties of clay minerals, though only specific types are challenging for GPR. These include smectite, vermiculite, and montmorillonite which exhibit high cation exchange capacity [CEC] (100-150 milliequivalents per 100g [meq/100g]) and a large capacity for holding water (Doolittle et al. 2007). Less impactful clay varieties include kaolinite (CEC 1-2 meq/100g), halloysite (5-10 meq/100g), and illite (20-30 meq/100g). These clays may hold more water than coarser-textured materials but they do not contribute as strongly to overall conductivity levels. However, CEC can increase when clay and water are combined with dissolved minerals, and the relatively high potential for water retention leads to an overall higher dielectric (when wet).

An interesting distinction is the difference between true mineralogical clays and 'pseudo-clays' which are comprised of clay-sized particles. Pseudo-clays, such as glaciomarine and glaciolacustrine deposits, appear and behave like true clays but they are composed of rock flour and are not the byproduct of long-term weathering. The CEC for these media is around 18-20 meq/100g, as compared to 100-150 meq/100g for vermiculite, 20-30 meq/100g for illite, and 1-2 meq/100g for kaolinite (NRCS 2020). Glaciogenic clays, which make excellent pottery vessels and bricks, do not have greatly enhanced CEC-related conductivity. However, like kaolinite and other low CEC clays glacially-derived rock flour deposits often exhibit relatively high dielectric values and generate more water-related banding and multiples than soils with low clay contents. Additionally, glacially-derived pseudo-clays are often massive at the scale of most ACF GPR investigations and therefore exhibit weak to non-existent stratigraphy. These issues are especially problematic for real-time data interpretation, and a creative bandpass filter could improve overall field data quality.

Other potential soil-related problems are generated from surface conditions or from coarse clasts in the matrix. Surface water is especially problematic for GPR, and when passing over standing water there are usually high amplitude ringing multiples that extend vertically throughout the GPR profile. Water puddles should be avoided if possible, and it might be worth postponing a GPR survey to wait for water levels to decrease. Coarse materials on the ground surface or in subsurface layers can scatter GPR energy and reduce overall data quality and penetration depth.

3.1.6 Bandpass filtering: to filter or not to filter?

External EM interference is almost always present in GPR data but the GPR antenna's proximity to the source and the strength of the transmitter can present immediate problems in the field. In some cases EM noise can completely overpower/overprint the GPR data and render them unreadable. In other situations the noise is strong enough to reduce data readability but real data can be seen beneath the noise overprint. Bandpass filtering can improve real-time data by reducing or eliminating external noise or soil-related data issues. A bandpass filter restricts bandwidth to remove unwanted frequencies above and/or below a specific range. Note that on SIR3000-based (16-bit) data this filter will affect your raw data; for SIR4000-based (32-bit) and UtilityScan (32-bit) data it will not. There are two options on most control units: Finite Impulse Response (FIR) and Infinite Impulse Response (IIR).

The FIR and IIR filters are a combination of horizontal (scan-based) and vertical (sample-based) filters. FIR filters employ a bounding box to limit the effect of distant scans. IIR does not use a bounding box, and thus the filter length can be infinite. For archaeological datasets, both in the field and during post-processing, I rarely employ horizontal filters (I avoid horizontal Stacking but sometimes use Background Removal). The difference between vertical FIR and IIR is the 'aggressiveness" of the filters. FIR is not very literal, and while in the vertical dimension it will try to remove the specified frequencies it still leaves some behind; it does not create a "clean cut" at the specified cutoffs. IIR is much more literal (and aggressive) and is more effective at removing unwanted frequencies. These filters use a High Pass and Low Pass value to constrain the frequency range. Like most concepts in geophysics these values are the opposite of what would be expected. The vertical ***High Pass*** is the lower number – I like to think of it as "I want to keep frequencies higher than XXX". The vertical ***Low Pass*** is the higher number – I like to think of it as "I want to keep frequencies lower than XXX". Never apply simultaneous vertical FIR and IIR filters; the two filters will conflict and create strange data artifacts.

A typical bandpass filter would use a "quarter and double" rule. For instance, a 400MHz antenna could be safely filtered using a high pass of 100 and a low pass of 800. These are the typical default IIR values on the control unit. However, there is often high frequency noise pollution from cellular communications, so you could drop the low pass to 700-650 if needed. Just be careful because filtering removes real data too, not just noise. Bandpass filtering can also reduce soil-related noise that may be derived from frequency-dependence issues or the rapid attenuation of the higher frequency components. On the other hand, as noted above, low frequency components are lower resolution and can cause "bleed out" or an undesirable thickening of reflectors that obscures features of interest. A High Pass filter (150 to 200MHz) can be applied to 400MHz data to remove low frequency components and some horizontal banding from continuous interference, and will reveal higher resolution data and sharper boundaries. In most cases an IIR filter is preferable to the FIR option because more of the unwanted frequencies will be removed. A bandpass filter can be an alternative to a Background Removal (see Section 3.1.7) whereby horizontal banding from low frequencies could be removed. This technique may potentially reduce the impact of horizontal noise bands, or soil-related banding, without removing the direct wave or other flat-lying reflectors that are real.

You can use IIR creatively to filter above or below an antenna's central frequency to look at only the high frequency (higher resolution) or low frequency (lower resolution) components (**Figure 3-9**). You might find that some datasets are best viewed this way, since either side of the spectrum will reveal different characteristics of your dataset or perhaps a dataset is plagued by low or high frequency noise components. GPR data in less-than-ideal soil conditions (like wet clay) can usually be improved with bandpass filtering. For any given antenna you should know the ¼ and 2x bandwidth around the central frequency, and use these values to inform your initial bandpass filter settings. It should be noted that a bandpass filter can effectively mitigate external interference but if the source of the transmission is nearby, and has a powerful transmitter, noise may be impossible to remove. Electromagnetic interference and soil noise could be muted by applying a bandpass filter, but there is no "recipe" for universally applying a certain high pass and low pass range. Each project area will have different environmental variables and you'll have to experiment with multiple bandpass settings to achieve the desired result. Just remember that filtering removes real data, and aggressive value ranges could destroy useful information without obvious warning signs.

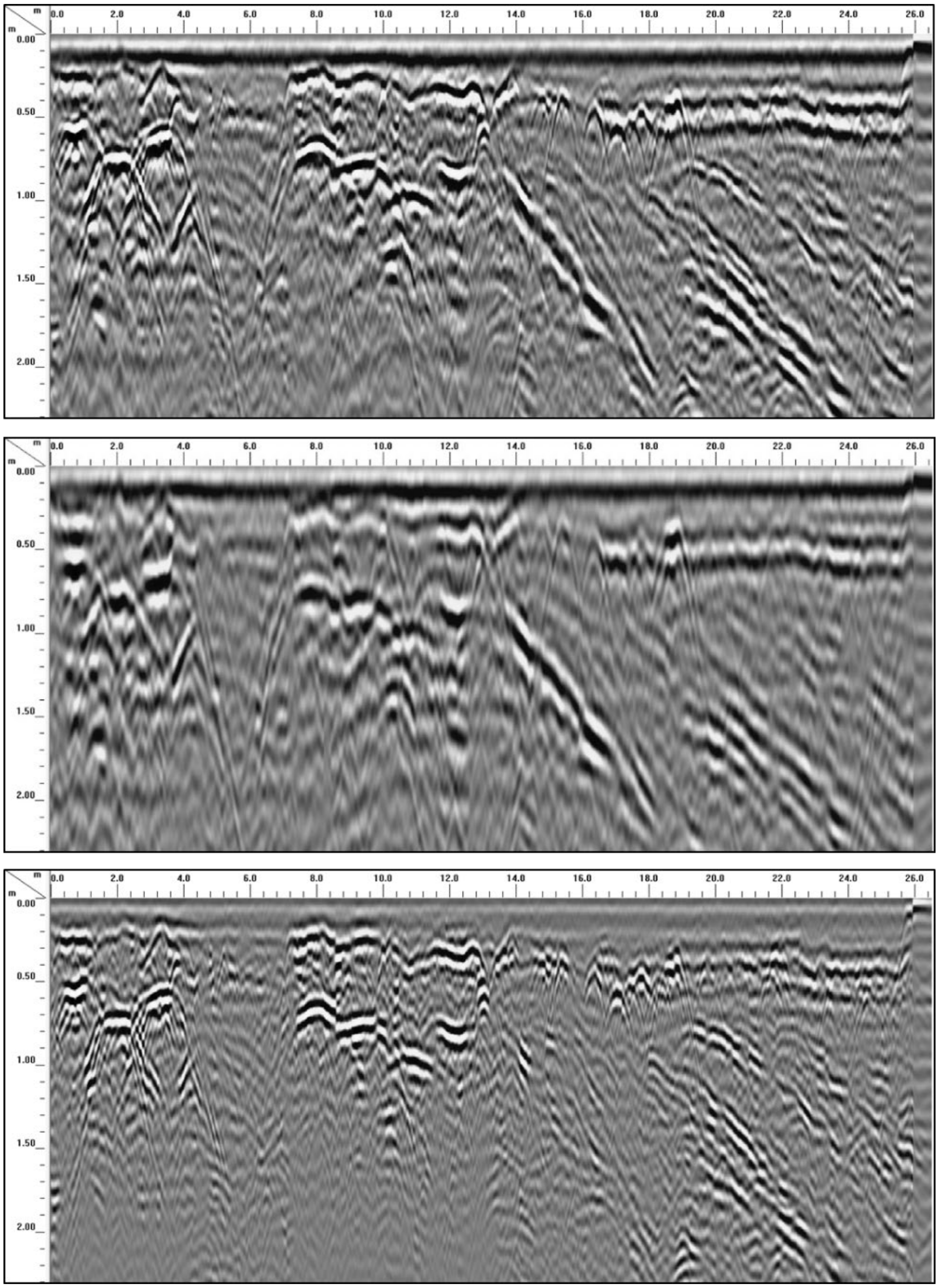


Figure 3-9 Example of bandpass effects on a single 400MHz profile. Top: original profile with no bandpass filter (100-800MHz). Center: lower resolution components below central frequency (100-400MHz). Bottom: higher resolution components above central frequency (400-800MHz).

3.1.7 Background Removal: useful (but dangerous)

During fieldwork horizontal noise bands from continuous external EM sources can be muted or altogether removed with a Background Removal [BR] filter. A BR filter length is entered as a number of scans. By entering a value you are telling the control unit that anything horizontal/flat-lying that extends for XX number of scans is background noise and should be removed. For convenience you can convert this value to distance by multiplying it by your scan density (typically 50 scans/meter or 18 scans/ft). With 50 scans/meter you would be collecting a new scan every 2cm. So, if you enter 100 scans in BR you will remove all horizontal reflections that are 200cm or longer. Here you will note that this can be very dangerous with a low scan number. Always start with ~200+ scans to make sure you aren't removing spatially-restricted soil layers or flat-lying archaeological features. Note that on SIR3000-based data a BR filter will affect your raw data; for SIR4000-based and UtilityScan data (Band Filter) it will not. When setting manual gain in the field a BR will flat-line your O-Scope and make it impossible to optimize the gains. You should set gains first and then apply the BR. A FIR BR is best for fieldwork. Just note that for any given BR value you have to collect at least that many scans for the filter to start working; it has to reference those scans to identify the horizontal bands.

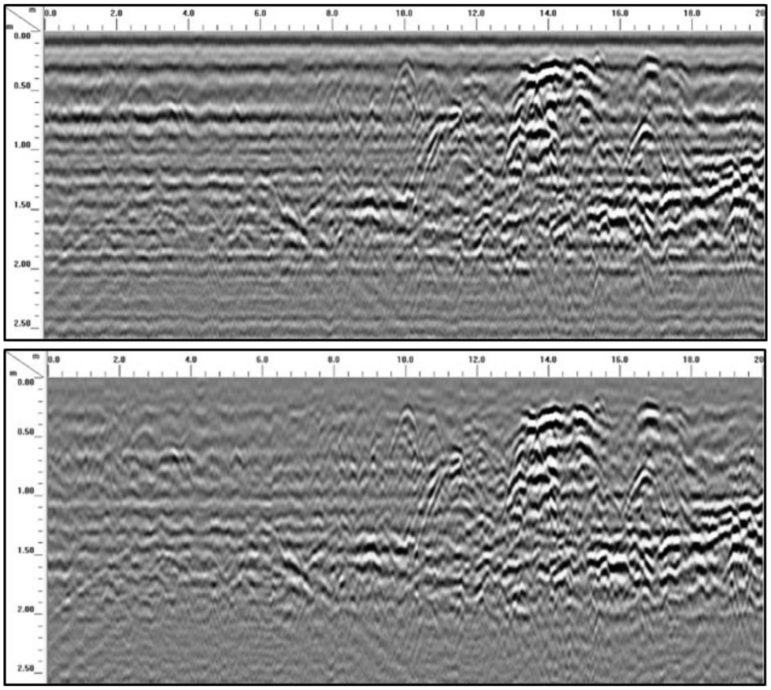


Figure 3-10 Original profile with horizontal banding (top) and the same profile after a Background Removal using 1024 scans.

Profiles with short but consistent noise bands can make good use of a creative BR, whereby a relatively small number of scans (50-100) may remove stubborn noise bands while preserving most of the real data. This method is especially useful for soil-related multiples that are generated from interfaces with large reflection coefficients and other sources. As with any filter, BR should be used only when needed and is best used with full knowledge of what the process actually does. When using a BR filter for real-time prospection just make sure that you are familiar with the data in the project area and that you are not removing any important data. A BR filter can greatly enhance visual quality and remove bands that otherwise may be interpreted as stratigraphic layers. This is especially relevant for trench and shaft features because the noise bands can "jump" over stratigraphic breaks and potentially affect their discovery. **Figure 3-10** shows a single profile that was used for a BR. The original profile (top) exhibits significant banding and is improved with a BR (bottom). Note the removal of horizontal bands and the Direct Wave, while real data are preserved.

In **Figure 3-11** a FIR BR (500 scans) was applied to the top profile. Note the removal of shorter bands that were preserved in the previous example (**Figure 3-10**, bottom). As the number of scans is reduced it is more likely that real layers (e.g. stratigraphy) could be removed. Did the bands represent real layers, or were they actually noise bands? In this case it is difficult to determine, thus caution is required. The bottom image in **Figure 3-11** shows the same profile with an aggressive FIR BR (11 scans). Note in this example that nearly all the data have been removed, except for steeply-dipping hyperbolic tails. This is because most of the stratigraphic data extended horizontally for more than 11 scans. Assuming a Scan Density of 50scans/meter, in the bottom example the BR filter removed everything that extended horizontally for 22cm or longer.

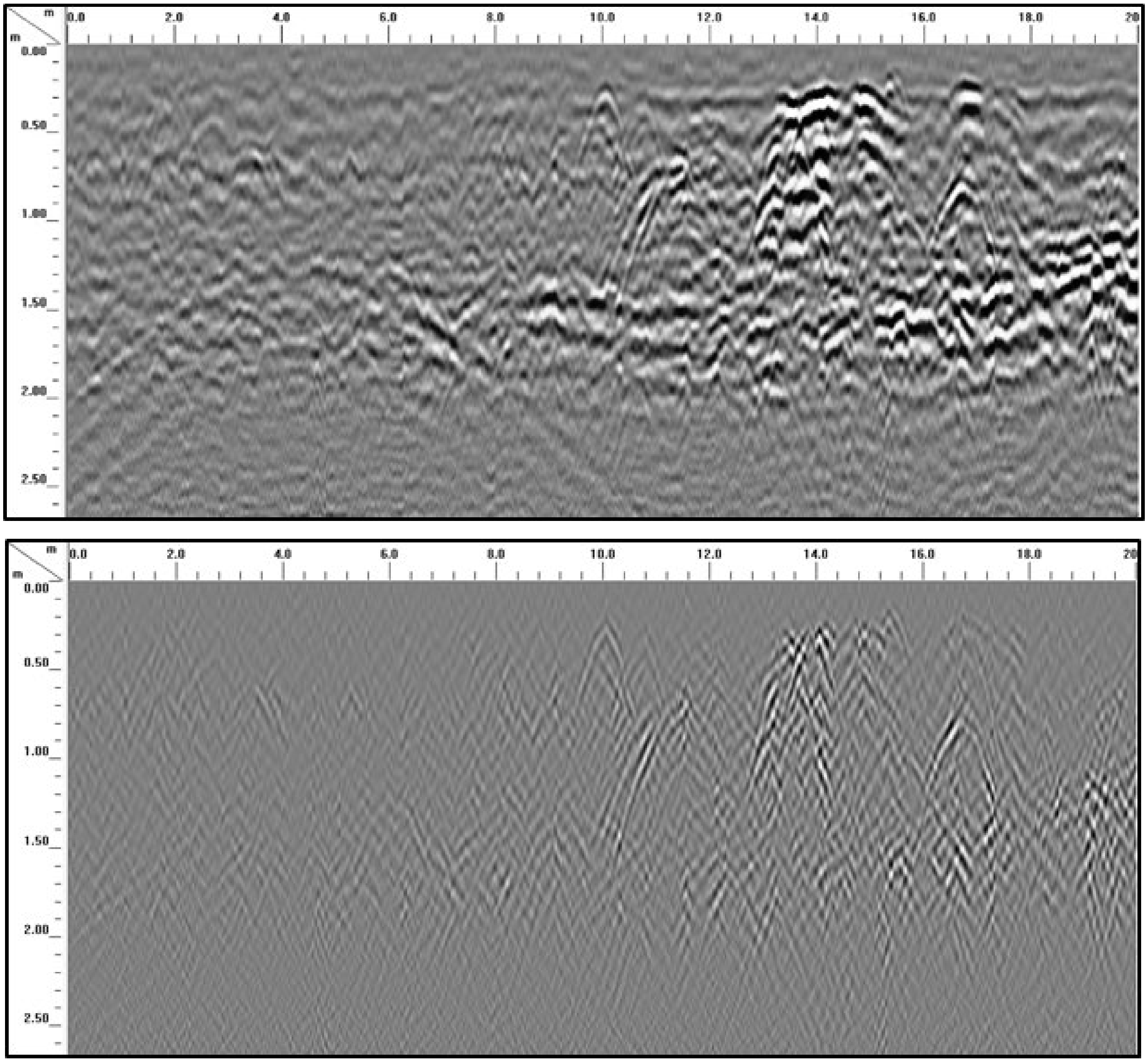


Figure 3-11 Comparison of BR using 500 scans (top) and the same profile using 11 scans (bottom)

3.1.8 Horizontal Stacking

Horizontal FIR- or IIR-based stacking is not commonly used during ACF data acquisition. This filter requires a user-specified number of scans much like a background removal. Stacking operates by weighting each new scan by 1/n, meaning that the current scan's influence on the profile is divided by the entered number of scans. Higher scan values reduce the impact of any individual scan and progressively smooth the data as larger values are entered (**Figure 3-12**). A low value (**Figure 3-12**, top; 2-6 scans) can downplay high-frequency sporadic noise by smoothing it out. This can be useful but in general it acts to reduce detail. Higher scan values (**Figure 3-12**, center; 7-12 scans) smear data, and extreme values (**Figure 3-12**, bottom; >15 scans) will remove most targets and distort layers. Higher values force the GPR system devote additional time for sampling each scan, and thus walking speed will be affected. Stacking is used by geologists and geophysicists to reduce unwanted details in GPR profiles and to accentuate layers at the expense of targets. This can be quite useful in cluttered soil conditions where the research interest focuses on the depth to bedrock or some other continuous phenomenon. If you must use stacking, I suggest using the FIR stacking option instead of the IIR option. For most ACF surveys real-time horizontal stacking is not recommended because small details are important. This is critical for surveys using SIR3000 or earlier control units; stacking will affect the raw data and cannot be reversed in RADAN. I'd recommend avoiding real-time stacking and only applying this filter during post-processing.

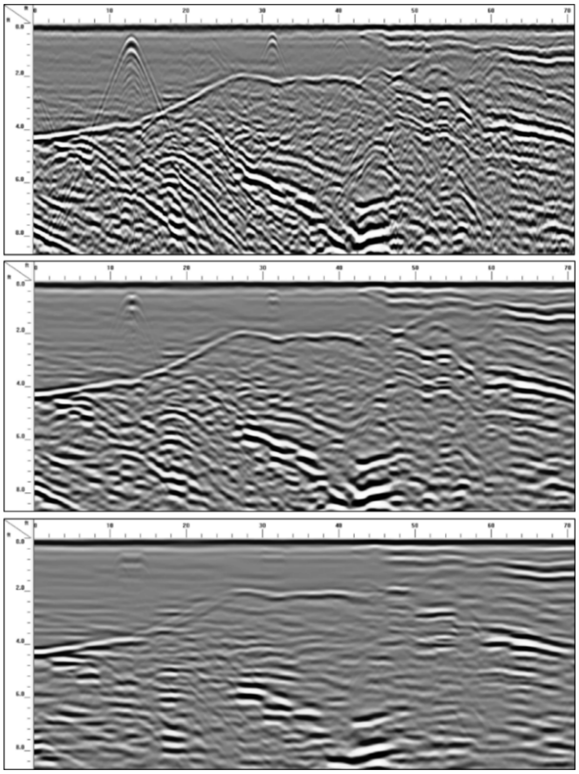


Figure 3-12 The effects of horizontal stacking

3.1.9 Attenuation vs. periodic/sporadic external noise

Attenuation refers to the dissipation of GPR energy with increased depth and/or an increase in conductivity (**Figure 3-13**). Attenuated signals can look similar to sporadic external noise in that each appear as a "snowy" overprint. Depth is an attenuation factor because GPR signals weaken with distance from the antenna, and every dielectric change that reflects GPR energy weakens the overall strength of the wave. Eventually the wave has no energy to reflect back to the antenna and the penetration limit is reached. This will affect any GPR antenna regardless of the central frequency. Attenuation from highly conductive media occurs when the GPR energy is dissipated in the ground and does not return to the antenna. This can happen at depth but also occurs at shallow depths in some materials (like wet clay and areas of salt-infused groundwater) or below localized features like concrete or brick walkways. The attenuated zone could manifest as a static-rich/snowy zone or a muted area where there are no obvious reflections from real interfaces or targets. Sporadic external noise is often most obvious at the base of profiles and usually appears as an area of static or snowy overprint that can overlap with attenuated areas. The main difference is that in the attenuated zone the data are completely replaced by unusable signals, while real data can often be seen through a sporadic external noise overprint. Attenuation (**Figure 3-13**, top) should not be confused with under-gained amplitudes with depth (**Figure 3-13**, bottom) which is the result of an inadequate gain curve.

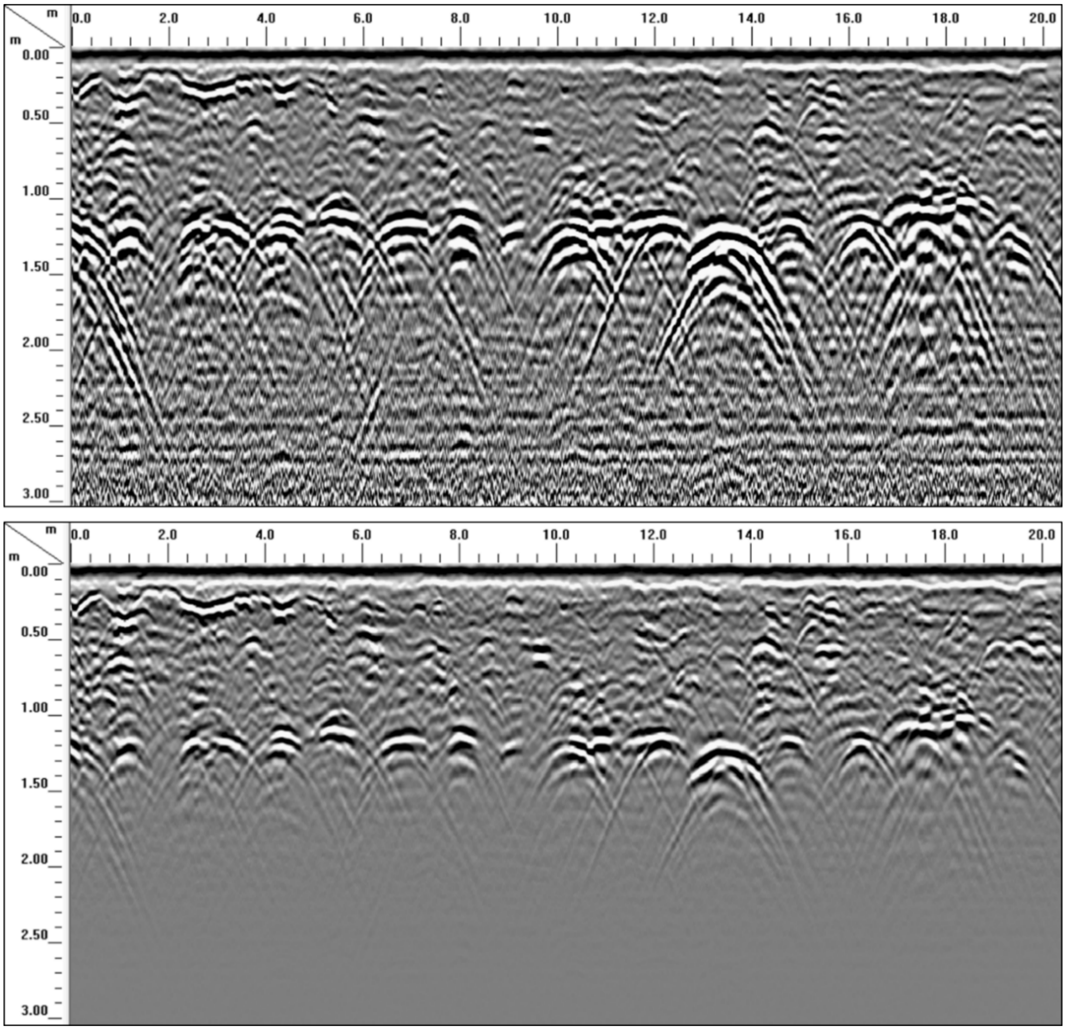


Figure 3-13 Top: attenuation with increased depth, and obvious noise bands and periodic noise in lower sections. Bottom: under-gained data in bottom half of profile

3.1.10 Asphalt surfaces

Asphalt parking lots and roads are common settings for ACF GPR surveys. Apparently archaeological sites are the perfect place for a parking lot, and roads are quite happy to cut through cemeteries, precontact and historical sites, and other cultural resources. The impact to the original landscape can vary from minor to downright destructive depending on the construction techniques used and the aggressiveness of pre-paving surface treatment (compaction, grading, cutting or filling). Parking lots and roads are often associated with other infrastructure installations and subsurface utility lines which may predate the paving or were more recently installed in cross-cutting trenches. These settings are not ideal for shovel test surveys but GPR is an ideal technique for discovering remnant archaeological features (if they survived) and informing excavation strategies. Asphalt is resistive and generally does not pose a problem for GPR surveys, but there are many aspects of asphalt surfaces that can heavily impact data quality.

The nature of pre-paving construction is of major importance. Road construction is generally quite disruptive to near-surface natural and anthropogenic materials. This usually involves cutting and grading to achieve a desired slope, heavy machinery driving around, quarrying of sediment to fill holes, and the compaction of fill units before paving. These activities will not only disturb cultural targets but they can directly impact the depth penetration of any GPR antenna. Surface compaction and the nature of the fill units are the major concerns. Compaction reduces the pore spaces between sediment grains and limits the amount of water uptake, and water content is one of the most important aspects of GPR wave propagation. The use of coarse-textured fill units, like gravel and rock, can scatter GPR energy while the use of certain types of clay may increase conductivity. Furthermore, after many years of service a road may have been repaved multiple times and this may add to the number of dielectric interfaces standing between the GPR and underlying features of interest. Last, but certainly not least, is the application of road salt to during the winter months. Salt has a very long residence time and when in solution will increase conductivity and may create dispersive saline “dead zones” that GPR cannot penetrate. Road plowing removes salt-enriched snow and ice from the road and thus areas of high conductivity may extend 10 to 15 feet from the road shoulders (**Figure 3-14**, top).

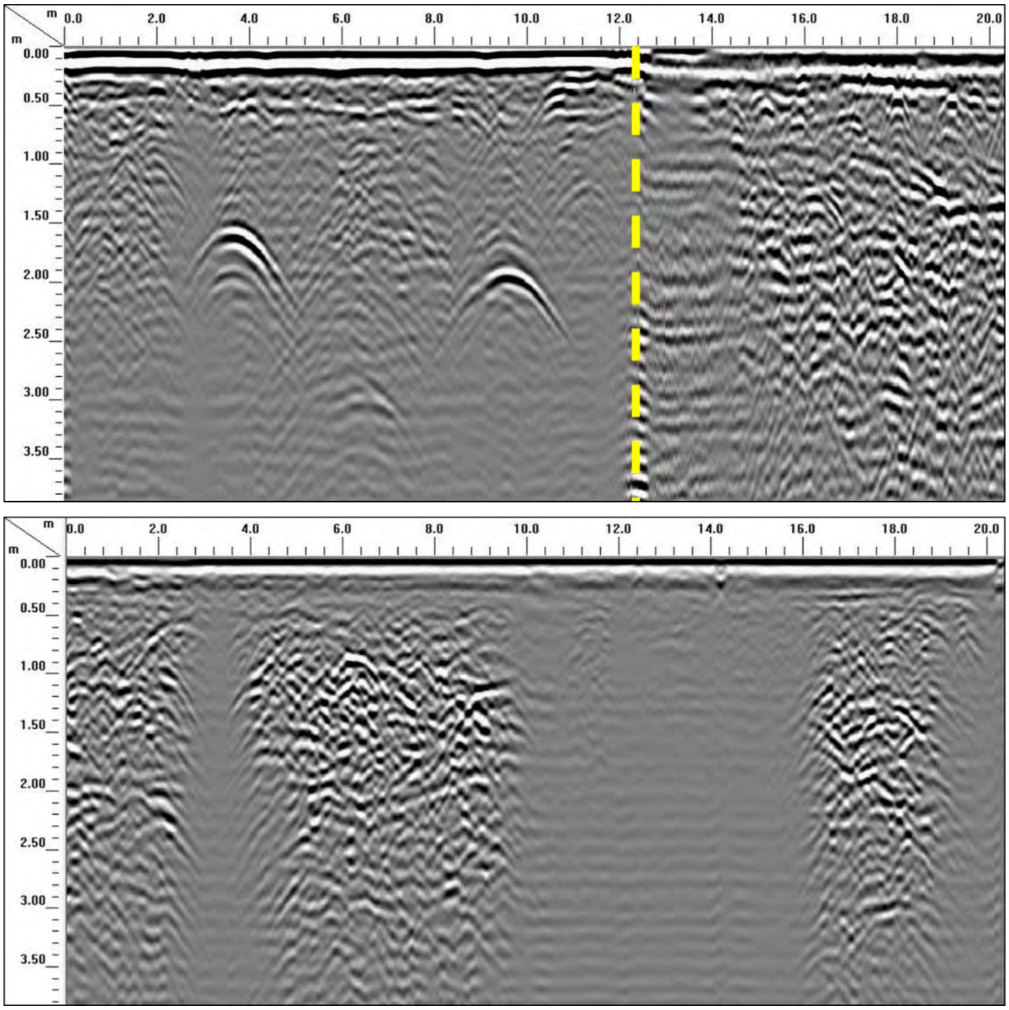


Figure 3-14 Top: example of attenuation from road salt along the edge of an asphalt road (road edge indicated by yellow dashed line). Bottom: example of extreme attenuation from road salt applied to a parking lot.

Parking lots and residential asphalt surfaces create similar problems but the pre-paving surface may not have been heavily impacted. Some grading and compaction may occur, and there will often be a fill layer between the asphalt and the underlying sediment. These settings are more favorable for ACF surveys and the preservation of cultural resources. However, there are still some problems that can arise. Road salt is the biggest concern. As with road surfaces parking lots are heavily salted in the winter, and since they aren't as regularly maintained as roads the salt can mobilize and migrate into surface cracks. Combined with rainwater or ground water the salt can create numerous and widespread saline "dead zones" that are a problematic for GPR (**Figure 3-14**, bottom). Pavement surfaces are efficient water barriers, and though salt and water may percolate through surface cracks much of the salt can wash off the pavement and pollute adjacent non-paved areas. Note that even a high amplitude target, like a metal water pipe, does not reflect energy back from an attenuated zone (**Figure 3-15**).

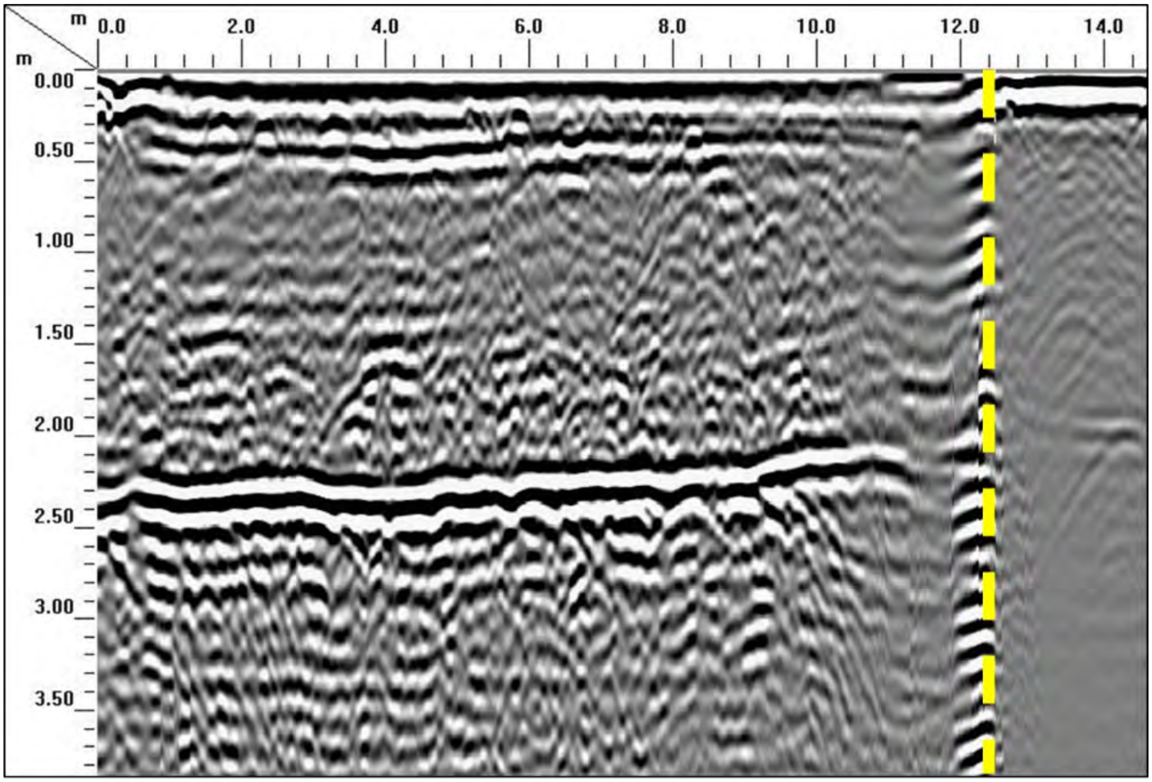


Figure 3-15 Effects of attenuation on high-amplitude targets. The relatively flat reflector is a metal water pipe, and as it approaches the road edge (yellow dashed line) and salt pollution it is no longer visible.

3.1.11 Concrete -- indoor

Concrete is an ideal resistive media for GPR penetration but it often generates noisy data from internal materials and from externally-applied coverings or chemical treatments. Indoor concrete is usually strengthened with reinforcing bar (rebar) or wire mesh. These can look slightly different on GPR profiles. Rebar is a rigid installation, often arranged in a grid pattern, and does not deform under the weight of wet concrete. The rebar mat will therefore appear as a series of well-patterned/spaced hyperbolic targets (positive-negative-positive polarity/phase or white-black-white color) at roughly the same depth across the slab. Wire mesh is usually supported on chairs/pedestals before the concrete is poured. During and after pouring of the wet concrete the mesh can sag under the weight and rest deeper in the slab. This will result in a evenly-spaced pattern of hyperbolic targets that will exhibit variable depths. The areas supported by chairs/pedestals will be shallower and unsupported in-between sections will slope down to a lower depth. Metal conduit, PVC pipe, post-tension and pre-tension cables, and radiant heating can also be present in concrete slabs. Each of these items will generate a hyperbolic target with varying phase and amplitude information. Pipes and other utilities are often installed below the slab and can generate hyperbolic targets.

The presence of rebar and wire mesh can impede GPR wave propagation and/or restrict depth penetration. This happens when the metal elements reflect a large portion of the total GPR energy and this reduces the amount that can travel deeper. Since the metal is close to the slab surface it can generate multiples/echoes and may obscure information below. This issue compounds with denser grid patterns and as more layers of reinforcement are encountered. Real-time prospection can benefit from creative Bandpass filtering (**Figure 3-16**) but the specific frequency parameters will not be consistent between different sites. Other penetration and data quality factors include the type and size of the aggregate, the presence of metal shavings in the concrete mixture, and whether the slab surface has been covered by thick rubber or carpet or a wooden platform floor with an underlying void space. Coarse aggregate may scatter most of the GPR energy and/or create abundant hyperbolic targets whose tails obscure and/or chop up underlying data (such as the concrete to sub-grade interface and possible air voids). The overlap of the tails can create artificial hyperbolic targets that can be confusing. Metal shavings in the concrete mix may completely block GPR penetration, while overlying surface coverings may have the same effect or at the very least reduce penetration depth. Wet (green) concrete is conductive, and as such it dissipates the GPR energy and should not be scanned until it has cured.

In forensic situations an indoor concrete installation may have been cut through, including metal reinforcement, and new concrete (without reinforcement) poured after placement of a clandestine burial. In these cases the post-burial concrete surface may have been painted or covered with carpet to hide the activity. Even so, in this situation the ***lack*** of concrete-related noise issues may be diagnostic of previous localized alteration. If the overlying surface cover is blocking GPR penetration it should be removed (if possible) to facilitate depth penetration and data quality. With

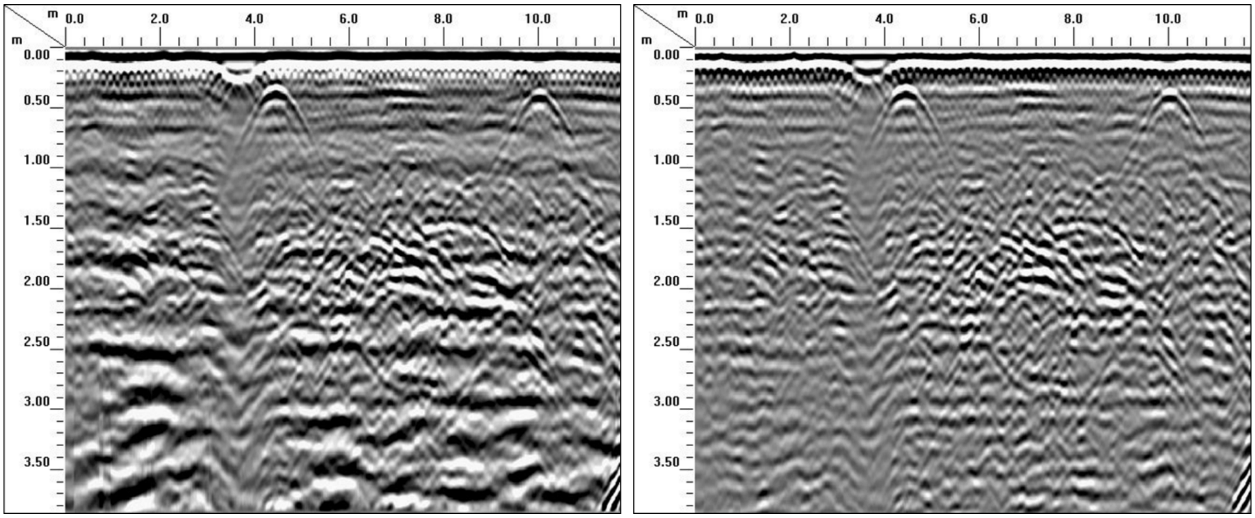


Figure 3-16 Real-time filtering to remove noise from metallic concrete reinforcement. For this 350MHz profile a 200MHz high pass was applied.

increased decomposition the burial fill will compact and could create a localized void space (**Figure 3-17**) of negative-positive-negative polarity/phase, regardless of whether it was deposited before or after the concrete was poured. Just remember that non-forensic processes can generate air voids, including natural soil subsidence, erosion from running water or water table fluctuations, or burrowing animals.

3.1.12 Concrete -- outdoor

Concrete poured in outdoor areas may exhibit internal reinforcement if it was installed for industrial purposes or was intended to be a load-bearing surface. It should also be noted that concrete slabs originally installed inside a structure may become exposed to the elements if the original structure is destroyed or removed. Aside from the potential problems associated with indoor concrete (see Section 3.1.11), outdoor concrete (either intentionally poured outside or exposed after a building is removed) can also exhibit issues from excess moisture and possibly from de-icing salt. Old outdoor concrete can weather and degrade, allowing water ingress through weathering cracks, freeze-thaw movement and expansion from salt crystal formation, and areas of general delamination. Increased water content will raise the concrete's dielectric and potentially create a high reflection coefficient at the concrete to sub-grade interface. Internal reinforcement may be absent if the slab was not a load-bearing surface or if it was poured by a homeowner (or hastily poured by a criminal). Salt pollution from winter de-icing can directly affect GPR data quality as it increases the conductivity of the concrete. This includes recently-applied salt, the compounding of many years of salt applications, and the long residence time of salt inside and potentially below the concrete. These issues compound as water is added.

Much like indoor concrete, in forensic situations an outdoor concrete installation may have been cut through, including metal reinforcement, and new concrete (without reinforcement) poured after placement of a clandestine burial. In these cases the post-burial concrete surface may have been painted or covered with a surface treatment to hide the activity. In this situation the ***lack*** of concrete-related noise issues may be diagnostic of previous localized alteration. It is highly unlikely that the identical concrete and aggregate mixture was used to patch the hole, and the recently-poured concrete patch may exhibit strong contrasts with the original slab or enhanced noise issues from the concrete mixture. With increased decomposition the burial fill will compact and could create a localized void space (**Figure 3-17**) with a negative-positive-negative polarity/phase. This and other information can indicate an area of high forensic interest. It is worth noting that other factors can generate voids, such as natural soil subsidence, water erosion, or burrowing animals.

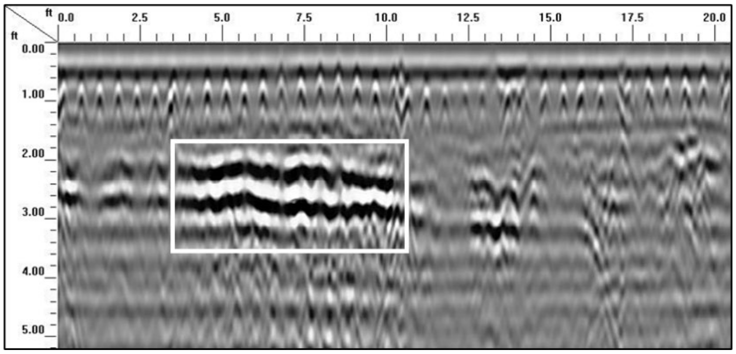


Figure 3-17 Example of an air void below a reinforced concrete slab. Air void, highlighted with white rectangle, is approximately two to three feet deep and between the 4ft and 11ft marks.

4 PREPARING FOR AND CONDUCTING A GPR SURVEY

4.1.1 What to do before you arrive at a site

Most GPR systems have low ground clearance because the antenna is ground-coupled and must touch the ground (or be as close as possible). Survey areas should be clear of dense vegetation, large rocks, corn stalks, etc. for optimal data collection. A good rule of thumb is "if your lawnmower can't go over it the GPR probably can't either". UtilityScan Pro system carts (3-wheel or 4-wheel) and rugged cart upgrades for UtilityScan can compensate for some surface conditions with vertically-sliding antenna mounts. In some cases there may be no option for pre-survey landscaping and clearing. If so, you should know this beforehand so you can bring the appropriate GPR equipment and other field gear. Ask the property owner if you can move rocks, sticks and other obstructions, and request permission to cut small bushes or remove dead limbs from trees. Don't assume that you can do whatever you want; ask first.

Go online to Google Earth or Google Maps and perform a pre-survey aerial inspection. Use Google Street View as well. Why be surprised? Know what you are getting into so you can plan accordingly. Are there any cellular, radio, or television towers in the vicinity? You should also find and write down the address for the nearest restrooms and the nearest hospital. If you can find high-resolution aerial photographs (Google, USGS EarthExplorer, NOAA, state GIS clearinghouses) or LiDAR data look for surface indications of subsurface anomalies, like vegetation patterns or surface depressions, animal burrows, large disturbances, or successor species plants that might indicate disturbed soils. Do historic maps and historical aerial photographs show any significant features in the vicinity that are no longer present? Have there been archaeological excavations that provide the rough or specific location of targets of interest?
Make sure that your GPR system's firmware is up to date and batteries are fully charged. Consider bringing a power inverter so you can charge batteries in your vehicle. Use a pre-survey checklist (see below) to ensure you have all of the necessary GPR parts/pieces and field gear. This includes tape measures, tent stakes, road cones, and other essential gear.

4.1.2 GPR hardware and field gear checklist

- GPR Control Unit
- Survey Cart (3-wheel or 4-wheel) and antenna tub/capsule

  <u>If not using a cart:</u>
    - Chest harness for control unit
    - External distance-encoding wheel
    - Pull handle, antenna shark fin, hitch pins for connecting pull handle to shark fin
- Main GPR antenna and others if available (like 900MHz)
- GPR batteries (at least 2; 4 preferred) – fully charged. Bring battery charger just in case.
- Control cable for control unit and antenna (analog or digital)
- Surveyor's tape measures (at least 4; two 50m and two 100m)
- Metal tent stakes (>20)
- Plastic tent stakes (10) or wooden stakes

- GPS (fully charged) and range pole (if available)
- Serial cable (RS232) to connect control unit/ antenna to GPS
- GPS tripod for survey cart (if available)
- Digital Camera
- Collapsible road cones (4)
- Spray paint (orange or other bright color)
- Flagging tape
- Sharpie or other indelible markers
- Weather-resistant notebook
- Mechanical pencils
- Graph paper
- Rain jacket
- Safety vest
- Hardhat and workboots (if required)

4.1.3 What to do when you first arrive at a site

The first order of business at any new project area is to set up your GPR system and spend 15-20 minutes (or more) ‘mapping on’ – this means becoming familiar with the above- and below-grade conditions by walking around and prospecting for targets, layers, and other information. Use this time to assess the quality of the GPR data and make settings adjustments as necessary. Do not configure the GPR system in the paved parking lot next to the project area and expect optimal data quality during your survey. Determine optimal parameters within the project area and make sure you understand how the subsurface conditions change across the site. This is your opportunity to prevent a lot of post-processing headaches and/or an unbudgeted return to the project area to reacquire data.

An ideal order of events is as follows:

1) Recall default settings for system (just every new project, not every day)
2) Calibrate encoder/survey wheel (10m or 30ft is fine). After calibration collect a profile along a surveyor’s tape to ensure that the calibration is accurate
3) 20 minutes of prospecting/mapping on – set depth so bottom 25% of profile is junk/ attenuated. Set manual gain levels (SIR4000 and SIR3000 only).
4) Lay out grids, GPS control (or total station) on significant grid nodes
5) Ensure that local grid coordinates, grid dimensions, and surface features are well-documented
6) Take notes and photographs. It is always best to over-document.
7) Start Surveying

Recall default settings

Most GSSI control units contain a comprehensive list of manufacturer-suggested default settings (see Chapter 7) for specific cart and antenna setups. These include ideal antenna parameters (scans/second, transmit rate, time zero position/offset), and suggested normal parameters (depth, dielectric, time range, scan density or scans/unit, samples/scan). Also recalled is the default distance encoder calibration value. Parameters that should be adjusted include scans/unit (typically

18 scans/ft or 50 scans/meter) depth range, time range, dielectric, samples/scan, manual gain curve and manual position (***avoid auto gain and auto position if possible***) and encoder calibration. Chapter 7 provides specifics for selected GSSI systems. Recalling default settings overwrites any custom encoder calibration, so first recall defaults and then perform an encoder calibration.

Calibrate Encoder

Encoder calibration is a straightforward process but there are a few tricks for making it perfect. First, choose the flattest area possible and lay out a tape measure to 30ft or 10m by staking the 0.0 end to the ground and stretching the tape tight. Stake down the other end as well. On the control unit the calibration dialogue will suggest setting the center of the antenna on the 0.0 mark. I recommend using a fixed reference location on the cart, like the center of the back axle, or the front edge of the antenna if using an external encoder wheel without a cart. Set the desired distance on the control unit, and move the system to the end mark making sure that the cart/antenna reference location stops at the end mark. Save the calibration, close the calibration dialogue, and turn the cart around 180 degrees. Place your reference location on the end mark and face the 0.0m/ft mark. The final step is to collect a profile by moving the system from the new start mark (30ft/10m) toward the 0.0 mark and approximately 1ft/50cm past the 0.0 mark. Finally, back up the system so the reference location is at the 0.0 mark at look at the accumulated distance noted on the screen. If this distance matches the laid out distance your calibration was successful. If not, redo the calibration and test line.

Mapping On to the Site

Now that the encoder has been calibrated you can set the other critical parameters (depth, time range, dielectric, samples/scan, scans/unit, gain curve). To set these correctly I recommend prospecting around the site for 15-20 minutes. During this prospection time you can evaluate whether you are maximizing your depth penetration – keep increasing your depth range until the bottom 25% of the GPR profile is attenuated/ junk data. Remember: ***GPR systems do not record data below the bottom of the screen***. Keep looking around the site to make sure there aren't any locations with anomalously deep penetration. If there are, set your max depth in these areas so you don't cut off any useful data. Keep in mind that archaeological targets can provide localized better-than-average penetration.

The next step is to determine the local dielectric using hyperbola matching. A calibrated dielectric will show you a fairly accurate depth scale and help you determine the true depth of penetration. If you find that your depth penetration is better than average (15-20ft/ 5-6m) you should change your samples/scan from 512 to 1024 to prevent aliasing (see Section 3.1.2). You should also find a portion of the site that represents "normal" background stratigraphy (if possible) to perform a gain curve calibration. By "normal" I mean a location that shows consistent stratigraphy without an abundance of targets or possible ACF anomalies. Collect a profile in this area and then look at the data to determine the most representative location. With the file still open back up to this area and then close the profile. Perform a manual gain (if possible) and use the O-Scope to optimize the gain curve. If using a UtilityScan this is a good location for an antenna calibration. Collect another profile and evaluate the new gain curve; the entire profile should be gained consistently with no horizontal bands of under-gained/over-gained data. If consistently gained but the data are somewhat washed out just increase the overall gain/linear gain to compensate.

The final step is to save a representative profile and then power off the system to conserve battery life while laying out grids.

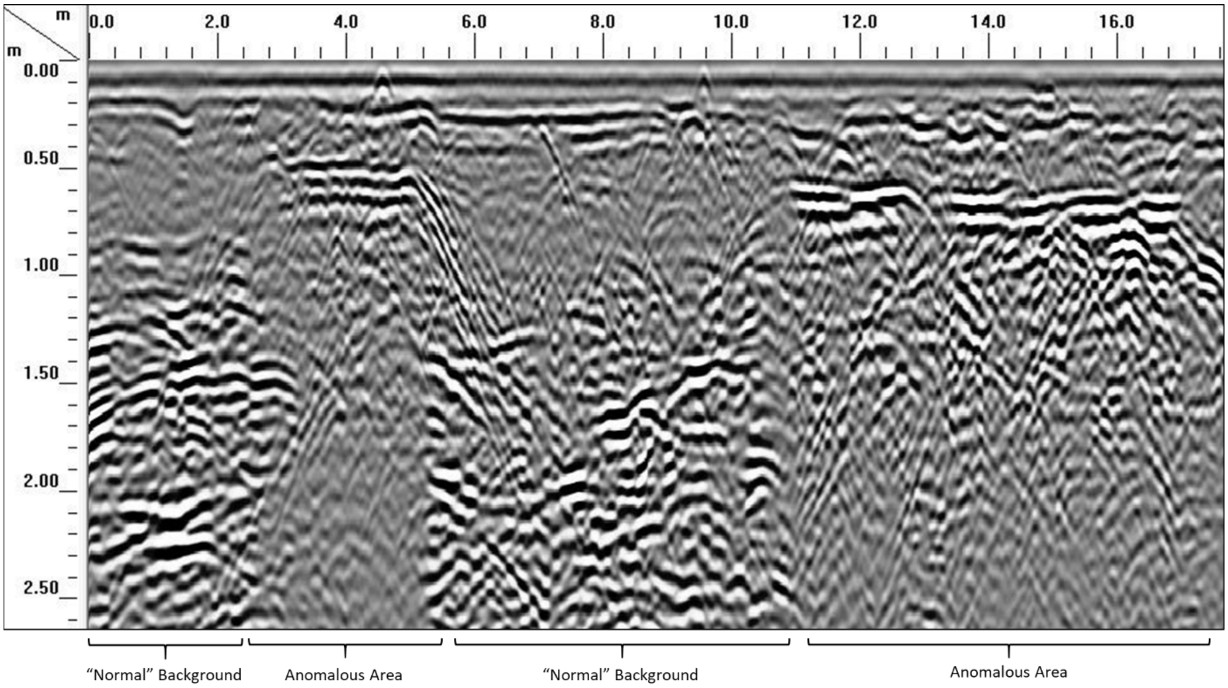


Figure 4-1 Example of "normal" background in comparison to areas with localized anomalous data. A manual gain curve or antenna calibration should be configured in "normal" areas so that amplitude deviations will be obvious.

Lay out Survey Grids

You are now ready to lay out GPR grids. The necessity of gridded GPR data collection for ACF surveys cannot be overstated. Gridded data ensure a more predictable data density and reduce the likelihood of gaps in coverage (aside from between-transect spacing). The resulting time slices capture the geometry of AFC targets, provide enhanced interpretive potential, and place individual features into a larger horizontal and vertical context. Time slices can be a detailed image of the subsurface, but it all starts in the field and poor field practices lead to poor data (garbage in = garbage out). To maximize the yield from 3D datasets there are numerous field practices that must be implemented. The next section covers the basic and advanced concepts and provides guidance on best practices for collecting gridded datasets.

4.1.4 Important considerations for gridded field datasets

I cannot stress enough that ***good data start in the field***. As a GPR field operator it is your job to constrain all possible variables, especially encoder calibration, depth/time range, and other critical acquisition parameters. Equally as important is to ensure that geophysical grids are properly laid out and measure the 'independent leg' to double-check each grid (see Section 4.1.6). Where possible, use existing local archaeological grid coordinates – this will reduce the compounding of mapping errors when relocating targets of interest. I also suggest using a high-resolution GPS, or a total station, to record all grid corners/ nodes. If these devices are not available, collect measurements to tie your grid(s) to a few permanent datum points (trees, telephone poles, house corners, etc.) to facilitate ground-truthing efforts or future additional data collection. Record these datum points in your field notes.

When collecting data on a grid the center of the GPR antenna must be positioned on the starting baseline and data collection should stop when the antenna is centered on the ending baseline. This is especially important for zig-zag/bidirectional survey methods. Stopping on the ending baseline is not as important for unidirectional collection but it is important for any 'rubber-sheeting' efforts during post-processing (see RADAN handbook). You should also consider limiting grid length in the direction of travel. Topographic inconsistencies can generate cumulative offsets as profile length increases. This could lead to data striping in 3D, and along-line offsets that create a 'zippered' appearance for targets. For gridded data collection I recommend a maximum profile length of 30-meters (100-feet). An ideal length would be 20-meters, but 30-meters is OK if transects are straight, topography is relatively flat, and the antenna starts/stops on grid baselines.

A note on encoder/survey wheel calibration: this is an important variable that must be controlled. When you recall the default setup for a given antenna and cart/external encoder setup you are restoring the default antenna ***and*** encoder settings. As cart wheels and external encoder wheels "settle in" or wear over time the default encoder calibration value becomes less accurate. It is critical to calibrate your encoder wheel before a survey (especially a gridded survey!). These errors become more pronounced with uneven localized topography (slope distance, roots and rocks, etc.) and in zigzag/bidirectional surveys. ***If you calibrate the encoder and then recall default settings the encoder calibration will revert to its default (uncalibrated) state.***

If data are collected across multiple adjacent grids, the acquisition parameters ***must be identical*** for each grid. This includes all critical parameters, such as time range, depth range, dielectric, scan density, samples/scan, bits/sample, and number of channels. Do not change these settings during a multi-grid survey – RADAN will not be able to match the data between grids. Additionally, during data acquisition set Position Mode and Gain Mode to Manual (if possible). This is especially important for SIR3000-based data but is also a good rule of thumb for SIR4000-based data. The Position Mode and Gain Mode cannot be changed to Manual on the UtilityScan system (Android-based). With Automatic settings, each time the SIR3000 or SIR4000 are initialized (battery swap, system shutdown/ power on, Run/Setup or Init button) the system automatically reconfigures the Position of the Direct Wave/ Time Zero. If this occurs halfway through collection of a grid, or in between collection of multiple grids, there can be offsets in the Position resulting in slight offsets between grids. For 16-bit data (SIR3000) re-initializing the system (battery swap, 2x Run/Stop in modes other than TerraSirch) will reconfigure the Auto Gain function and lead to amplitude differences between grids. This is not an issue with the SIR4000 unless the 3D grid is created with .DZX files (see Section 4.3 of the RADAN 7 handbook). This will lead to a 'checkerboarding" effect and is not easy to correct during post-processing.

I highly recommend collecting gridded datasets with the 2D modules on GSSI control units (TerraSirch, Expert Mode, Digital 2D), instead of using 3D modules (Quick3D, Digital 3D). The 2D modules offer many advantages over 3D modules. Though the ease of grid setup in Quick3D/Digital 3D is handy, there are limitations. On perfectly flat surfaces the automatic line closing function is a real time saver. However, on topographically complex surfaces this could lead to some distance-related issues. For instance, the GPR encoder wheel records slope distance, not straight-line distance. This means that compounded topographic errors could increase the length of your profile, causing the auto stop function to terminate the line before you hit the baseline. I'd rather collect from baseline to baseline and sort out issues in RADAN.

The most important distinctions are the ability to collect data beyond your formal grid boundaries and to add obstacle-avoidance lines. In Quick3D/Digital 3D, your profile is automatically stopped at the specified distance – you cannot collect data beyond the upper baseline. With 2D modules you can do whatever you want, making it much more flexible. Another advantage to 2D modules is that collecting data on either side of an obstacle is more straightforward. This is possible in Quick3D/Digital 3D, but it is easy to mess it up and you end up building the grid in RADAN anyway. Lastly, the data generated from 3D modules inherit field display parameters (gain, filters, etc.). To reduce uncertainty, I prefer to process my data starting from the raw format by creating manual 3D grids in RADAN.

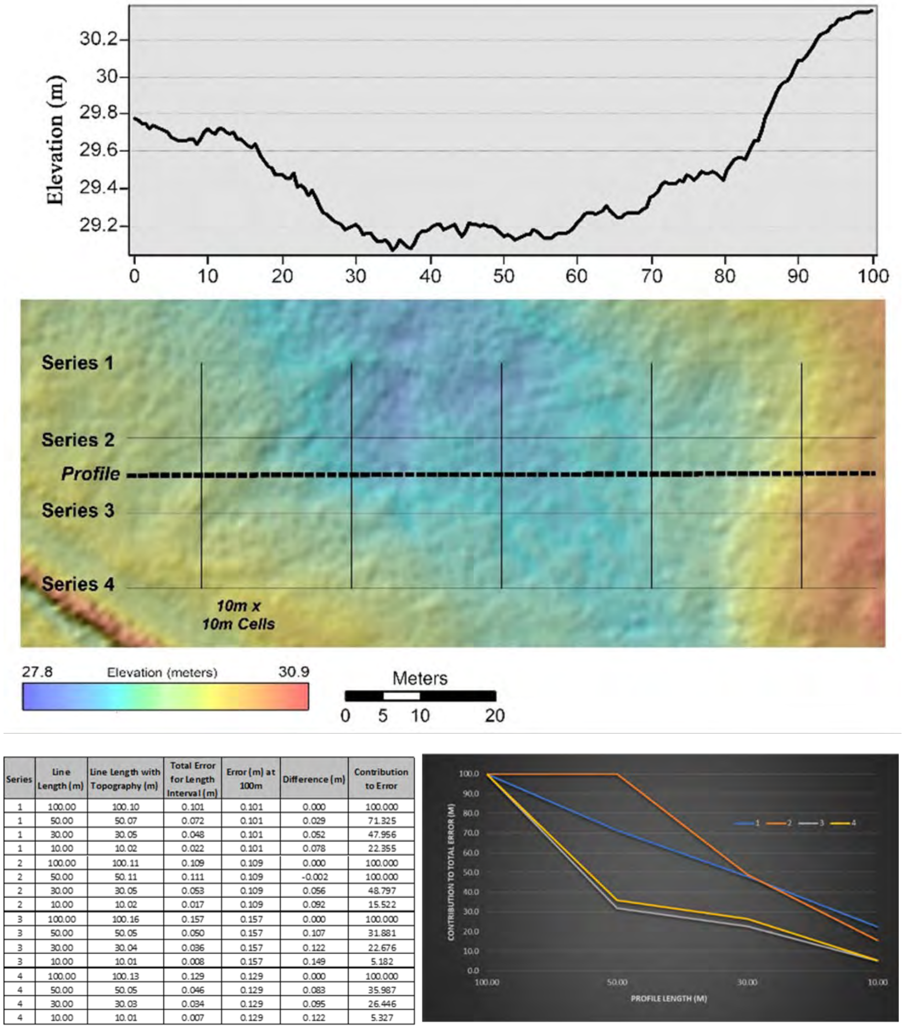
Become familiar with RADAN's 3D creation options (refer to RADAN 7 handbook) so you can make informed decisions in the field. For example, you should understand the information RADAN requires to insert line segments when dealing with obstacles (see Section 4.1.9; see RADAN 7 Handbook). Adding segments to a 3D Dataset is critical for maximizing survey coverage but requires detailed notes for the starting and ending X/Y coordinates. Another important consideration is the X/Y coordinate pair for grid origins. This will always be in the lower left corner of a grid (relative to Grid North) regardless of the origin corner/baseline for data collection. These coordinates will be essential for combining coincident/adjacent grids into a Super 3D file.

4.1.5 Unidirectional vs bidirectional transects

Transect orientation/collection method is critical for ACF datasets. To save time, most operators employ a ***zig-zag/bidirectional*** collection pattern, where the first profile is collected from the starting to the ending baseline. The next profile is collected from the ending to the starting baseline, and so on. While this method is certainly faster, local ground surface conditions can lead to data striping, an overall reduction in the 3D geometry of targets, and uncertainty about where the errors came from. ***Unidirectional*** transects always begin on the same baseline, and after a file is collected the system is returned to the baseline to start a new profile. This is the slowest collection method, but 3D geometry is markedly improved and there is consistency in the antenna's transmitter/receiver orientation (Goodman and Piro 2013). I recommend this method (when possible) because the geometry of targets/anomalies is often a diagnostic characteristic for interpreting 3D datasets. Data offsets and striping can significantly reduce 3D interpretability, especially in cemetery and forensic projects and in precontact surveys. An added benefit is that profiles are displayed in the same orientation during post-processing.

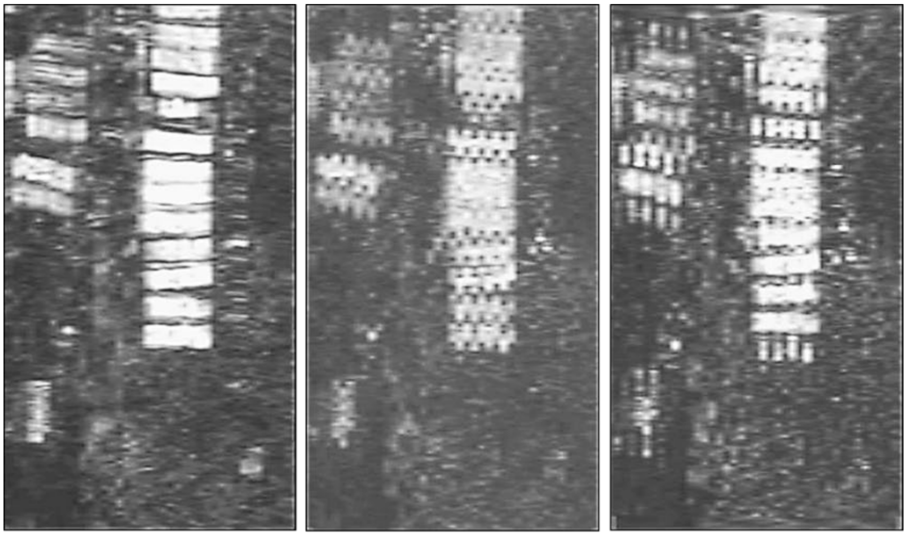
The basic concept is that longer profiles compound greater (and even less predictable) errors from topography and other variables. GPR profiles can never be shorter than the transect length unless the antenna stops short of the baseline, there is an encoder calibration error, or something (like tire ruts, ditches, or other depressions) prevents the encoder wheel from turning. Consider the example from **Figure 4-2**: four sets of profiles of different lengths (10m, 30m, 50m, 100m) collected on the same transects and spaced 10m apart. The local topography exhibits approximately 1.0m of variation across 100m. Looking at the associated table, and assuming a perfect distance encoder calibration, we can see that line lengths of 10m accumulated an average of 1.0cm of topographic error, whereas 100m lines accumulated an average of 12.5cm of topographic error (min: 10cm; max: 16cm). These errors could be quite different in other survey areas that have greater topographic variability.

Now, consider how these topographic errors would compound even further with zig-zag/ bidirectional survey patterns. It is obvious that the errors would manifest as between-line offsets, meaning that the true location of a target would not be represented equally across all profiles. In 3D time slices with minor offsets this would appear as a “zippered” effect, while progressively larger offsets would create greater geometric displacement (**Figure 4-3**). The main issue here is that we collect 3D grids to capture the geometry of targets; our data are far less interpretable if target geometry is distorted (or altogether obliterated) by data offsets. This is especially true for ACF targets that do not have predictable geometry such as precontact features, some human graves, and clandestine burials.



Series	Line Length (m)	Line Length with Topography (m)	Total Error for Length Interval (m)	Error (m) at 100m	Difference (m)	Contribution to Error
1	100.00	100.10	0.101	0.101	0.000	100.000
1	50.00	50.07	0.072	0.101	0.029	71.325
1	30.00	30.05	0.048	0.101	0.052	47.956
1	10.00	10.02	0.022	0.101	0.078	22.355
2	100.00	100.11	0.109	0.109	0.000	100.000
2	50.00	50.11	0.111	0.109	-0.002	100.000
2	30.00	30.05	0.053	0.109	0.056	48.797
2	10.00	10.02	0.017	0.109	0.092	15.522
3	100.00	100.16	0.157	0.157	0.000	100.000
3	50.00	50.05	0.050	0.157	0.107	31.881
3	30.00	30.04	0.036	0.157	0.122	22.676
3	10.00	10.01	0.008	0.157	0.149	5.182
4	100.00	100.13	0.129	0.129	0.000	100.000
4	50.00	50.05	0.046	0.129	0.083	35.987
4	30.00	30.03	0.034	0.129	0.095	26.446
4	10.00	10.01	0.007	0.129	0.122	5.327

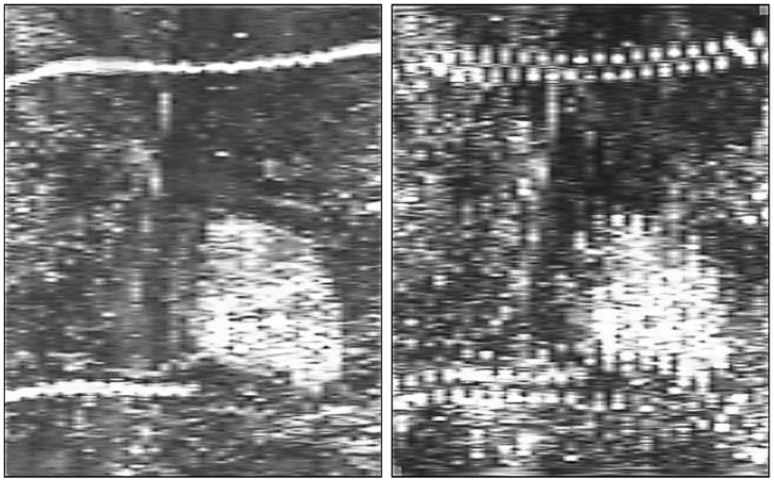
Figure 4-2 The compounding of distance-related errors with local topographic variation. Four series of transects with increasing length (10m, 30m, 50m, 100m) inherit distance offsets as line lengths increase, and these errors are different for each series location



Unidirectional

Bidirectional
15cm error

Bidirectional
50cm error



Bidirectional
minor errors

Bidirectional
60cm error

Figure 4-3 Examples of distance-related errors and the resulting "zippering" effect with bidirectional surveys and greater distance offsets. The top example shows data offsets relating to burial vaults. Bottom example is a historical (1920's) golf course sand trap (not visible on surface) and utility lines

4.1.6 Laying out GPR grids

Geophysical grids are typically laid out in 20mx20m blocks, a practice established in the early days of geophysical surveys. The 20m square was a useful convention for early magnetometer, electrical resistance, and GPR surveys since it provided a manageable "bite-sized" chunk for exhausting time-based and probe insertion data acquisition. For modern distance-based GPR surveys we need not be restricted to 20mx20m grid cells. While the ideal transect length in the direction of collection is 20m, the grid dimension perpendicular to the path of travel can be as large as needed. Consider a 20m (Y) by 200m (X) survey area where unidirectional Y-axis lines will be collected at 50cm intervals. In this case, the Y-axis dimension (20m) is ideal for reducing compounded topographic errors. Were we to use the 20mx20m convention we would have to lay out 10 individual 20mx20m grids in the project area. This would take more time and require more detailed notes (a good chance for errors to be incorporated). Instead, we could simply lay out a single 20m (Y) by 200m (X) grid. This would vastly simplify the fieldwork and note taking, and would save a lot of time during post-processing.

Gridded GPR data are only as good as the grid layout. Improperly surveyed grids lead to numerous errors, some of which cannot be corrected during post-processing. Take your time and properly lay out your grids. Much like excavation grids at archaeological sites, errors in GPR grid layout can compound rapidly across large survey areas. Grids could be created in GIS software before fieldwork, uploaded to a survey-grade GPS, and then laid out in the field. However, this method usually requires some field modification anyway and in general it is best to lay out grids in the field and then collect GPS data on each grid node. Some fieldworkers find it convenient to lay out grids using a simple right triangle ratio like 3:4:5, but in my opinion restricting yourself to this convention can be frustrating in irregular or complex survey areas. A more flexible approach is to simply use the Pythagorean Theorem to quickly lay out squares and rectangles with any combination of side lengths. To lay out a grid of any size, we first need to know the length of the sides (**Figure 4-4**). Once these measurements are established we can then calculate the hypotenuse of the grid and lay out four right angles (essentially two right triangles) to create a square or rectangle. For right triangles $A^2 + B^2 = C^2$. So, if a survey area is 25m x 60m, we can calculate the hypotenuse as $625 + 3600 = C^2$ or $4225 = C^2$. We can then derive the hypotenuse as $\sqrt{4225}$ or 65.

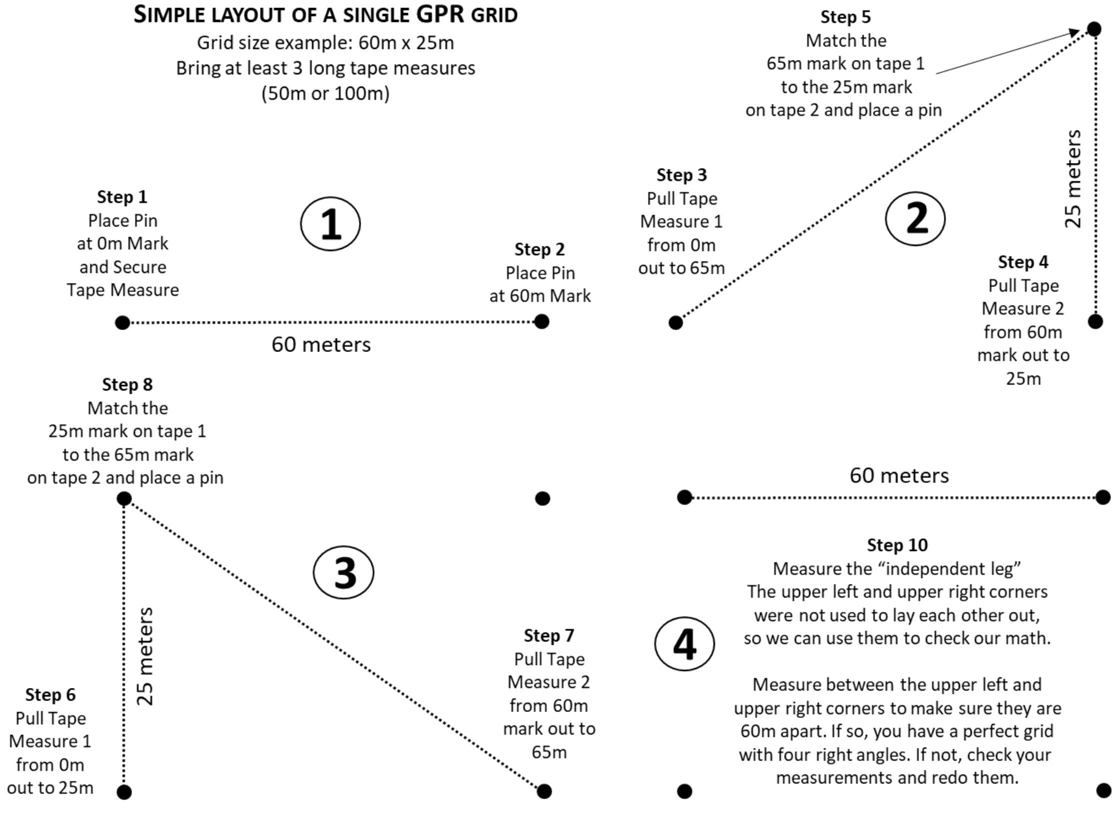


Figure 4-4 Layout of a single grid with surveyors tape measures

Once all four corners of the grid are established choose two corners that were not used to lay each other out. Typically these will be the upper left (grid NW) and upper right (grid NE). Pull a tape measure between corners; the measurement should be the same as the baseline length. This is called 'measuring the independent leg', and is an excellent way to check grid math. If the measurement is incorrect you should redo your math and reestablish the grid corners. Mapping errors will compound if this grid is incorrectly laid out and other grids are tied into it.

Bring at least three tape measures (preferably more) that are 50m or longer. Always have at least one really long tape on hand (100+ meters). If surveying in feet you should purchase surveyor's tapes in engineered feet (10ths of feet). This will make grid layout much easier. Use surveyor's tapes for your baselines (not rope, string, or spray paint marks) so you can minimize errors and start/end on the correct marks. Once the grid baselines are laid out look for any sections of the tape measure that are not flush with the ground surface. These will often be present around tree roots, tire ruts, and other surface disturbances. Insert a tent stake in these locations to minimize the chance of tripping over the tape (historically, this is the single most common source of an untimely tape measure death) or catching the GPR antenna on the raised tape. Even if the ground surface is perfectly flat you should place a tent stake every 10m to keep the line straight and prevent tape movement from wind and other factors.

For larger survey areas it may be necessary to lay out more than one grid. Using the single grid procedure above, you can lay out the first grid and then use its corners to triangulate the extents of other grids (**Figure 4-5**). When surveying multiple grids on the same coordinate plane it is critical that you use existing grids to lay out additional ones and record the local coordinates for the lower left corner of each grid. The lower left corner (Grid SW corner relative to grid north) is the coordinate origin for grids ***no matter which corner you start collecting from***. GPR grids do not have to be oriented to true or magnetic north. In your field notes always describe which corner you started from and on which axis (or axes) you collected data (**Figure 4-5**). I also recommend using large numbers for the origin of your first grid, like X1000 Y1000. This will prevent grid coordinates from being negative numbers if you have to add grids to grid west or grid south of your origin. Always avoid laying out a grid with a central X0Y0 line that is expressed as either N/E or S/W pairs – this is too confusing and will lead to headaches during post-processing.

3D grids should be established across the project area with the intent of maximizing the GPR coverage. There are some conditions that may prevent complete coverage, like dense vegetation, obstacles and fences, but these can often be overcome with creative grid layout and data collection techniques. Large survey areas may preclude collection of a single grid due to line length restrictions and dealing with vegetation. These areas are ostensibly easy to grid out, but there are many different approaches and some may not maximize survey coverage. Another consideration is that when grids are exceptionally wide (>100m) a 100m-long tape measure might not be long enough for the hypotenuse measurement. In such cases it would be wise to lay out long grids in two smaller sections (two 50m wide sections) but to survey it as one continuous grid.

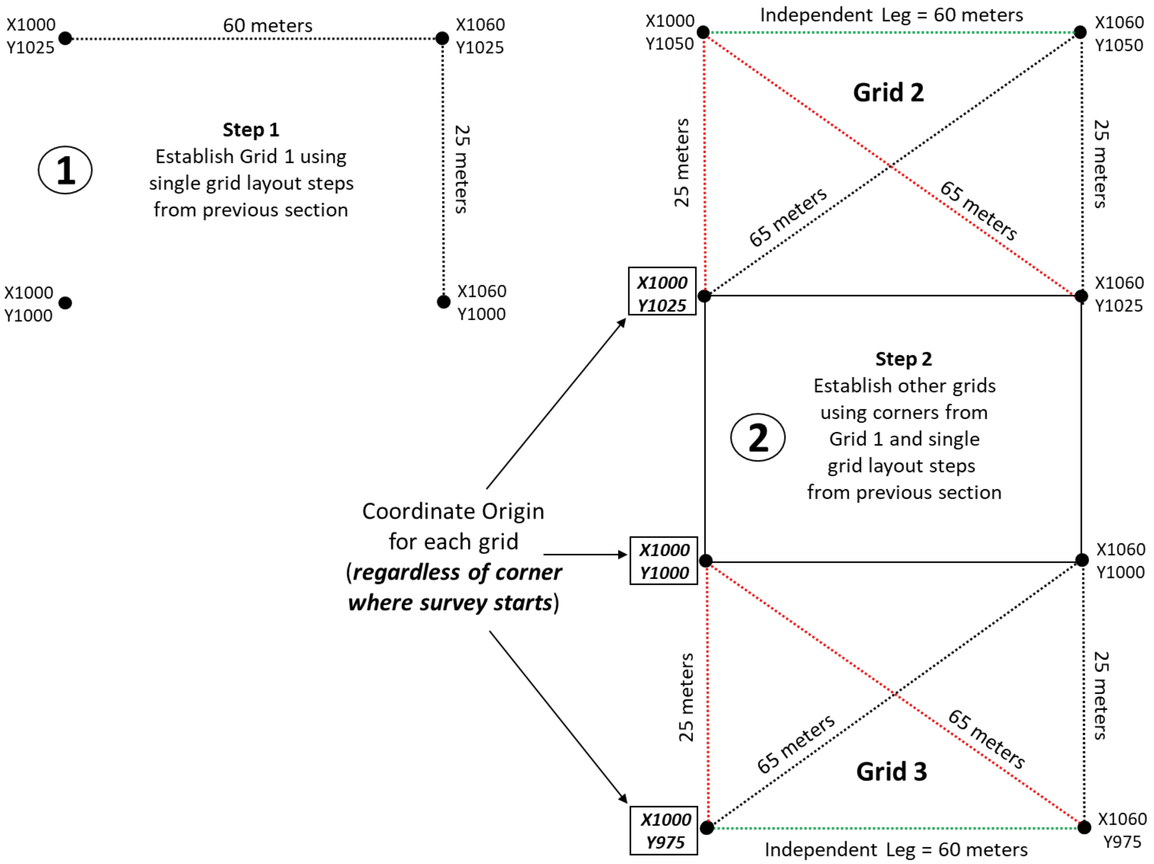


Figure 4-5 Layout of multiple grids on the same coordinate plane. The resulting data can be combined in RADAN 7 as a Super3D grid. All the grids can then be viewed and processed simultaneously.

Grid notes should contain as much information as possible. Graph paper and a ruler, though somewhat anachronistic in the age of mobile GIS, are superb tools for site mapping and describing grid layout. Though most field workers will have a sub-meter or RTK GPS on hand there really is no substitute for an old-fashioned analog field map. This is especially true for small survey areas or places where GPS signals are unavailable (inside building or caves, concrete jungles, etc.). I like to record GPR-related information on a sheet of graph paper (**Figure 4-6**), and add more detailed written notes to a field notebook. Here's a list of important basic information to add to your field map:

- Date, time, and location of survey, project name, client name, and personnel involved
- Equipment used during the survey
- Orientation of grid north and reference scale (don't assume you'll remember the scale later)
- Any obstacles, significant landscape features, significant cultural features, or vegetation
- Grid nodes with a stake left in the ground, and those that were recorded with GPS
- Size of grids and their relationship to each other
- Local coordinates for each grid corner (especially the lower left/ grid SW origin!)
- Starting file and ending file number for each grid axis
- File numbers at set intervals (every 5 or 10 meters)
- Add-on vs grid-normal lines (see Section 4.1.9)

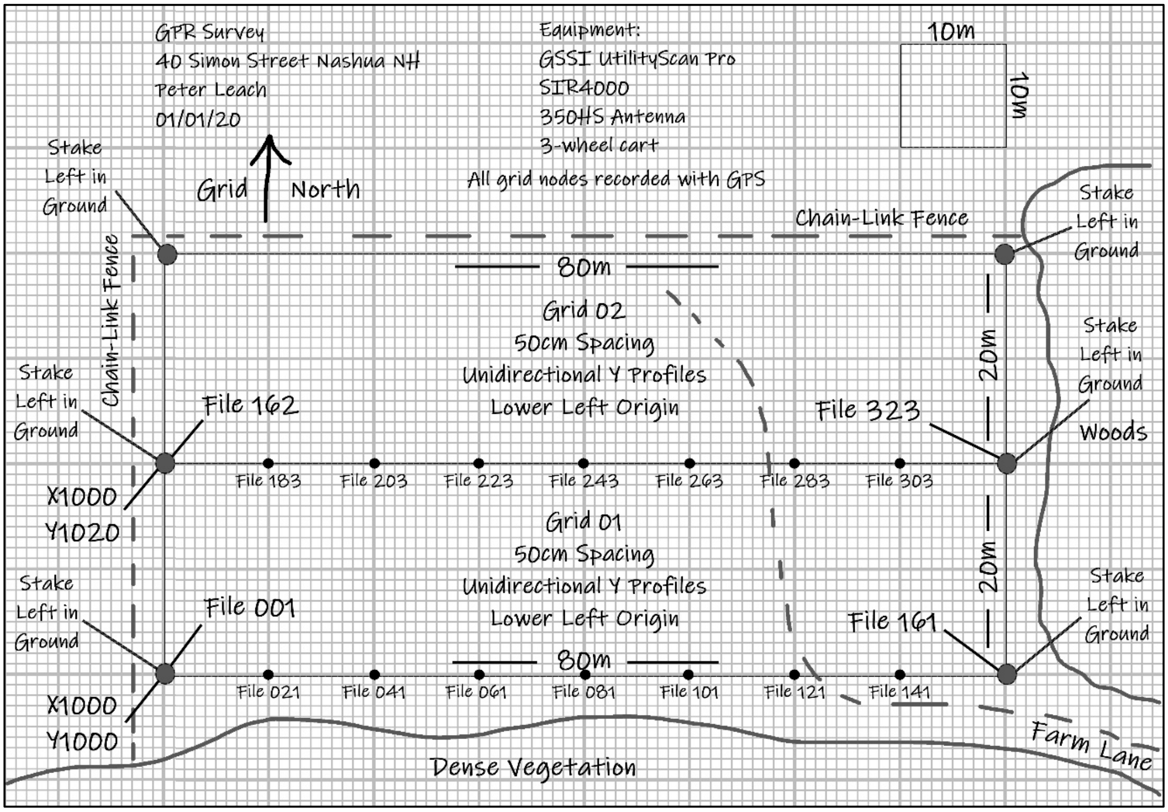


Figure 4-6 Example of field notes for two simple co-adjacent grids

4.1.7 Line spacing in different landscape/ site settings

Transect spacing is a critical parameter in 3D data collection. Tighter spacing generates higher resolution 3D time slices and can capture smaller targets. Coarse line spacing (>1-meter) saves time but the low-quality time slices reduce interpretive potential and small targets may not appear in the data. The typical rule of thumb is to space transects no more than half the expected size of your targets of interest. This rule becomes ridiculous if you are searching for small post holes, but for most site types there are some established conventions to follow. For historical archaeological sites I recommend 50cm transect spacing (approx.1.5ft), but 25cm (approx. 1.0ft) is ideal if permitted by time and budgetary constraints. For cemetery and forensic surveys (where the location and orientation of a target are generally unknown) I highly recommend 25cm spacing. For surveys at precontact sites there are a few things to consider. If the site is a precontact village or larger residential area, 50cm spacing should be adequate but 25cm is preferable. For smaller sites (occupation, ephemeral camp site) and spatially-restricted features (hearths, storage pits, etc.) I suggest 25cm spacing. The reasons for tight transect spacing on precontact sites are that features are small and not always obvious, tighter line spacing means that more profiles will cross targets of interest, and higher resolution slices provide greater detail and more refined geometry.

High-resolution surveys (<50cm spacing) have a few drawbacks but these are outweighed by the dramatic increase in data density and time slice interpretability. Tightly-spaced lines obviously take longer to collect, and some budgets can’t handle the increased time and expense. More lines means a greater chance to incorporate errors, and it is easy to skip a profile. I recommend writing down the profile number at specific distances along the grid, such as every 5m or 10m. This will allow you to identify errors and move back a short distance to correct them. It is also possible to erroneously place the cones; if you are used to 50cm transects and then use 25cm you might move a cone 50cm and not realize it. Or perhaps your cone-moving assistant was involved in a heated social media debate and wasn't paying attention. There are additional issues, such as dealing with abundant obstacles and the number of Add-On lines that are generated. Despite these and other potential problems I suggest the tightest line spacing that your budget can handle. The data quality will be worth the extra effort.

4.1.8 X-axis, Y-axis, or both?

During gridded data collection you can collect profiles on only the Y-axis, only the X-axis, or along both axes (**Figure 4-7**). When searching for relatively small-diameter linear targets (pipes/utilities) a X/Y pattern is ideal because the linear features cannot fall between profiles (and be missed). For other target types/shapes, collecting both X-axis and Y-axis profiles can be 'overkill' and greatly increase survey time. I generally collect profiles with tight transect spacing (25-50cm) along a single grid axis and in a unidirectional collection pattern. This ensures that even small targets (25-30cm in diameter) will be covered by at least one profile, and the resulting 3D slices will be high resolution with minimal geometrical offsets. The only downside to single-axis collection is that it limits cross-sections (profiles) of features and landscape elements to the path of travel. If the trend of features and landscape components is parallel to profile orientation it can be difficult to assess stratigraphic relationships and to generate geomorphic inferences.

When collecting gridded data you are not restricted to one axis of collection across every grid – feel free to collect one grid with Y-axis transects and the next grid with X-axis transects (or both… see below). RADAN can handle profiles on either grid axis and profile origins in any corner and on any baseline of your grid(s) but the software will need to know which corner was the profile origin and which grid axis was used. These details must be recorded in your notebook to ensure proper grid generation in RADAN (**Figure 4-6**).

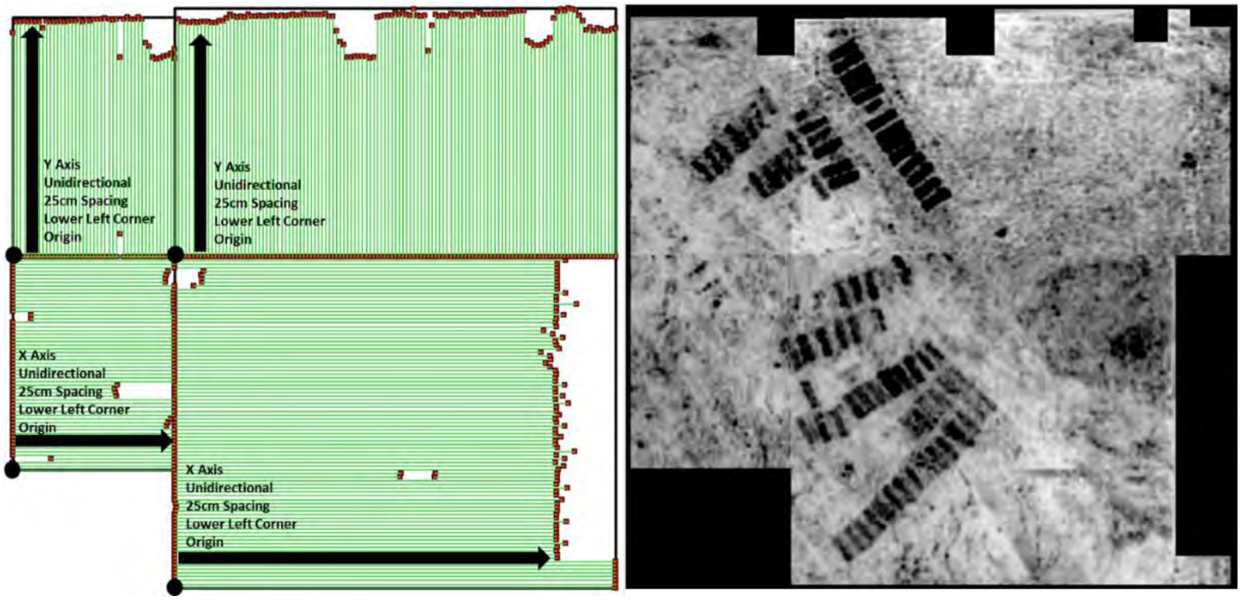


Figure 4-7 Collection of gridded GPR data along different axes for each grid

4.1.9 Dealing with obstacles in GPR grids

I recommend collecting gridded datasets in 2D Modules (TerraSIRch, Expert Mode, Digital 2D, etc.) rather than using 3D Modules. This is because 2D Modules are more flexible and make it much easier to deal with complex survey areas with multiple obstacles. In your notes it is critical that you record as much information as possible (**Figure 4-6**). See **Figure 4-8** (to right) for a simple example with a single obstacle, and **Figure 4-9** for a more complicated scenario with multiple obstacles and reversed profiles. You need to note when a baseline-origin line stops at an obstacle (Grid Normal Line), when a line starts on the opposite side of an obstacle (Add-On Line) and its starting or ending X/Y coordinates, and whether files were collected in reverse due to obstacles on the origin baseline (classified as Grid Normal) or as Add-On line to avoid an obstacle. Note: I recommend collecting Add-On lines immediately after their associated Grid Normal line, instead of collecting Add-On lines after all Grid Normal lines are completed. This will make note-taking easier and prevent some mistakes.

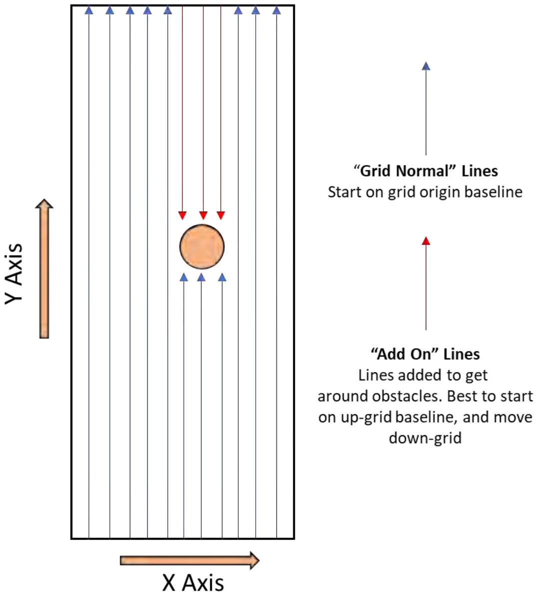


Figure 4-8 Handling an obstacle in a GPR grid for ease of use in RADAN's manual 3D grid creation function

During data acquisition you'll collect Grid Normal lines (forward or zig-zag) until you reach an obstacle. Do not be tempted to swerve around large obstacles and keep going – this will create distance-related striping issues in your 3D time slices. When the GPR antenna stops at an obstacle, close and save the current file. In simple cases (only one obstacle on the transect) you have two options: move to the opposite baseline, face the obstacle, and collect a new profile (Add-On line) from the baseline to the obstacle; or start on the opposite side of the obstacle and collect a line that stops on the opposite baseline (Add-On line). Either method is fine, but good notes are critical for this procedure. The most important step is to know where an Add-On line starts or ends. This will make it easier to add it to a 3D grid in RADAN. To insert Add-On lines properly during 3D grid creation RADAN needs the starting X coordinate, ending X coordinate, starting Y coordinate, and ending Y coordinate. If you collect data with a distance encoder (as should always be the case for land-based surveys) the total accumulated profile distance will be stored in each profile's file header and is accessible by RADAN. However, the system does not know where the profile started/ended in relation to the overall grid. There are multiple methods for easily determining these coordinates.

First, let's assume you are collecting unidirectional Y-axis profiles in the grid north direction spaced 1m apart. The Y-axis grid length is 15m. You collect Grid Normal profiles from baseline to baseline up to X=3m. On the X=4m transect there is a tree that is too big to cut down. You'll collect a Grid Normal profile up to the tree and then save/stop the file. Your options are now:

1. Move to the other side of the tree and start a new file that starts at the tree and ends at the upper baseline. In this case, your starting and ending X coordinate is 4m (you did not leave

the X=4m transect). You do not know your starting Y coordinate, but your ending Y coordinate is Y=15m. In RADAN you can locate the Add-On line's total length (in the file header) and subtract this number from Y=15 to calculate your starting Y coordinate.

2. Move to the opposite baseline and start a new file that runs from the baseline to the tree. In this case, you know that your starting/ending X coordinate is X=4m. You do not know your ending Y coordinate, but your starting Y coordinate is Y=15m. In RADAN you can locate the Add-On line's total length (in the file header) and subtract this number from Y=15 to calculate your ending Y coordinate.

For X-axis Add-On lines the start/end Y coordinate will be the same number. For Y-axis Add-On lines the start/end X coordinate will be the same number. You should already know the start or end coordinate for a X or Y axis line if you started or ended the file on one of your baselines. It is important to record the start/end coordinates in your notes, and any other relevant information that will be useful later. You can also reverse profiles in RADAN. This is useful when an obstacle is on or very close to your origin baseline (such as trees, park benches, rocks, etc.). In this case, in your notes (**Figure 4-9**) just mention that the profile was reversed and started on the opposite baseline (also note the known start/end XY coordinates).

In a complex situation (two or more obstacles on the same transect) you can use the same principles with a few modifications (**Figure 4-9**). Your Grid Normal profile will start on the origin baseline and end at the first obstacle. You already know how to deal with this profile. Your first Add-On line will start on the opposite side of the first obstacle and end at the second obstacle. Since we have no Y-axis coordinate reference the only way to place this profile on the grid is to use a tape measure and measure from the origin baseline to the center of the GPR antenna (at the start of the line). You do not need to measure the ending position because the file length is stored in the file header (unless you want to!). If the second Add-On line ends at the opposite baseline its coordinates can be calculated using the methods above. If it does not end at a baseline you can use the tape measure to determine its starting Y coordinate.

Refer to GSSI's RADAN 7 for Archaeology, Cemeteries, and Forensics handbook for more information on dealing with Grid Normal and Add-On lines during the 3D creation process. In brief, when you download your data, make two folders in your working directory. One called "Grid Normal" lines and one called "Add-On" lines. Place all Grid Normal lines into the Grid Normal folder. Put all your Add-On lines in the Add-On folder. When you build your 3D file in RADAN, use the Grid Normal directory for your working folder. You will use the manual 3D creation option for this process (G – Assemble Data File – 3D File). Add Grid Normal lines like any other grid and enter grid size, line spacing and other parameters. You'll then use the Add File option to insert individual Add-On lines, and use your field notes to place them into their correct locations.

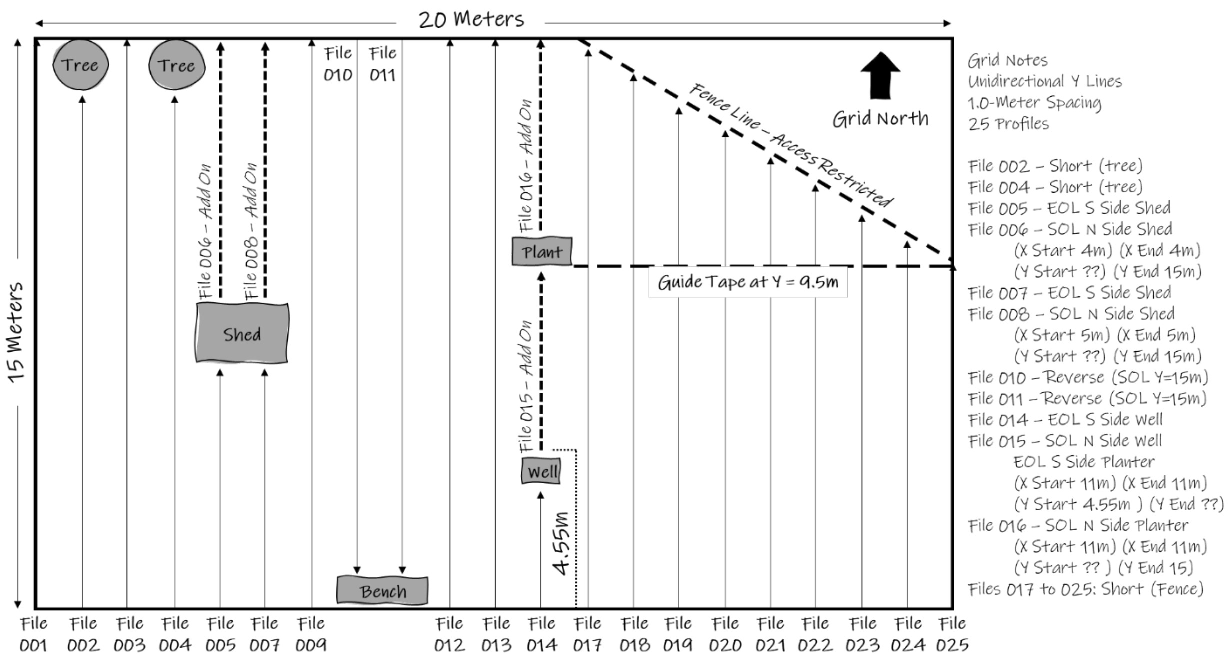


Figure 4-9 Example of GPR field notes for a grid with multiple obstacles, reversed profiles, and irregular boundaries

4.1.10 The "Cone Method" and other variants for collecting gridded data

During gridded data collection there are numerous methods to assist with walking straight transects from baseline to baseline. The first, but most labor intensive, is placing a pin flag or other marker at each transect position on both baselines. The GPR operator would remove the flag at the current position on the baseline, and then aim for the flag on the opposite baseline. The flag would then be removed and the process would continue. This would obviously take a lot of time; on a 20m-wide grid with 50cm transect spacing this would mean placing 41 pin flags/markers on both your upper and lower baselines. An alternative method is stretching a string or rope between target marks on your baselines and running the GPR along the line. This ensures really straight lines, but generally requires one to two assistants for the entire data collection process and can be really annoying in survey areas with trees, gravestones, or other obstacles. The simplest and fastest method is to use a road cone or some other visible and easily-moved marker to demarcate the start and end points of the current transect (**Figure 4-10**). This method is straightforward and requires only one person.

For unidirectional surveys (let's assume 50cm spacing, 20m transects in Y direction) the center of the GPR antenna starts on the X=0/Y=0 mark and Cone 1 is placed on the X=0.5/Y=0 mark. Cone 2 is placed at X=0/Y=20 on the opposite baseline. Move the GPR antenna to the X=0/Y=20 mark, and move Cone 2 to the X=0.5/Y=20 mark. Return the GPR antenna to the origin baseline, set the antenna at X=0.5/Y=0 and move Cone 1 to the X=1/Y=0 mark. Continue this process until all lines are collected. In this method, Cone 1 shows where you are starting next, and Cone 2 shows where you are currently heading.

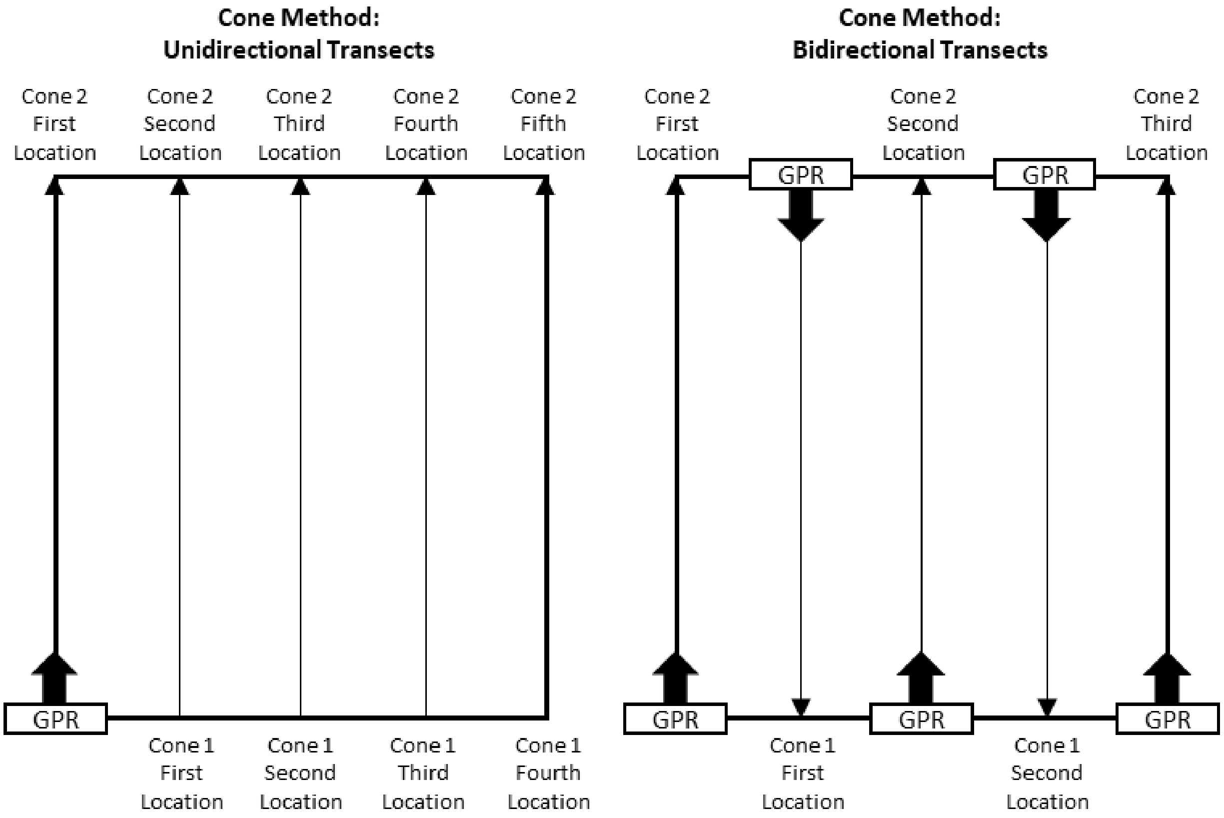


Figure 4-10 The Cone Method for collecting GPR transects on a grid

For bidirectional surveys the GPR will start on the X0/Y0 mark, with Cone 1 at X0.5/Y0 and Cone 2 at X=0/Y=20. Once the first file is collected you'll move the antenna to X=0.5/Y=20 and Cone 2 to X=1/Y=20. Collect the second file, then place the antenna at X=1/Y=0 and Cone 1 at X=1.5/Y=0. Continue this process until all lines are collected. In this method, Cone 1 shows where you are ending next, and Cone 2 shows where you are currently heading. The important point here is that each cone is moved two marks ahead, as opposed to one mark with unidirectional surveys. Using two cones keeps the survey organized and provides two opportunities to double check that you are on the correct starting/ending position. My recommendation is to also write down the file number at specific grid intervals, like every 5-meters. This quick organizational step will save a lot of time if you find that you've made an error, the cones are not properly offset, or something else occurs (like a strong wind blows your cones away). You'll only have to move up to 5-meters to correct the error, as opposed to potentially greater distances. Just remember to note the files that must be deleted after your survey data are downloaded. I do not recommend deleting files during the survey; there are too many opportunities to make mistakes. Just download the files after the survey is complete and delete the problem files on your PC.

4.1.11 Surveying with GPS

For GPS-encoded surveys collecting one long ribbon of data across the survey area is not recommended. This method often results in large gaps in coverage, and overcomplicates post-processing. Long profiles will inevitably inherit distance-related issues from topographic irregularities, and sharp turns can generate artifacts that could look like legitimate targets. My suggestion is to collect individual files as straight as possible, keeping the profile lengths under

30m/100ft, and stopping the file at the end of a transect. When the length limit is reached, or a sharp turn is required to avoid an obstacle, stop the file and start a new one once you are facing the next transect orientation.

The trouble with GPS-encoded profiles is that there is usually no grid reference to ensure equal data coverage. To make things easier I would recommend setting up a large grid and marking the baselines, and then using the baselines and the Cone Method to ensure consistent start and end positions. Use unidirectional collection (if possible) so that all profiles are oriented in the same direction; this will vastly simplify post-processing and data interpretation. For cemeteries and project areas with abundant obstacles straight lines will usually not be possible. It is tempting to collect a large area with GPS-encoding and then create a 3D dataset from the resulting files. If there is no grid reference you'll end up with large gaps in coverage and RADAN will be forced to interpolate over long distances. This is not ideal for creating high-quality time slices. A better option is to collect gridded datasets without GPS encoding, and to then record the corners of the grid(s) with the GPS. The corner coordinates can be added in RADAN during post-processing.

GPS receivers require a minimum number of satellites to provide the expected accuracy and resolution. This can be monitored on some GPS units and GPR control units by noting the number of satellites and the HDOP. Lower HDOP (< 2.0) is preferred and indicates an acceptable signal to noise ratio. Dense tree canopy or tall buildings will limit the GPS's sky view and reduce the number of satellites and overall resolution. The GPS receiver should be mounted above the center of the GPR antenna. Do not place the GPS receiver directly on top of the antenna as this could block the receiver's view of the sky. Try to mount the GPS at waist level or eye level to maximize reception. I recommend using a cart- or antenna-mounted tripod to secure the GPS and raise it to the appropriate height.

5 RECOMMENDATIONS FOR SPECIFIC PROJECT TYPES

5.1.1 Historical sites

Historical archaeological sites are ideal locations for GPR surveys. The features are often numerous and fairly large, and they usually exhibit contrast with surrounding soil matrix. Early colonial sites (16th – 17th century) usually have lower artifact density and sometimes fewer features, especially for occupations of short duration. These sites are difficult to identify with standard archaeological testing though they might be obvious in GPR datasets. In later historical sites the artifact density typically increases exponentially, as do the number of features and landscape alterations. Historical sites generate some of the best GPR data due to easily identifiable geometry and overall density of features, but despite these advantages GPR is not an ideal "Phase 1" method. Geophysical prospection is often more successful when some previous research, either archaeological (field walking, shovel test units, metal detection) or from historical documents (maps, books, letters, tax records), has refined the potential location of targets of interest. Large project areas (>2 acres) can be overwhelming and time consuming, and previously collected information can refine areas for GPR grids and provide an interpretive baseline. Ideally GPR data would be collected after Phase 1 (exploratory) fieldwork and prior to Phase 2 or more targeted excavation. It is never a good idea to collect GPR data while excavation units are open and when people are working at the site; everyone just gets in each other's way and there are too many unnecessary obstacles. If GPR must be used late in the process, like during Phase 3 data recovery efforts, it could be deployed to fill in the gaps between excavation units or to extend the survey area as part of a creative mitigation strategy.

Research is the key to improving the success of GPR surveys on historical sites. Find historical maps or documents if available, or any other source of relevant information like local informants. Aerial photographs from the 1920's and later may reveal former cultural features and they are an excellent resource for surveys in densely populated locations and suburban communities. For many U.S. urban areas there are Sanborn fire insurance maps (late 19th century and later) and Beers Atlas maps (mid-to-late 19th century and later) that show highly detailed locations of buildings and roads, and these often include information on the number of stories, construction material (brick or wood), and if there was a basement. Other maps, like historical USGS topo quads or charts from the US Coast and Geodetic Survey, can be of high quality with roads and small markers for buildings and some cemeteries. Consult these documents for additional historical information. You might find that early maps show a house but later maps do not, or perhaps there were multiple houses on the property at different times. For 19th century and earlier properties that predate indoor plumbing you might expect privies and wells in the vicinity (**Figure 5-1**), and likely barns and other outbuildings. Understanding the use history of the site will allow initial prediction of potential feature types and other critical information. Note that precontact sites could share the same landform as historical sites and preserved features may exhibit similar GPR signatures.

The strength of GPR and other geophysical methods is the ability to collect landscape-scale data for assessing overall feature associations, establish vertical and horizontal patterning, and to reconstruct the layout of the site. Humans constantly disturb landscapes, especially homeowners but also in public, industrial, and agricultural areas. People add fill units, strip topsoil, plow fields, tear down houses and build new ones, plant trees, pull up trees, rob stones and bricks from old foundations, dig drainage ditches, dig looters trenches, etc. These and other taphonomic factors will impact historical sites and could create signatures similar to actual cultural features. However, just as GPR can provide a landscape scale layout of site features it can also generate a similar view of landscape history. Plow zones can be quite obvious as relatively uniform areas near the top of the profile. Historical plowing with horses may not have cut as deep as more recent mechanized/ industrial plowing. Near steep slopes or rivers you might expect an "over-deepening" of the plow zone due to soil surface aggradation from sediment deposition. In these environments, and in urban areas, this could lead to a buried plow zone that is difficult to interpret if you aren't expecting it.

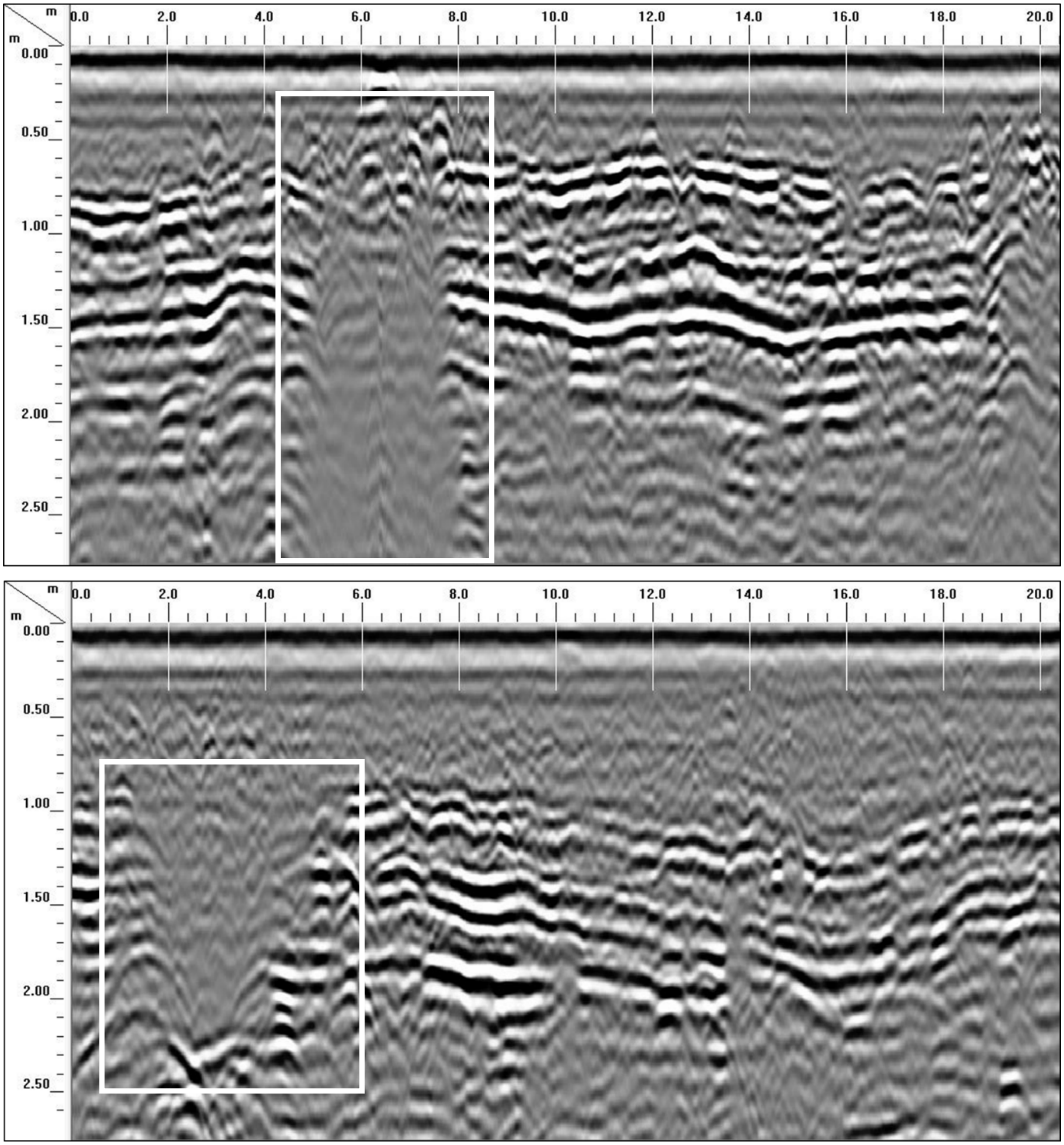


Figure 5-1 Examples of possible 17th century wells cut through alluvial sediments. Top: lined well with near-surface rubble fill. The rubble reflected most of the GPR energy and underlying data were attenuated. Bottom: lined well or privy with stepped excavation and possible rubble at base.

Expect any number of feature classes, like cellar holes (**Figure 5-2**) and foundation remnants, wells, privies, storage pits, root cellars, and historical roads or driveways. Features with a vertical expression or those that cut though natural stratigraphy should be fairly obvious on profiles and in time slices. Shallower and more ephemeral features like roads and driveways may be difficult to identify in profiles and will be much more obvious in time slices. The site is not limited to the house remains and adjacent yard. It includes the entire livable and workable area, such as the front yard, back yard, gardens, agricultural fields, and other domestic areas. To understand site layout all of these areas should be linked by multiple GPR grids. When possible it is always best to collect more data across a larger area. Increased coverage may take more time but site patterning will be easier to interpret and unexpected features may be present across, or just outside of, the boundaries of small grids.

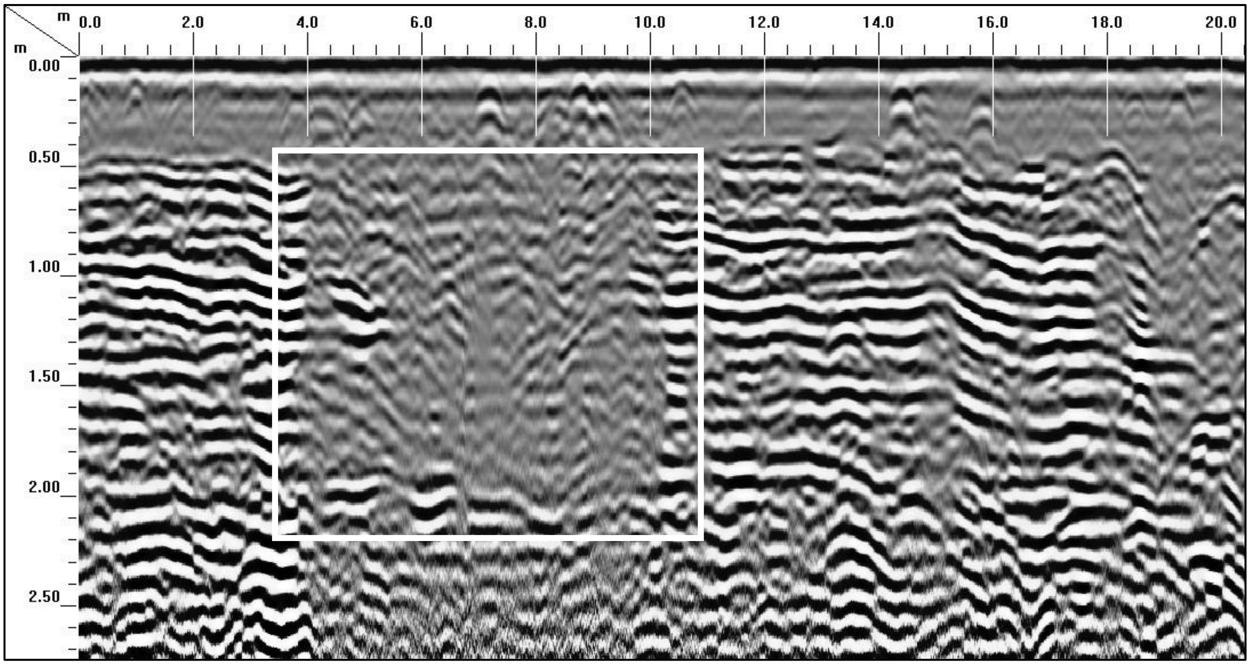


Figure 5-2 Example of historical cellar cut through alluvial sediments. Note the truncation of stratigraphic layers, single hyperbolic tails on excavation edges, and presence of internal stratigraphy suggesting numerous possible filling events.

Historical features that cut through soil layers tend to provide a "window of penetration", where undisturbed subsoil may limit penetration but the nature of feature fill may enhance penetration potential. Keep this in mind when setting your maximum time/depth range. You should look for localized areas of deep penetration during your initial "mapping on" to the site (see Section 4.1.3) and set parameters accordingly. There is nothing worse than finding a textbook cellar hole or well in GPR but not penetrating to the bottom of the feature. Believe me; I know from first-hand experience. With this in mind you should not focus exclusively on 3D data for interpretation. All of the real data are in the 2D profiles, and they will reveal important information about the feature contents, nature of the fill units, and other information like cross-cutting relationships and disturbances (like truncation of the top of the feature). Much like GPR data from other site types historical site data require post-processing to maximize interpretation efforts. In some cases real-time prospection is possible when looking for larger features like cellar holes. For other features you'll have to pass directly over them to see anything and this can be tricky for random-walk style prospection. I recommend grids with 50cm spacing maximum and unidirectional transects. Limit grid length in the direction of travel to 30m (100ft) or less. Doing so will greatly reduce the compounding of distance-related errors from topography and other variables (see Section 4.1.5).

If you are not conducting the archaeological excavation you should ask the investigators to share field results. You should then compare the 2D and 3D GPR data with the field data and maps. ***Be prepared to be wrong***. Compare GPR and archaeological data for obvious features and also for features that were not seen in the GPR data. Consider the possibility that your data could have been processed in a different way to reveal subtle features. This is the best possible learning scenario and will greatly improve your ability to read GPR data and your confidence in your interpretations. You should consider leaving plastic tent stakes or other markers on significant grid nodes. Note these markers in your field notes along with their local X/Y coordinates (and lat/long or UTM if available). The excavation team can then use these markers to accurately relocate targets of interest, and limit the incorporation of mapping errors. You might have to return to the site for additional data collection as projects evolve or perhaps an interesting feature was not fully captured by your grids. You never know, so I recommend planning ahead just in case.

5.1.2 Precontact and contact period sites

Precontact archaeological sites can be excellent locations for GPR surveys, though features of interest are often small and exhibit relatively low amplitudes. These sites often share the same taphonomic issues (and the same landforms!) as historical sites (see Section 5.1.1). The size of precontact sites can range from quite small, single-use occupations to sprawling urban complexes with dense concentrations of features and even palisade trenches or other defensive installations. Local topography can be variable, and in some cases burial mounds and other raised earthen features are present. Most sites have some type of vegetation cover, with ubiquitous trees that serve as grid obstacles and taphonomic agents. In other cases, due to the age and location of precontact and contact period sites they often exhibit evidence of agricultural plowing. For shallowly-buried sites, and those in non-depositional areas plowing can eradicate most of the cultural features. In these cases truncated remnants of storage pits, pit houses, and other deeper features could be preserved below the plow zone or altogether obliterated. In depositional settings (floodplains, coastlines) features can be preserved below the depth of plowing. In stratified to weakly-stratified sites ground-disturbance from feature creation and other relevant anthropogenic activities should be visible as a vertical stratigraphic cut or truncation of strata. Later occupations may be truncated by plowing or other more recent disturbance but earlier site components could be well-preserved.

Features at many precontact sites are relatively small, not always geometrical, and can be at variable depths. The nature of feature fill is also hard to predict, and some features may have fire-cracked rock or other coarse materials while others may contain relatively fine-grained or organic materials. It is nearly impossible to accurately predict feature depth, size, and shape even if previous archaeological data are available. The features have most likely reached a moisture equilibrium with the surrounding matrix, and this will result in overall lower amplitudes from smaller dielectric contrasts. Because of these and other anthropogenic and environmental variables you should avoid real-time prospection, unless a subsequent formal survey is anticipated. Live, in-the-field GPR profiles will be very difficult to interpret; there is simply too much variability in feature characteristics and in inherited soil and environmental noise. Precontact features are often small and difficult to see in GPR data (both in profiles and time slices) so I highly recommend gridded surveys with 25cm profile spacing along unidirectional transects. This method will ensure that more GPR profiles cross smaller targets and the geometry of potential features will be much improved compared to those from bidirectional/zigzag transects. Most of the data interpretation will involve analysis of 2D profiles, but time slices may help to pinpoint anomalous areas for more in-depth profile analyses. If the soil matrix is relatively 'clean', with no high amplitude targets or areas, precontact features may be more obvious in time slices.

Burial mounds are an altogether different story. These manufactured topographic features offer unique challenges due to steep sides and often small surface area on top of the mound. The mound topography could be muted by plowing or altogether erased in the case of low mounds. Interior features could include burnt clay floors, burials in pits or stone crypts, and possible other features. Confounding variables include looter's pits, former archaeological excavations, pits and redeposited materials from tree falls, and animal burrows. In large burial mounds standard antenna frequencies (350MHz to 900MHz) may not penetrate to the base and lower frequency antennas are necessary; just remember that lower frequencies generate lower resolution data.

Interior stratigraphy will be culturally-emplaced, and may manifest as coherent layers or the lack thereof. Coarse materials like rocks and gravel could be included in the fill and these will generate hyperbolic targets. Modern tree roots will generate hyperbolas, as will animal burrows. In mounds with weak to non-existent stratigraphy high amplitude reflectors may represent actual anthropogenic floors and these may be more obvious due to large dielectric contrasts. Burials in the mound may not have been emplaced after construction, such as interments followed by floor construction, and thus they will not be associated with stratigraphic cuts (except for looters trenches or archaeological units). In this situation obvious high-amplitude reflections from prepared surfaces, and discrete anomalies below them, may be the best indicators.

It may be impossible to collect gridded data on top of mounds, and in these cases single GPR profiles may be the best approach. I'd recommend connecting a GPS for positioning information. If the GPS is not RTK/ survey grade you won't be able to rely on the vertical accuracy for topographic correction. The 'old-school' workaround is to lay out a surveyors' tape measure and to place flags at set intervals. When the center of the antenna passes by a flag you can add a user mark to the data. Using a total station or similar mapping tool you can then record the relative or absolute elevation for each flag. Assuming good note taking these elevation data can be added to profiles in RADAN.

During archaeological surveys shovel test pits are often excavated below sterile levels to prospect for deeply stratified cultural materials. GPR surveys benefit from the same method; you should set your GPR time/depth window so that the bottom 25% of the profile is attenuated. This will ensure that you get the maximum depth and capture unexpectedly deep sequences. This could also capture underlying geological data to place the site into a broader geologic context. For precontact sites this is especially important, since in floodplains and other depositional settings the ground surface usually does not conform to subsurface paleogeography. It might be possible to use GPR to evaluate intra-site settlement patterns that are related to paleogeography, and this could help to focus areas for targeted excavation. In these and other cases you might not identify archaeological features in GPR data, but you might see high-amplitude and continuous or discontinuous reflectors that indicate paleosols, former stable land surfaces, or relict geomorphic features like paleochannels or point bar deposits.

5.1.3 GPR surveys and forensic searches

Forensic work is one of the most important, satisfying, and challenging GPR applications. Unlike other project types it is difficult to predict how forensic targets will manifest in the GPR record. Clandestine burials could be at any depth, any orientation, any size or shape, and in any number of different landscape, industrial, or residential settings. They could be inside a container, wrapped in materials that do not reflect GPR energy, or completely decayed. Perhaps they were buried quickly by hand or with heavy machinery, entombed behind walls or under/inside concrete, or deposited in any other place that suits the criminal mind. When approaching forensic projects it is critical that GPR operators work closely with law enforcement (Schultz 2007) and carefully consider all available evidence including cadaver dog hits. This will help to refine the search location(s) and provide some guidance on the appropriate GPR equipment to mobilize. Just remember that additional information can also lead to biased field strategies; we often miss what we aren't expecting. Approach forensic investigations scientifically and develop a field strategy that will encompass multiple scenarios.

My recommendation is to avoid real-time forensic prospection if possible. I realize that this is impractical for many investigations due to the short time frame for warrants and the need for quick and efficient scanning in advance of other fieldwork. Like other applications, forensic GPR data inherit all of the issues and artifacts derived from external interference, soil noise, and other environmental factors. Forensic targets, like historical graves, usually are not obvious high-amplitude targets that sharply contrast with the background. They often are subtle, and may look like non-related targets such as landscaping efforts, tree removal, pet burials, holes for burning trash, and natural subsurface variations. These and other factors often manifest as "false positive" forensic targets because their GPR signature is consistent with expected forensic markers. Since many clandestine burials are not in a formal coffin or other large container you will often not be looking for the target; ***you will be looking for the hole that the target is/was in*** **(Figure 5-3)**. Therefore your system settings must be optimized to highlight lower amplitude areas and stratigraphic disturbances. This effort begins in the field, where you'll want to configure an adequate depth range, perform a range gain/manual gain on "normal" background levels, and set a relatively accurate dielectric for depth calibration. You might consider using a Bandpass filter (see Section 3.1.6) or Background Removal (see Section 3.1.7) to reduce unwanted noise.

Gridded data are the absolute best approach for forensic surveys if the landscape, infrastructure, vegetation, and project constraints allow it. Recent ground disturbance may not be obvious on the ground surface or in 2D GPR profiles, but in 3D time slices disturbed areas can be easier to identify based on their geometry and other characteristics that contrast with surrounding data. Higher-resolution time slices are preferred here, and I recommend 25cm profile spacing along unidirectional transects (not zig-zag or bidirectional; see Section 4.1.5). If there are obstacles in the survey area you can consult Section 4.1.9 for guidance. Try to maximize grid coverage and do not avoid areas directly adjacent to buildings. Also, if time permits your grid(s) should extend outside the designated survey area (if you have permission) to place anomalous areas into a larger landscape context. More data are always preferable to less data, and anomalies can really pop out if the rest of the survey area has no other obvious irregularities. Consider collecting data on the X and the Y grid axes to account for unexpected target orientation. You can later combine these data in RADAN to create one composite grid from both axes, or view them as separate datasets.

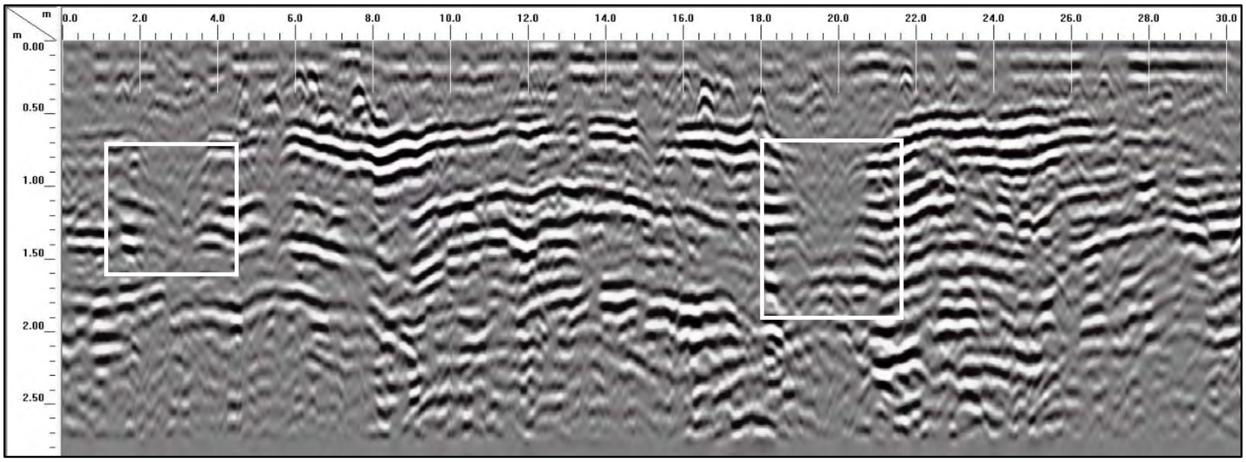


Figure 5-3 Example of potential forensic anomalies. Profile exhibits two disturbances (between 2m and 4m marks and 18m and 22m marks) that cut stratigraphic layers, including single hyperbolic tails on shoulders of trenches/pits.

5.1.4 GPR Surveys in Cemeteries

Cemetery surveys are common GPR projects due to the vast number of unmarked graves in the world's burial grounds and/or the potential for unexpected burial disturbance during construction or standard burial practices. Much like forensic surveys, in cemeteries the goal is usually to identify the presence (or absence) of human burials with no obvious surface evidence or other indications. Alternatively, GPR can be used to investigate conspicuous surface features like localized depressions or vegetation changes (like dead grass or especially healthy grass). Grave stones can be 'lost' for many reasons. Stones may fall over and become buried, or perhaps good Samaritans or landscaping crews moved the stones to an out-of-the-way location. Sometimes grave stones are stolen by miscreants or removed by unscrupulous developers. In cemeteries for indentured persons or paupers there may never have been grave stones or the original markers have long since decayed. Regardless of the historical circumstances the identification and protection of unmarked graves is an important undertaking. I highly recommend avoidance of real-time prospection for burials. Much like other applications, GPR data from cemeteries can inherit external noise, soil-related issues, and other unavoidable data problems that inhibit real-time interpretation. GPR may be an ideal method for locating burials but it is not a "silver bullet"; the GPR does not produce an audible sound when passing over a grave (unfortunately…) and the resulting GPR anomaly usually looks like any number of other targets (roots, rocks, gopher burrows, etc.). Also, ***not all hyperbolic targets in cemeteries represent human burials***. Cemetery data should be collected on grids, if possible, and post-processed to remove unwanted noise and other data artifacts. Post-processed data can then be evaluated for evidence of simple or complex hyperbolic targets across multiple profiles, the presence of stratigraphic breaks, and other burial-related information.

Burial orientation is often assumed to be roughly magnetic east to magnetic west, but this is not always the case. In Christian or Catholic cemeteries the overall trend might be east-west, but landform characteristics, local or personal preference, and cemetery size may lead to other arrangements. Victorian-age cemeteries were often engineered landscapes, and in these settings you can expect any number of different orientations because the burial pattern usually follows the trend of the landscaping. Cemeteries for indentured persons or paupers usually do not conform to established practices, nor do some rural family plots or the occasional war-related single or mass burial. If some information is known prior to the survey, or a consistent orientation is observed during system setup, grids should be laid out so that GPR transects cross burials at 90 degrees to their long axis. This will generate the best cross-section of the grave shaft and the cleanest hyperbolic target on coffins and vaults. A perpendicular approach will ensure that the maximum number of profiles will cross any given interment. If well-preserved graves are crossed parallel to their long axis coffins and vaults (when preserved) will look like a table-top, with a flat top and single hyperbolic tails extending from the foot and head of the container. Crossing burials at other orientations will skew the resulting hyperbolic target and grave shaft indicators.

Initial real-time prospection and mapping on to the site should incorporate marked graves to get a baseline for optimal settings, including time range/ depth, gain levels, and dielectric. Burials are rarely “six feet under”, and depth-to-interment may vary wildly across the same cemetery. Coffin burials are *usually* four to six feet deep, but the top of a burial vault (concrete or brick) will likely be only one to two feet below the surface (**Figure 5-4**). Do not set the time range/depth to six feet; always overshoot the depth until the bottom 25% of the profile is attenuated. If your dielectric is inaccurate your depth scale will be as well, and this could lead to shallower-than-expected penetration. Deeper penetration will also reveal any potential stacked graves (more than one burial in a grave shaft) or will account for any historical or industrial fill emplaced over the cemetery. It is also important to look for marker beds or other relatively shallow stratigraphic indicators that will have to have been cut through to place an interment (**Figure 5-5**). Note that a plow zone can cross-cut cemeteries and burials, and in this case stratigraphic breaks from grave shafts will not extend to the ground surface unless the burial happened after the land was plowed for the last time. Brick and concrete vaults are “hidden in plain sight”, as they are much shallower than expected and often overlooked. However, they do exhibit high amplitudes and can cause local attenuation or amplitude reduction in underlying data. The attenuation/ low amplitude can relate to a high reflection coefficient at the grave fill/ vault contact, and thus minimal energy remains to reflect from deeper areas. Note that a scattering effect from domed vaults could reduce the overall amplitude and make identification difficult.

Make sure that you set your dielectric in the field and set an adequate depth/time range. Note that in older, pre-20th century New England cemeteries the interment can be on the opposite side of the writing on the stone. This may also be the case elsewhere in the USA. In the absence of footstones this can be hard to evaluate, so make sure you cover both sides of any single gravestone or row of grave markers. Historical graves are often closely-spaced, and this is especially true for pauper and slave cemeteries. In 2D profiles closely-spaced graves can look like layers rather than individual targets (**Figure 5-4**). Furthermore, closely-spaced burials (even with coffins) may not exhibit discrete grave shafts for each burial since all of the individual shafts could effectively coalesce into one large “trench” with no interior separations (refer to **Figure 3-13** for an example).

When laying out grids try to incorporate marked graves into the overall grid footprints. You can use these data as reference points for identifying unmarked graves. I suggest placing a User Mark in your data whenever the center of the antenna passes by a grave stone, regardless of what side of the stone you are on. User Marks will be visible in RADAN and your field notes should describe why each User Mark was added. If time permits consider surveying on both X and Y axes to capture variable orientations. In crowded cemeteries single-axis collection is the ideal method. Be suspicious of any large gaps in cemetery rows or large open spaces within cemetery boundaries. These are high potential locations for unmarked graves and should be investigated.

For single monuments with multiple names listed you'll have to survey around all four sides to achieve complete coverage. If you already know something about burial orientation you can plan accordingly and pass over the graves at 90 degrees to their long axis. In some cases real-time prospection can provide this information, but not if the coffins are badly decayed or the soil conditions are less than ideal. You can either collect one single grid that encompasses the monument and use Add-On lines to deal with the obstacle (see Section 4.1.9), or lay out two non-overlapping grids and survey from different directions (see Section 5.1.10). While these situations might be OK for real-time prospection, a gridded dataset will be optimal especially if the burials are close together.

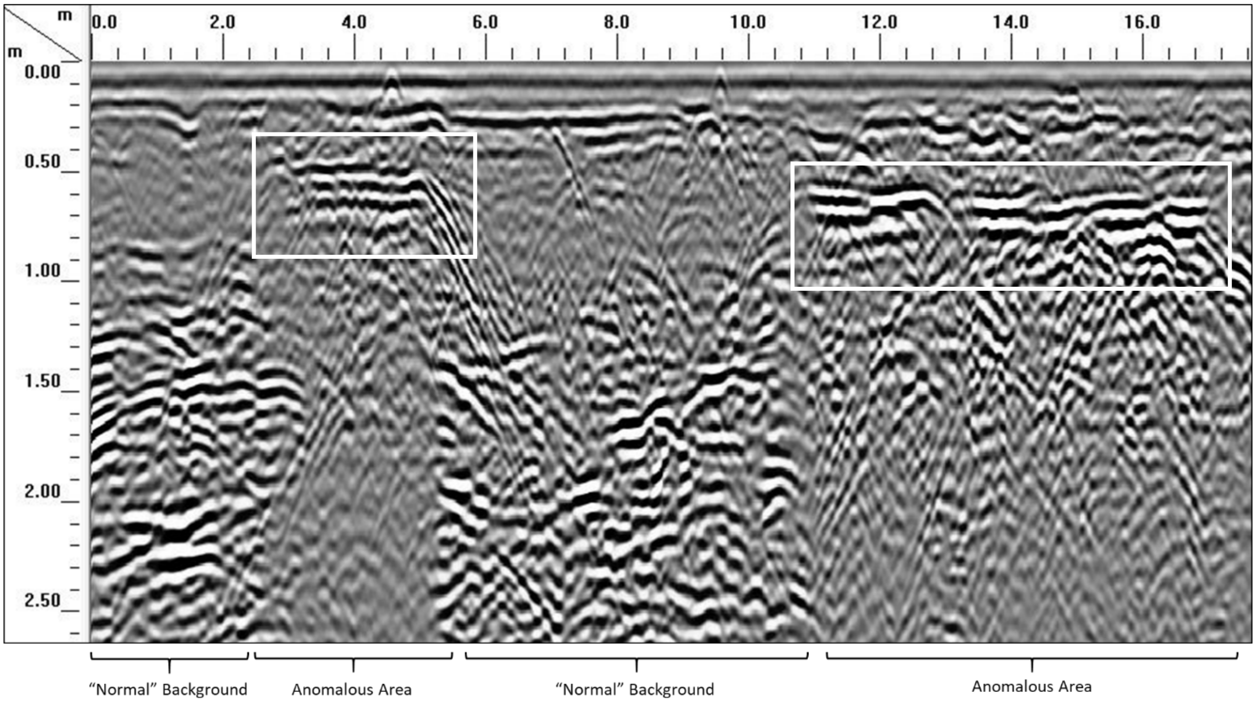


Figure 5-4 Example of closely-spaced concrete burial vaults (11m to 17m) where individual targets are expressed as a layer reflection. Crossing a burial parallel to long axis (3m to 5m) will create a 'table-top' reflection. Also shown are 'data shadows' below the vaults that manifest as attenuated/ low amplitude areas

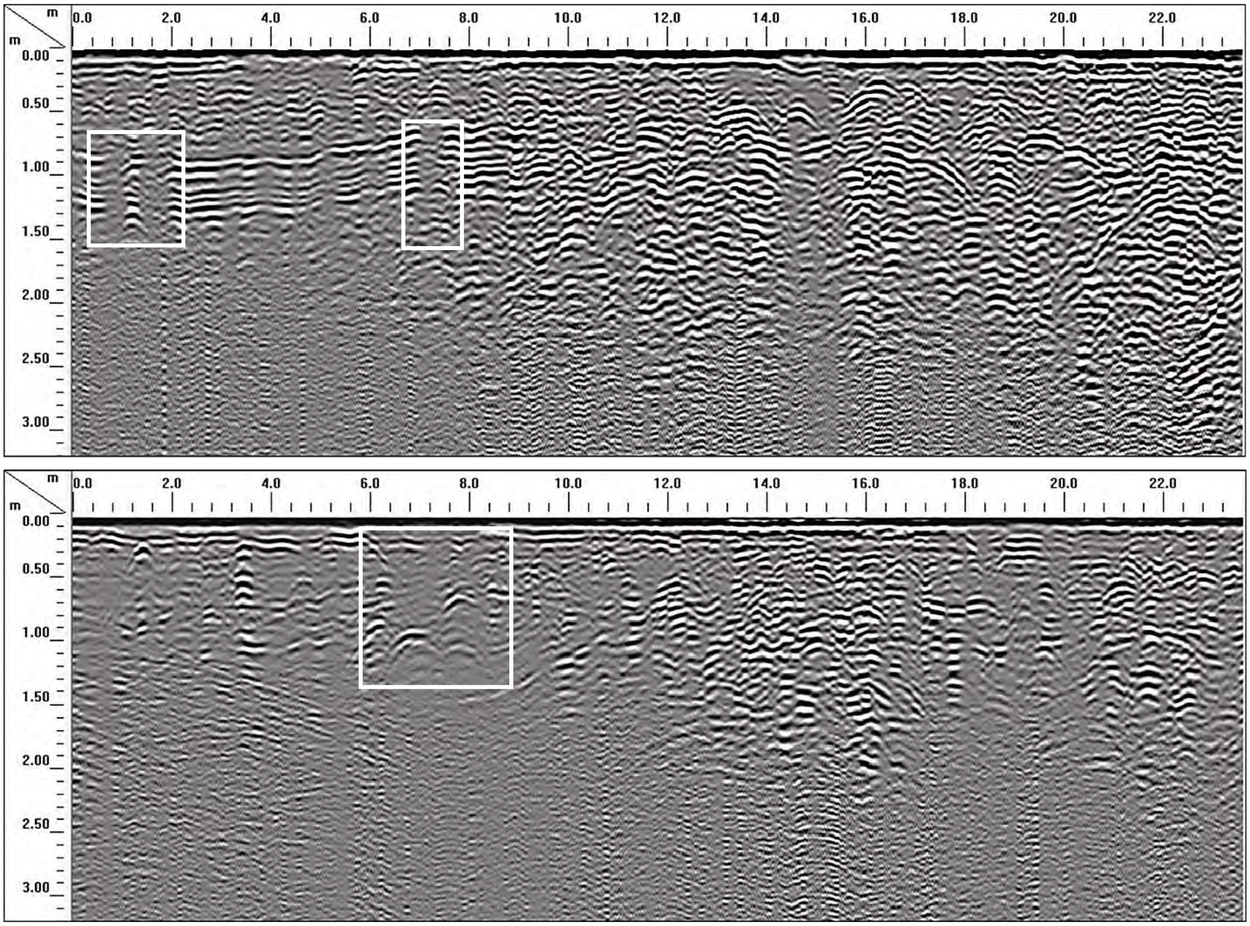


Figure 5-5 Examples of historical coffin burials and associated stratigraphic breaks through marker beds. Top: probable graves located at approximately 1-meter and 7-meters into profile. Bottom: two likely graves side-by-side between 6 to 8 meters into profile. At 6-meter mark note single hyperbolic tail at edge of grave shaft.

5.1.5 GPR surveys in crowded cemeteries

Cemetery surveys for unmarked graves in relatively open areas are fairly easy to deal with. In cemeteries with few (if any) vacancies it is quite difficult to lay out survey grids and to minimize the number of obstacles. This is a similar conundrum to surveying in dense woods. In these cases, it is critical to maximize the amount of coverage along a row of graves. Some survey areas may preclude the use of a survey cart due to the size of the cart relative to the width of grave rows (especially in historical cemeteries with narrow rows). In these cases it is best to remove the antenna from the cart and use an external distance encoding wheel. ***Do not use time mode collection for cemetery surveys***. The recommended approach is to lay out a long tape across multiple rows and lay out individual narrow grids, on the same coordinate plane, for each row. This will vastly simplify grid creation in RADAN and data interpretation because you can combine all grids into one Super3D grid and slice through them simultaneously. An added benefit is the ability to process all the data concurrently. Unidirectional transects are required here; otherwise the grid creation process will melt your brain. The ideal method is to determine the angular layout of the rows and collect lines parallel to the rows of stones (**Figure 5-6**). This is not always easy (or possible) but it can usually be accomplished with proper planning. If obstacle-avoidance (Add-On lines) profiles are necessary refer to Section 4.1.9 for guidance. An alternative option is to collect GPS-encoded profiles that allow for maneuvering around obstacles. The trouble with GPS-encoded profiles is that there is usually no grid reference to ensure equal data coverage. To make things easier I would recommend setting up a large grid and marking the baselines, and then using the baselines and the Cone Method to ensure consistent start and end positions. Use unidirectional collection so that all profiles are oriented in the same direction; this will vastly simplify post-processing and data interpretation.

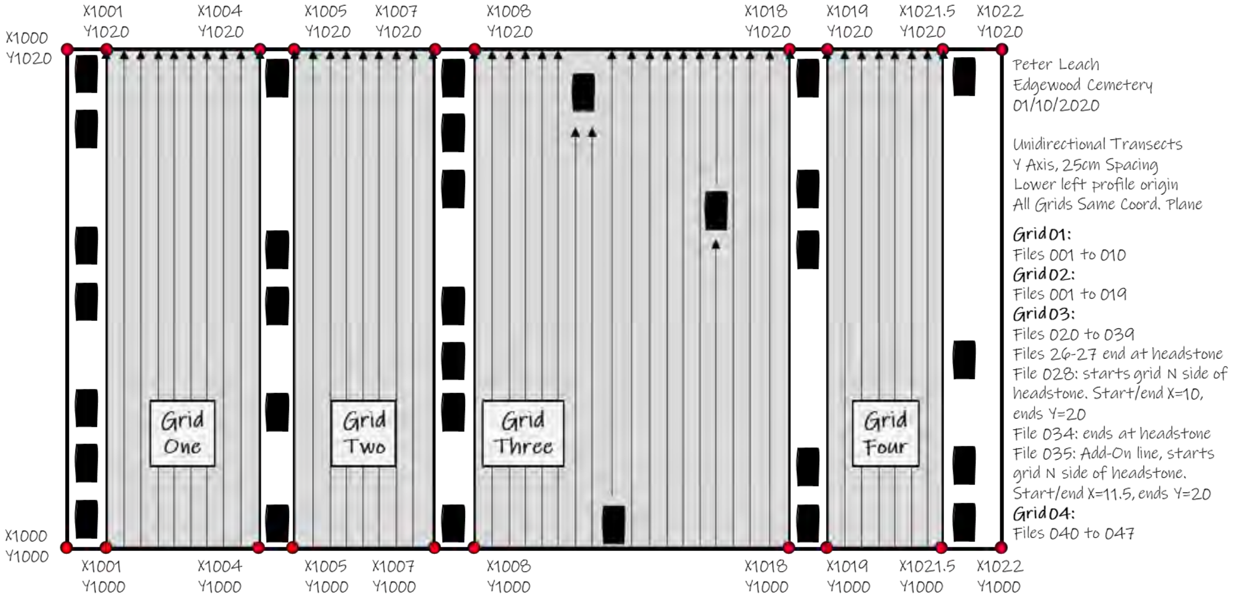


Figure 5-6 Example of GPR field notes from multiple cemetery grids on the same coordinate plane

More complex settings, like New England's early colonial cemeteries, are often quite difficult to survey with complete (or near-complete) coverage. In these cases there are likely many unmarked graves but the grave rows are fairly close together, alignments are somewhat parallel but not perfectly aligned, and it is difficult to walk a straight line let alone push/pull a GPR around. Given some adequate time to plan a course of action it is usually possible to arrange co-adjacent grids, on the same coordinate plane, in overcrowded and irregular cemeteries. I prefer to fly a drone and construct a photogrammetric digital elevation model and then plot the grave marker locations in GIS software (**Figure 5-7**). Grid orientation, size, and direction of transects can then be planned out. This can be accomplished in the field with a little trial and error and the help of a field assistant. The resulting grids can then be combined as a Super3D grid in RADAN 7 and viewed/processed concurrently.

If you have to survey really complex cemeteries it might be best to integrate a high resolution GPS. Even when surveying with integrated GPS I recommend limiting line length. You will collect more profiles but sticking to a small area will facilitate walking straighter lines and minimizing gaps in coverage. A single pass across a row of graves may not provide enough information to identify unmarked graves. Coffin decomposition will differ between interments, even those that are in close proximity, and the age of adjacent burials may be decades or centuries apart. The center of one coffin may have collapsed, while others in the vicinity are completely decayed or completely collapsed. If possible three or four profiles should cross an unmarked grave, and more if there is enough space between the headstones and footstones. A larger number of profiles will allow a more complete characterization of the interment and they may capture obvious burial elements that would have been missed on a single profile. The other advantage is that multiple passes will allow comparison of potential graves across adjacent profiles and increase interpretive certainty. Lay out an overall large grid that encompasses part or all of the project area and use it to walk “even-spaced” transects and to minimize gaps in coverage. When you encounter an obstacle do not make wide turns to avoid it; this can create strange data artifacts that will be confusing and potentially misidentified. Just stop the current file, move to the other side of the obstacle, and collect a new file.

Figure 5-7 Left: small grid aligned to approximate orientation of grave rows and GIS overlay of a 2-meter by 2-meter grid. Right: multiple grids roughly aligned to grave row orientation, ideal origin corners and optimal direction of transects. Graves mapped using a drone and digital photogrammetry.

5.1.6 Snow cover/ winter conditions

Frozen soil conditions are not a major issue for GPR. The dielectric of ice is quite low, and GPR energy moves quickly and virtually unimpeded through it. There are a few factors to consider that are relevant to GPR data quality. First, in low dielectrics the wavefront is much broader than in higher dielectrics. This means that the wavefront is less focused, and while hyperbolic targets will be wider there will also be more distortion of layers with increasing depth. Another potential issue is the eventual vertical interface between frozen soils and those that have liquid pore water. At this boundary, whether a sharp line of demarcation or a more diffuse interface, there will be a large dielectric change that will exhibit a significant reflection coefficient (i.e. a strong reflection). If this is an abrupt ice/water boundary it could reflect a large portion of the GPR energy and greatly limit depth penetration. Alternatively, the ice/water boundary could coincide with targets/layers of interest and mask their signatures since it is not a true stratigraphic boundary that can be cut through.

Snow usually does not reduce GPR transmission as it has a low dielectric. However, snow cover may reduce penetration depth. When the GPR energy moves through the snow at a relatively high speed (snow is quite resistive) it will encounter the snow/soil interface and decelerate to some degree depending on the underlying soil conditions (frozen, semi-frozen, saturated, semi-saturated). The greater the deceleration the larger the resulting reflection. A stronger snow/soil interface will reduce the total energy that enters the ground and will directly affect the depth of penetration. Choice of distance encoder is important, as deep snow may prevent continuous rotation of the wheel or ice and snow buildup can increase the diameter of the wheel and create distance-related errors.

5.1.7 Waterborne surveys (freshwater only)

GPR energy travels unimpeded through freshwater, though it does move really slow. Make sure to set your field dielectric to 81; otherwise your depth conversion will be wildly incorrect. Almost all water-based surveys use non-metallic boats, canoes, or rafts to mobilize the antenna. Most anything that floats will work, though there should not be a significant hull thickness between the antenna and the water. This is especially important for inflatable rafts that may have a thick internal air gap. Also make sure that the antenna is safe from splashing water, and is secured to the boat to prevent any movement. Lower frequency antennas (200MHz, 100MHz) are recommended for water-based surveys, even if the water is fairly shallow (<10 feet). A lower frequency will have overall lower resolution than a higher frequency, but the downloading effect (see Section 3.1.1) for a dielectric of 81 will boost overall resolution. A low frequency antenna will facilitate the profiling of deeper water bodies and improve penetration into subbottom strata (**Figure 5-8**).

Water-based surveys almost exclusively use time-based collection since using a standard distance-encoding wheel is not feasible. SIR4000 and SIR3000 control units can be switched from distance mode to time mode. The UtilityScan (Android-based) cannot collect time-based data. Some other control unit settings will need to be adjusted, including scans/second, samples/scan, dielectric, and time range. Scans/second controls the speed at which new scans are recorded. If the boat is moving slowly then a low scans/second value is appropriate, whereas fast boat speed will require higher scans/second. Since time-based collection is not triggered by distance the watercraft must maintain a consistent speed to generate a consistent scan density; otherwise slowing down will stretch the profile and speeding up will compress it. Samples/scan will usually need to be higher than 512 due to the increased time range required for water-based surveys. Refer to **Table 3** for recommended samples/scan values for different antenna models and time ranges. Dielectric should be set to 81 to accurately calibrate the depth scale for the water column. The time range/depth range should be increased until you can at least see the bottom of the waterbody. If you can penetrate the underlying sediments keep increasing time/depth until the bottom 25% of the profile is attenuated; this will ensure maximum penetration. If you are surveying an entire waterbody set the time/depth parameters in the area of deepest water; this way you will not miss any important information.

I highly recommend connecting a GPS to your control unit/antenna and encoding geographic coordinates into the GPR profiles. A RTK survey-grade GPS may not be necessary, but I'd suggest sub-meter resolution at least. Not only will this tell you where the profile was collected, but you could use the length of the track to distance normalize the profile in RADAN (see RADAN Handbook) and achieve a more consistent scan density. If the boat makes sharp turns you should add a user mark to denote the change in direction. Ideally water-based profiles, regardless of whether a GPS is connected, should be as straight as possible with few if any turns. Avoid collecting one long ribbon of data across the project area as this will be extremely difficult to figure out during post-processing. Instead you should collect individual long and straight profiles, stop the file before turning the boat around, and start a new file when facing the new transect orientation.

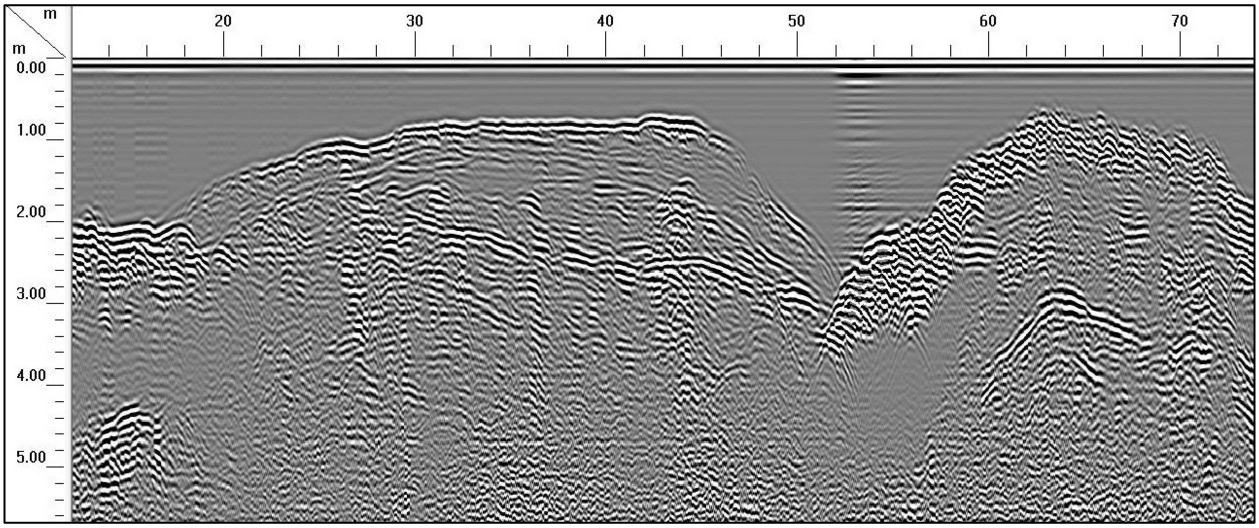


Figure 5-8 Example of water-based data collection on a shallow river. Note excellent penetration into subbottom sediment and variability between fine-textured stratified areas (between 10 to 50 meter marks) and high-amplitude areas representing an erosional lag deposit (between 50 and 75 meter marks).

5.1.8 Surveying through freshwater ice

Ice is an ideal medium for GPR propagation and presents no major issues for winter surveys (Arcone 2009). Just make sure you know the ice thickness before you walk on it. Some states have ice fishing or ice thickness reports that monitor seasonal ice conditions. If you see people ice fishing you could ask them as well. The GPR antenna can be placed on a sled, especially if there is snow cover, and this will make it easier to bring equipment from the vehicle to the survey area. Just be conscious of the sled's thickness (1-2 inches max) and make sure that the antenna sits flush on the bottom of the sled and there are no significant air gaps. A 3-wheel or 4-wheel survey cart may be feasible, but you can also use an external distance-encoder (if available) to acquire distance-based data with consistent scan density. Calibrate the encoder before surveying to ensure a proper distance calibration.

Like surveys in other environments some control unit settings will need to be adjusted, including samples/scan, dielectric, and time range/ depth. Samples/scan will usually need to be higher than 512 due to the increased time range required for water-based surveys. Refer to **Table 3** for recommended samples/scan values for different antenna models and time ranges. The one tricky part of through-ice surveys is dealing with the dielectric differences between ice, water, the sediment-water interface, and saturated sub-floor sediments. These dielectric variabilities present difficulties for establishing a depth correction. In the best case scenario you could use an average dielectric for all the media types but this would still be inaccurate. My recommendation is to ignore dielectric (or set it to 81) and to keep increasing time range/depth range until you can see the bottom of the waterbody. If you can penetrate the underlying sediments keep increasing time/depth until the bottom 25% of the profile is attenuated; this will ensure maximum penetration. If you are surveying an entire waterbody set the time/depth parameters in the area of deepest water (**Figure 5-7**).

As with water-based surveys I highly recommend connecting a GPS to your control unit/antenna and encoding geographic coordinates into the GPR profiles. A RTK survey-grade GPS may not be necessary, but I'd suggest sub-meter resolution at least. Ideally ice-based profiles, regardless of whether a GPS is connected, should be as straight as possible with few if any turns. Avoid collecting one long ribbon of data across the project area as this will be extremely difficult to figure out during post-processing. Instead you should collect individual long and straight profiles, stop the file before turning the antenna around, and start a new file when facing the new orientation. If the survey area is relatively small you should consider collecting a grid of data to achieve higher-density coverage. Laying out one or more grids on ice is identical to land-based methods, but you'll have to secure the baseline with something other than tent stakes.

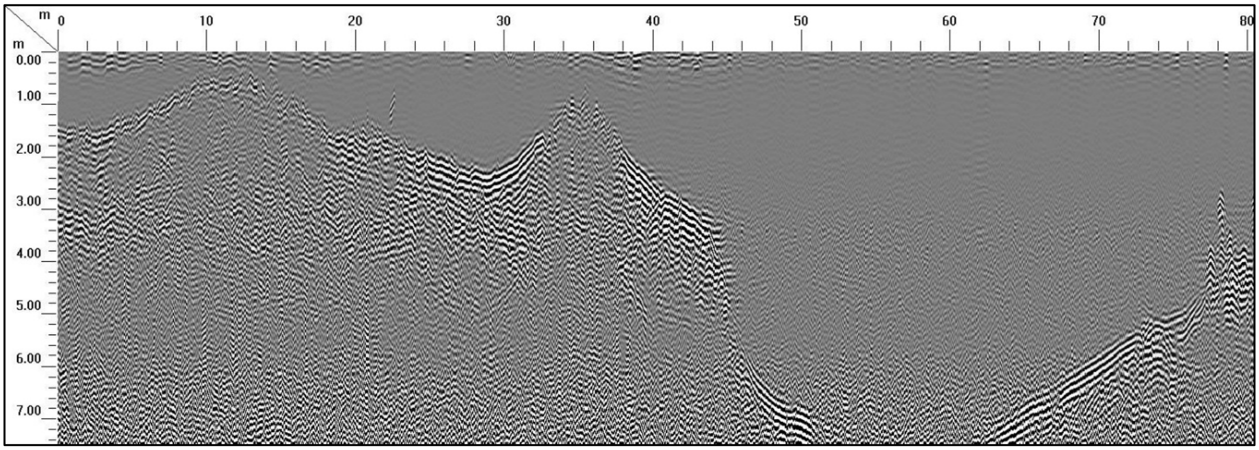


Figure 5-9 Example of lake survey data collected through ice. Note penetration of subbottom sediment but depth window was not optimal for reaching the deepest area.

5.1.9 Surveying over variable topography

Minor topographic variations are relatively easy to overcome, but some sites (burial mounds, tombs in cemeteries, platform mounds, etc.) exhibit large topographic changes that can be problematic for 2D and 3D surveys. Much like the compounding of small landscape changes with increasing profile length (see Section 4.1.5) large changes can generate extreme between-profile offsets and data striping in time slices (**Figure 4-2**). An additional consideration is the tilt of the antenna relative to the ground surface; if you are on a slope the GPR wave is transmitted perpendicular to the ground surface (not straight down). If surveying in 2D only, you can deal with topography using careful notetaking and laying out fiducial markers as reference points. The basic concept is to lay out a surveyor's tape measure (or use a total station or GPS) to place markers at set intervals along straight transect paths. The elevation of the marker locations is then measured and recorded. When the GPR system passes each marker the operator will add a user mark to the data. These user marks will be visible in RADAN, and using RADAN's Tables Pane (see RADAN Handbook) the elevation for each mark can be entered to perform a Surface Normalization (topographic correction). If surveying with a RTK GPS interfaced with the GPR the elevation of each marker will be added to the file along with Lat/Long coordinates. I would not trust the elevation data from non-RTK GPS units.

For gridded 3D surveys topography is a larger issue; RADAN currently does not allow topographic correction of 3D slices. For localized topography (small burial mounds or tombs) the best option is to lay out a grid that completely encompasses the feature. For large landscape elements it is best to survey on top of the feature and avoid the steep side slopes. In either case data collection should use unidirectional profile orientation to minimize additional slope-related errors. There will be offsets due to slope and other factors, but since the GPR is measuring depth below surface you can use this information to gain insights into subsurface features and their vertical and horizontal patterning. If you are a GIS user you can export the data points or time slice to ArcView or QGIS, and then extract the topographic elevations from LiDAR or other elevation sources. A final step would be to subtract the GPR-derived depth of features from the extracted topographic data.

5.1.10 Surveying around houses and other large obstacles

Laying out GPR grids on open lawns, fields, and well-manicured golf courses is a great way to spend your day, but these unfortunately are fairly uncommon site conditions. Most survey areas have multiple small obstacles that must be dealt with but some have really large obstacles, like buildings, pools, or bull-fighting rings (true story) that pose unique problems. In these situations it is nearly impossible to lay out a single grid that straddles the obstacle(s). You'll need to be creative to maximize survey coverage and to minimize the number of grids and the time it takes to lay them out. Fewer grids also means easier assembly during post-processing. There are other less-obvious issues like the size of survey carts and how close to a wall you can get, and how to deal with obstacles that have a non-square or non-rectangular outline. Historical and modern homes pose these field issues, especially when there are numerous smaller architectural elements attached to the house and/or barn/garage.

A convenient strategy is to lay out two grids that enclose the obstacle but do not overlap on the coordinate plane (**Figure 5-10**). It will be difficult for RADAN to display grids that have overlapping data, so I'd just avoid it altogether. Consider a survey area with a house, later historical extension, and connected barn. The road-facing side of the structures present straight lines that are easy to deal with, but the backyard has a relatively large space where the addition and barn are not flush with the back of the main house. The first consideration is whether to collect in a unidirectional or bidirectional/zig-zag pattern. Unidirectional survey is ideal in this case because there will be more flexibility and line length irregularities will be easier to handle. A zig-zag survey would require that the center of the GPR antenna be placed on each baseline. Given the size of survey carts, or length of external distance-encoding wheels, the grids will have to be offset from the house walls and survey coverage will be sacrificed. My recommendation is to first lay out the survey area as one large rectangle or square around the obstacle. This may require a few additional grid nodes to deal with the house and barn; you probably won't be able to pull a long hypotenuse measurement through the obstacle(s).

If possible, lay out your first baseline tape along a straight portion of the obstacle or landscape elements to provide a straight-line reference. Otherwise you might find that your overall rectangle is at an odd angle relative to the obstacle's footprint. Once the overall grid area is established stretch a tape from the Grid NE to the Grid SE corner and place a marker at the mid-point. Do the same for the Grid NW and Grid SW corners. These marks will be the suture points between Grid One (Grid South section) and Grid Two (Grid North section), and you'll have to lay out the corresponding grid nodes due east/west of these marks using other parts of the grid or triangulating from the overall grid corners. One final suggestion is to lay out "intermediary baselines" in your grids to account for the irregularity of the survey area. These baselines will allow you to place Cone #2 on an actual grid point rather than trying to walk a perfectly straight line with no guidance. Trust me on this one; using the tire tracks from the previous transect to walk a straight path is about as accurate as not having a grid at all.

Since you've decided to use a unidirectional collection strategy, the best option for Grid One is to collect Grid-North-oriented Y Axis transects starting in the lower left (Grid SW) corner and progressing to Grid East. These profiles should end with the center of the antenna exactly on the upper baseline of Grid One (also the lower baseline of Grid Two). For Grid Two, collect Grid-South-oriented Y Axis transects starting in the upper right corner (Grid NE) of the coordinate plane and progressing to Grid West. This will allow all Grid Normal lines to start on a consistent Y-coordinate. These profiles should end with the center of the antenna exactly on the lower baseline of Grid Two (also the upper baseline of Grid One). Grid Two has that annoying gap behind the house extension, and rather than avoiding it you can integrate it into Grid Two (do not make a whole new Grid Three in that area). First, lay out the Grid North baseline for Grid Two. Next, place two additional grid nodes on the Grid NE and Grid NW corners of the house/barn, making sure you can pull a tape between them and not hit any structural elements. The last step is to place two grid nodes into the gap area and place a tape measure between them. You can then survey the entire backyard using the Cone Method (see Section 4.1.10) and minimize gaps in coverage.

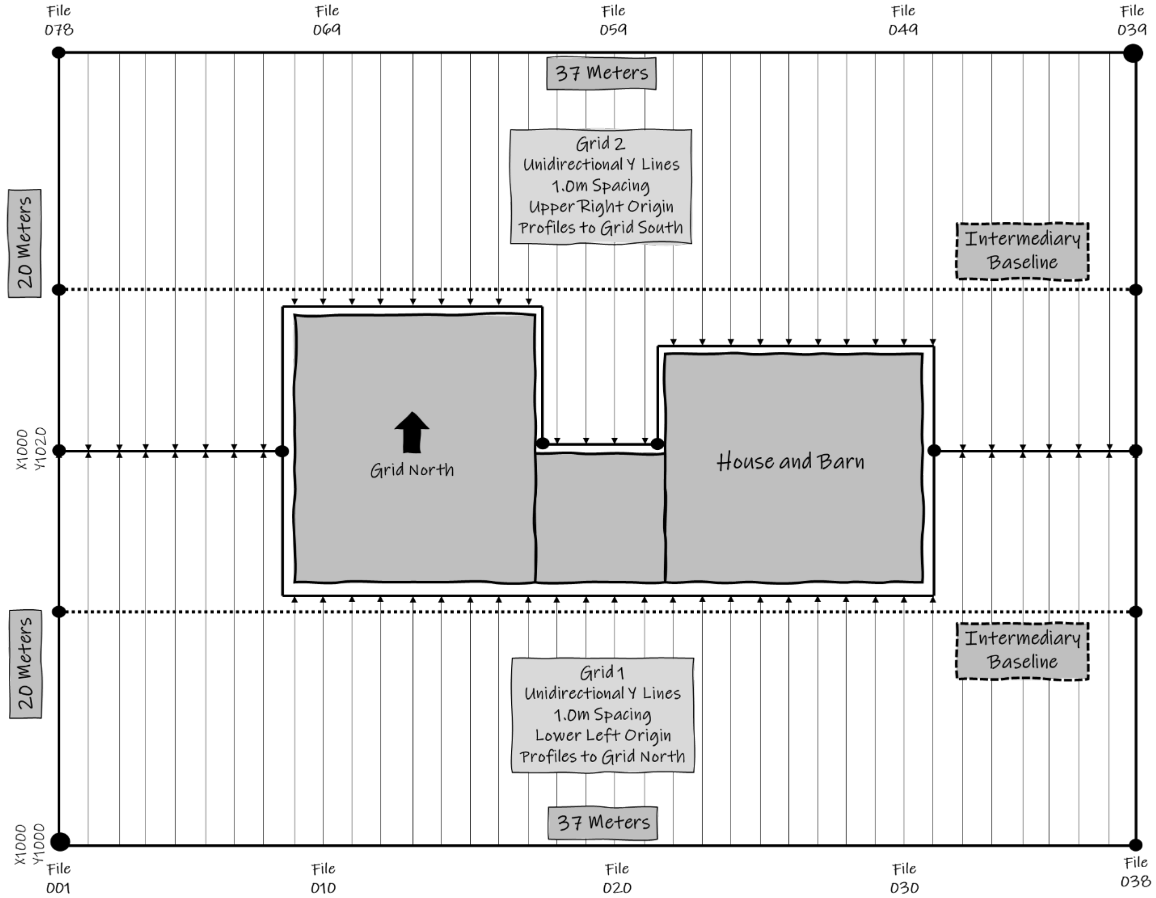


Figure 5-10 Example of GPR field notes and grid layout around a large obstacle

5.1.11 Geomorphic surveys using 2D profiles

Gridded data provide predictable and even data density, and grids are the recommended collection strategy for relatively small (1-2 acres) survey areas. However, large-scale geomorphic and geologic surveys may preclude the use of grids, or may not require tight transect spacing or generation of time slices (see Section 4.1.4). Individual GPR transects can reveal paleogeographic information, like the layout of former paleochannels or other features, bedrock configuration, or general stratigraphic relationships. Without some type of spatial positioning, either interfaced with the GPR or collected separately, individual profiles are difficult to place on a landscape (even with good notes). I recommend connecting a GPS directly to the GPR so you can encode geographic coordinates into each profile. These GPS data will be available in RADAN, and tracklines and/or digitized targets/layers can be exported. For geomorphic investigations the general rule of thumb is to collect profiles perpendicular to structure for maximum stratigraphic information. For example, if surveying along an ocean or lake the profiles should run perpendicular to the shoreline. On floodplains, transects perpendicular to the river/stream will reveal important details about the alluvial sequence and meandering history. Profiles should still be collected parallel to structure so as not to miss anything important, but these will generally just reveal stratigraphic relationships and not horizontal boundaries, erosional areas, or nick points.

The use of high resolution GPS units will improve the spatial resolution of GPR tracklines and allow more accurate re-location of areas of interest. In general, over-the-counter, consumer-grade GPS units are not recommended (Garmin, Magellan, etc.). Use a sub-meter GPS for general surveys, like a Juniper Geode, Trimble GeoXT, or similar model. For projects with more strict resolution requirements a RTK GPS (either with or without base station) is recommended. Note that most RTK base station and rover setups (see Section 3.1.3) use a radio modem to broadcast corrections. The frequency of the radio modem could overlap with your GPR antenna’s bandwidth and create periodic noise if you are close to the base station (**Figure 3-5**). Make sure you understand how the GPS connects to your GPR model, and that you have the necessary adapter cables. GSSI uses two connection types: 9-pin serial cable and Bluetooth. The SIR4000 control unit connects with a RS232 serial cable. If using an analog antenna the serial cable connects to the SIR4000; if using a digital antenna (350HS, 300/800DF) the cable connects to the antenna. For UtilityScan and GS Series systems a Bluetooth GPS is required. A SIR3000 needs a Serial Data Recorder (no longer manufactured) that connects on one end to the SIR3000 by serial cable and on the other end to the GPS by serial cable.

6 REAL-TIME PROSPECTION FOR ACF SURVEYS

Real-time prospection is not recommended for any ACF project due to a host of confounding variables. You should inform your coworkers and clients about the potential pitfalls of real-time GPR data, and ensure that they understand why gridded data collection and post-processing would be beneficial. The issues with real-time data have been covered elsewhere in this document, but it is worth reiterating the important considerations. External EM interference from radio, cellular, and television broadcasts is sometimes just a nuisance, but it often will manifest as severe data noise that can overprint or completely obscure targets of interest. Continuous EM noise will generate horizontal noise bands that span soil disturbances and give the impression that soil layers are continuous, and proximity to the transmission source will compound this issue. Sporadic EM noise can generate a ‘snowy’ or static overprint and obscure real data. Soil conditions create their own noise signatures, and usually these are exacerbated by certain clay varieties and overall water content. Salt, nitrates, calcium carbonate, and other chemical components will increase conductivity and reduce penetration depth while vastly reducing interpretive potential. The equifinality of GPR reflections is also of concern, as targets and layers from completely different origins can be indistinguishable on GPR profiles. For example, rocks, roots, animal burrows, coffins, and other point sources all generate hyperbolic targets. Tree removal, pet burial, clandestine burials, utility trenches, and other ground disturbance all share similar characteristics and real-time interpretation of solitary GPR profiles can be quite difficult. Despite these real-time agents of obfuscation some field projects, like forensic searches, may have no time for post-processing and thus this chapter attempts to provide guidance for increasing the success of real-time surveys.

The most important consideration is the ability to predict what targets of interest should look like on GPR profiles. Armed with this information you will be in a better position to recognize potential important anomalies. For example, when looking for graves or clandestine burials you should understand what these features would like look in reality. What obvious characteristics would they have if they were visible in the wall of an excavation unit or backhoe trench? While GPR does not provide a literal stratigraphic record, visualizing features in the ground will help you interpret them in GPR profiles. A soil disturbance, whether a grave or a precontact/post-contact storage pit, should be visible as a break in continuous GPR reflections. The nature of the feature walls could scatter GPR energy but the broken reflectors will still be visible. Collect additional profiles near targets of interest and determine their approximate length and width. You’ll often find that hyperbolic targets are only present on one profile, and this suggests a single point source object like a rock. However, a careful assessment of the point source could reveal an overlying disturbance suggesting intentional burial. If anomalies continue across multiple profiles, mark them with pin flags and see where they go. Some knowledge of site conditions and land use history will also be of use, especially if a landform has been plowed or otherwise reworked. Amass all possible sources of important information, such as historical maps, property deeds, eyewitness accounts, and insights from property owners. Use Google Earth and other GIS platforms to conduct a virtual walkover survey before you arrive. The more information you have the better choices you can make regarding proper GPR antenna frequency and antenna mobilization methods.

All of the research in the world will not make up for a lack of familiarity with your GPR system. You must have a detailed understanding of system setup, parameter optimization, and real-time filtering options. Real-time GPR data quality, and the likelihood of identifying subtle yet important targets, is directly related to proper field settings. These include time/depth range, dielectric, and scans/unit, but other parameters like manual gain optimization and real-time filters are the critical factors. Gain levels should be set manually in a location that approximates "normal' background levels. Collect a few test profiles across the project area and use the data to initially differentiate disturbed areas, locations with abundant targets, and places where soil layers seem to be in their natural undisturbed state. If you calibrate gains to the normal background any anomalous areas will stand out and be easier to identify. Conversely, if you calibrate manual gains over a clandestine burial or a target of interest (a good example of Murphy's Law) similar features will not contrast as sharply with the background levels. You should therefore evaluate your data in real-time to determine the best location for optimizing gains and other system parameters.

Become familiar with the powerful (but potentially dangerous) bandpass and background removal filters. The SIR3000 and SIR4000 have these options, while the Android-based UtilityScan system uses Band Filter for background removal. In less-than-ideal soil conditions these filters could vastly improve your data, though they could just as easily make your data worse. An in-depth understanding of GPR profiles will help you evaluate whether your filters are helping or hindering data quality. A bandpass filter (I suggest IIR) can remove some external EM noise and suppress horizontal banding from continuous sources of interference. I'd start with a conservative frequency range (1/4 to 2x the antenna's central frequency) and collect a few test profiles. You'll need to know what your data look like with only minor processing; you can then compare more heavily processed versions to decide on optimal settings. Try to evaluate if noise (external or soil-related) is related to low or high frequencies (or both). If you can identify a relatively narrow noise band you can then remove it without affecting the rest of the data. For aggressive bandpass filtering I'd recommend High Pass values at or above the antenna's central frequency (**Figure 6-1**). For example, with a 400MHz antenna I might use a bandpass filter with a high pass of 400MHz and a low pass of 800MHz. This technique will downplay low frequencies and remove the lower resolution data components. A background removal can effectively remove noise bands, but used incorrectly most of the real GPR data will be removed as well. Unfortunately, many operators tend to use a low scan value and essentially 'break' their data. I recommend starting with a larger scan value (200 to 300 scans) and then reducing it to evaluate the impact on your data. As the scan value decreases you'll start to see real layers disappear, and eventually you'll only see hyperbolic tails.

For most real-time ACF surveys you should consider laying out a rough grid with tape measures and pin flags. You can then use the grid to walk straight lines and prevent gaps in coverage. Have a quiver of pin flags or some other markers on hand and mark interesting anomalies as you pass over them. You could even write an initial interpretation on the flag. Once you've covered the project area you can return to flagged locations and reassess. For cemetery and forensic surveys this method can be quite helpful because in large project areas you may otherwise be unable to relocate your initial discoveries. In formal cemeteries spend some time prospecting over marked graves and becoming familiar with burial signatures from different time periods. Use these data to inform your interpretation of potential unmarked burials. Additionally, do not expect cemetery and forensic targets to generate a classic hyperbolic reflection. There is a good chance that the human remains and/or burial container have completely decayed. You'll therefore be searching for ***the hole that the target was in***, and this could be a subtle, low-amplitude feature. Finding these and other easily-overlooked features will require optimized range gain and creative and informed use of processing filters.

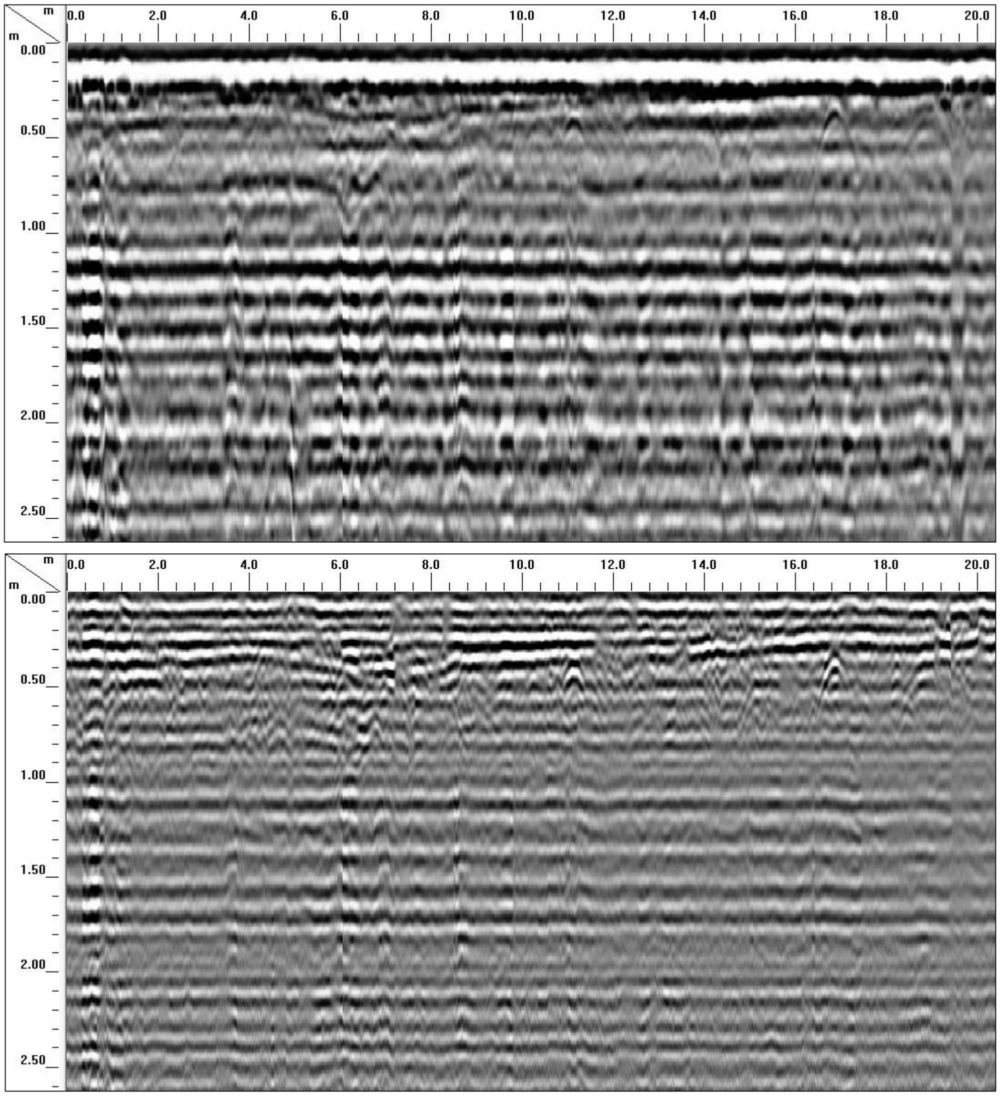


Figure 6-1 Top: Example of GPR data in especially poor soil conditions. Most of the real data are overprinted by soil-derived noise. Bottom: the same profile with an aggressive IIR Bandpass filter applied (HP: 350 LP:900). The data are now more usable for real-time interpretation. Adding a Background Removal filter and adjusting manual gain levels could further improve the data quality.

Save your data along with complete and informative field notes even if you foresee no future use for them. You might be called upon to discuss the data at a later time, or present the data in court. I never throw away data; they can always be useful later. Do not be discouraged if ground-truthing of real-time data leads to a lot of “empty” holes and recitation of every non-specialist’s favorite mantra: “the GPR didn’t work”. The GPR did work (unless you forgot the batteries) and helped you identify areas of anomalous reflections. When operating a GPR for ACF projects your job title should be “manager of expectations”. This includes educating clients, coworkers, and other stakeholders by discussing what GPR actually does (and what it does not do). Setting and maintaining realistic expectations, especially for real-time surveys, are important parts of the GPR method.

7 SYSTEM-SPECIFIC SETUP AND RECOMMENDATIONS

Pro Tip: I recommend avoiding 3D modules for increased versatility in collection strategies. Instead, use 2D Modules to collect gridded datasets.

UTILITYSCAN PRO 4000

See SIR4000 User Manual for additional information and recommendations. I highly recommend enrolling in GSSI's UtilityScan Pro 4000 class to receive hands-on hardware instruction.

The SIR4000 uses a 32-bit data format. Filters applied during collection will not affect raw data (.DZT) and will be stored (.DZX) for use in RADAN 7. The only exceptions are the on-board IIR vertical High Pass/ Low Pass filters for the 350HS antenna and Position Correction for all antennas.

Figure 7-1 GSSI SIR4000 control unit

- Utility cart: 3-wheel or 4-wheel
- No cart: SIR4000 chest harness, shark fin and pull handle, Model 620 distance encoding wheel

Recommended first step after choosing collection mode and naming a project (see below): Navigate to System – Recall Setup and restore the default settings for your cart/encoder and antenna configuration

- **Collection mode: Expert Mode (analog antennas) or Digital 2D (digital antennas)**
    - Select antenna model from main menu (for analog antennas without a Smart ID)
        - Only for Expert Mode and analog antennas
    - Set appropriate units (feet or meters)
    - Set GPS parameters (if needed, otherwise ignore)
    - Create new project for each survey, enter a meaningful project name.
        - Use Last Used Settings for surveys that span multiple days
    - When a new project is created, go to the System Menu – Recall Setup. Choose your cart model and antenna. This will recall GSSI-recommended settings.
        - Only do this before surveying on the first day of a new project.
    - After Recall Setup, go to System – Calibrate SW [survey wheel]. Perform a 10m/30ft calibration and save the value. See Section 4.1.4 for more information.
        - Only do this before surveying on the first day of a new project.

- **<u>Radar Menu:</u>**
  - Collect Mode: Distance (use Time Mode only for water-based surveys or other special applications)
  - Scans/Second: Analog antennas: as high as possible. 350HS digital antenna: 100 Scans/Second. For the 350HS scans/second can be reduced to enhance the HyperStacking process. However, if the value is too low (below 60 to 70 scans/second) your survey speed will be dramatically reduced.
  - Samples/Scan: 512 for most shallow (2-3m) surveys. Consult **Table 3** for deeper surveys
  - Scans/Unit: 50 scans/meter or 18 scans/foot
  - Units/Mark: Set to 0.0
  - Dielectric: Start with default value (8-10). Use Hyperbolic Matching to refine.
  - Soil Type: Ignore
  - Depth Range: Ignore (use Time Range instead)
  - Time Range: start with 75nS and keep increasing until the bottom 25% of the GPR profile is attenuated
  - Position Mode: Use Manual mode for more control. This setting configures the position of Time Zero. This is typically the center of the direct wave's first positive peak.
    - Only for Expert Mode and analog antennas
  - LineTrac: Off
    - Only for Digital 2D Mode and digital antennas
- **<u>Process Menu:</u>**
  - Gain Mode: Manual
  - Edit Gain Curve: Add at least two gain points then modify gain curve so that all O-Scope peaks touch the two thin, black vertical lines on left and right of centerline
  - FIR Low Pass: Off. Vertical bandpass filter.
    - Only for Expert Mode and analog antennas
  - FIR High Pass: Off. Vertical bandpass filter.
    - Only for Expert Mode and analog antennas
  - FIR Stacking: Off. Horizontal filter.
    - Only for Expert Mode and analog antennas
  - FIR BG Removal. Off. Background removal. Horizontal filter. Leave at 0 for most surveys, use sparingly with large values (>200 scans) if needed
    - Only for Expert Mode and analog antennas
  - IIR Low Pass: Use default value or ¼ of antenna's central frequency. Vertical bandpass filter.
    - Only for Expert Mode and analog antennas
  - IIR High Pass: Use default value or 2x antenna's central frequency. Vertical bandpass filter.
    - Only for Expert Mode and analog antennas

  - IIR Stacking: 0. Horizontal filter.
  - IIR BG Removal: 0. Background removal. Horizontal filter. Leave at 0 for most surveys, use sparingly with large values (>200 scans) if needed
  - Signal Floor: Off
  - Filters Off: Ignore. This will turn of all filters and you'll see horrible real-time data
- **Output Menu:**
  - Vertical Scale: Depth
  - Vertical Units: Meters or Feet
  - Scale Color: White on black
  - Show O-Scope: On
  - Show Hyperbola: Off
  - Colormap: 11
  - Color Stretch: 0.0 to 0.50
  - Color Slide: 0.0
- **System Menu:**
  - Brightness: Usually 100%, but lower values can extend battery life
  - Volume: 95%
  - AutoSave: Off (will generate a save/discard prompt when file is closed)
  - Save Setup: Can be useful for saving personal settings. I usually ignore this option
  - Recall Setup: Loads GSSI-recommended settings for specific antennas and default encoder calibration value for 3-wheel and 4-wheel carts and the Model 620 distance encoder
  - Calibrate SW [survey wheel]: Should be the first step after Recall Setup
  - GPS Config: Another opportunity to configure and enable an attached GPS
- **Lower menus during data acquisition:**
  - Focus: Off. Focus On will collapse hyperbolic tails based on currently set dielectric value.
  - Gain: Adjust in real-time to increase or decrease overall display gain level
  - Zoom: 1X. Change to ½ to compress profile and see more of longer profiles
  - H Cursor [Horizontal Cursor] Off
  - Dielectric: set this value during data collection by pressing the Output button, turning on Show Hyperbola, and exiting the menu. Back up the system until the backup cursor is centered on a hyperbolic target. Press the H Cursor button and use the control knob to place the H Cursor at the top of the hyperbola. Press the Dielectric button, then roll the control knob clockwise (increase dielectric) or counter-clockwise (decrease dielectric). Match the blue hyperbola to the hyperbolic tails in your data. Once finished you can turn off the H Cursor and in the Output Menu turn off Show Hyperbola.
  - Output Menu:
    - Dielectric: Ignore. Change this value using the steps outlined above

        - Hilbert Txfm [Transform]: Ignore
        - Show Hyperbola: see dielectric (above)
        - Colormap: 11
            - This color scale (black on the left, white on the right) displays the most dynamic contrast and color range. Other color tables preferentially highlight the highest amplitudes at the expense of mid- to- low-amplitudes.
        - Color Stretch: 0.0 – 0.50
        - Color Slide: 0.0
    - Play Mode: Allows playback of saved profiles
    - File Info: Displays Radar Parameters, Antenna Information, Positioning, and Processing History.

UTILITYSCAN (ANDROID-BASED)

See UtilityScan Quick Start Guide for more information.

- I highly recommend enrolling in GSSI's UtilityScan class to receive hands-on hardware instruction.
- UtilityScan systems are quite versatile as shipped, but I recommend using a ruggedized 3-wheel or 4-wheel cart upgrade to improve 'off-roading' capabilities
- UtilityScan systems do not have an integrated 3D Module.
- Assign a designated USB flash drive for data transfer. Insert into tablet (using adapter for consumer tablet model) and format USB flash drive through Android.

Figure 7-2 GSSI UtilityScan System

- **<u>Mode: Scan Max</u>**
- **<u>First Menu Screen: Upper Carousel</u>**
    - <u>Project</u>: Select Project 1 through 6. Use the same project number during multi-day surveys.
        - Each project can store 999 GPR profiles. Do not exceed this limit.
    - <u>Gain Control</u>: Normal. Configures the update rate of adaptive range gain. Useful for real-time prospection and evaluation of data quality
    - <u>Scan Density</u>: Normal (60 scans/m or 18 scans/ft) or High (100 scans/m or 24 scans/ft). Assigns the number of individual scans collected across one meter or one foot of distance. Higher values stretch the data more than lower values and increase file size.
    - <u>GPS</u>: Use the tablet's internal GPS (low resolution) or an external Bluetooth GPS to encode geospatial information into profiles.
        - NOTE: to use an external Bluetooth GPS you must first establish a Bluetooth connection through the Android OS before opening the UtilityScan app.
    - <u>LineTrac</u>: Off

- **First Menu Screen: Lower Carousel**
  - Calibrate Antenna: Configures the Time Zero position (ground surface) and establishes a baseline for adaptive gain. For optimal results you should use this function within your project area (not in the parking lot next to the survey area).
  - Calibrate Survey Wheel: Calibrate the encoder wheel (back right wheel) to a set distance. I recommend 10m/30ft.
    - When using a ruggedized 3-wheel or 4-wheel cart this is a necessary step; the UtilityScan app does not include default calibration values for these carts.
  - Save Prompt: On or Off depending on preference. Save Prompt On will generate a save/discard option when you click Close Profile or New Profile. When set to Off, the file will save automatically and you will not be prompted to save or delete.
  - Display: A+B. During data collection his mode will display the GPR profile and the O-Scope for your current scan.
  - Antenna Auto Connect: Off. You'll select the antenna each time the Android app is opened. This prevents Android-related issues with Wi-Fi IP addresses.
  - Factory Reset: Restores all settings to GSSI-recommended defaults.
    - ***Use this for all new projects***. Do not use this every day for multi-day surveys.
  - Version Control: Displays current firmware versions. Compare these versions with those listed on GSSI's website. If not current you should update as soon as possible (using the pre-installed Update Launcher app and an internet connection)
  - Select Language: GPR surveys are not the best time to learn a foreign language.
  - Units: English (feet) or Metric
  - Theme: I prefer the Ice theme because its high-contrast color palette is optimal for use in bright sunlight

- **Scan Setup Menu**
  - Band Filter: Off. This filter applies a real-time background removal. Only use this feature if your data exhibit excessive horizontal banding (from external continuous EM interference)
  - Depth: Start with 2 to 3 meters (6 to 9 feet). Keep increasing depth range until the bottom 25% of the GPR profile is attenuated
  - Dielectric: Ignore during initial setup. You'll configure this when collecting test profiles
  - Focus: Off. Real-time migration function that will collapse hyperbolic tails based on currently set dielectric.
  - Zoom: 1.
  - Color Table: 1. This color scale (black on the left, white on the right) displays the most dynamic contrast and color range. Other color tables preferentially highlight the highest amplitudes at the expense of mid- to- low-amplitudes.

- **Lower menus during data acquisition:**
  - **Pushing cart forward** and collecting new data:
    - New File: Closes current file and opens a new one
    - Mark: Place a user mark in the data at the edge of the screen
    - Close File: Closes current file and returns to Scan Setup menu
  - **Pulling cart backwards** and scrolling through previously-collected data:
    - Gain: I recommend adjusting the Gain Level to 6 or 9 depending on your preference. Shallow and Deep gain can be useful but I often ignore them
    - Zoom: 1
    - Focus: Off
    - Save Image: Captures a screen shot of everything currently on the screen
    - New File: Close current file and start a new one. If Save Prompt is On you'll see an option for save/delete
    - Close File: Close current file and return to Scan Setup menus. If Save Prompt is On you'll see an option for save/delete
    - Mark: Place a User Mark in your data. There are two options: 1) move backwards and place a mark – this will place a vertical mark at the location of your backup cursor; 2) back up to a target, use your finger or a stylus to place a horizontal cursor at the desired depth, and press Mark button to place a mark where the backup cursor and horizontal cursor intersect. You can choose the color for your mark. Both types of User Marks will be visible in RADAN 7 and if a GPS is connected and enabled the GPS coordinates will be saved with each User Mark.
    - Calibrate:
      - Set Dielectric: Uses hyperbolic matching to set average dielectric value. To use, back up the system until the backup cursor is centered on a hyperbolic target. Use your finger or a stylus to place a horizontal cursor at the top of the hyperbola and then press the Calibrate button to display a blue hyperbola. Slide your finger or a stylus up or down the vertical scale bar to resize the blue hyperbola. Once it matches the hyperbola in your data you can press Accept and then Previous.
      - Save Image: Captures a screen shot of everything currently on the screen
      - Set Depth: This feature sets a dielectric value based on the known depth of a target. To use, collect a profile over a target with a known depth (do not guess) and back up so that the backup cursor is in the center of the hyperbola. Use your finger or a stylus to place a horizontal cursor at the top of the hyperbola, and then press the Set Depth button. Slide your finger or a stylus up or down the vertical scale bar to change the depth of the horizontal cursor. The current cursor depth will be displayed near the top

left corner of the screen. Once the displayed depth matches the known depth you can press Accept and then Previous.

UTILITYSCAN 3000

Figure 7-3 GSSI SIR3000 control unit

Refer to the SIR3000 User Manual for more information regarding specific settings. I recommend enrolling in GSSI's UtilityScan 3000 class to learn about SIR3000 setup and optimization.

Recommended Collection Mode: <u>TerraSIRch</u>

The other available 2D modules are streamlined for specific applications. TerraSIRch is the better choice because of its versatility and access to all settings. Avoid Quick3D mode and focus on manual 3D collection.

The SIR3000 is previous-generation hardware and thus it will only interface with GSSI analog antennas. You cannot connect GSSI digital antennas (350HS, 300/800DF, 200HS). There were two SIR3000 model numbers: 1100 series and 2100 series. The 1100 was the first model and had an earlier file system format, and as such it has a smaller internal memory and can only use 2GB or smaller Compact Flash cards with FAT16 file format. The 2100 series accepts larger compact flash cards. I recommend using a compact flash card with both models so you can save files directly to the card and then transfer data to your PC using a Compact Flash card reader. To write files directly to the Compact Flash card it must be inserted before powering on the system. You can transfer files from internal storage to a USB flash drive, but this method is still limited by storage size and file format. Earlier Windows versions could accept a USB connection to a SIR3000 but this capability does not extend to Windows 10 PCs.

IMPORTANT: Be aware that the SIR3000 data are not raw when collected and loaded into RADAN 7. They inherit all field collection and display parameters. You should ensure that your O-Scope peaks do not extend outside the O-Scope window – if the peaks are truncated then you are clipping the data amplitudes and the clipped information is not recorded. Do not apply aggressive real-time filters (IIR, FIR, Stacking, or Background Removal) if you intend to post-process your data.

Change any Auto settings to Manual, such as Position and Gain. This will keep settings consistent between battery replacement and multi-day surveys.

After you power on the system and choose TerraSIRch mode, navigate to System – Setup – Recall and choose your cart/encoder and antenna configuration. This will recall GSSI-recommended settings, including the default encoder calibration value. Calibrate your encoder after recalling a default setting. To access the encoder calibration menu, expand the COLLECT menu, expand the RADAR menu, then highlight Distance and press enter. In the following popup window highlight Time and press enter, then highlight Distance and press enter. See Section 4.1.4 for more information.

- **Collect Menu**
    - **Radar Submenu:**
        - Antenna: Select the correct antenna from the list.
        - T_Rate (Transmit Rate): Set by the system based on antenna model.
        - Mode: Distance (use Time Mode for water-based surveys). Never select Point Mode unless you intend to use it. If Point Mode is selected, choose Distance Mode and then immediately recall default settings (see below).
        - GPS: None (unless you have a Serial Data Recorder).
    - **Scan Submenu**:
        - Samples: 512 for most 400MHz surveys shallower than 100nS. If using a lower frequency antenna (100-200MHz), with a time range deeper than 100nS, use 1024 or more Samples/Scan.
        - Format: 16 bits.
        - Range (nS): Time range in nanoseconds. TerraSIRch mode uses time range and dielectric to calibrate the depth scale. For most surveys I'd recommend starting at 75nS and increasing/decreasing as necessary.
        - Diel: Dielectric. It is not possible to perform a hyperbolic match on the SIR3000, so you'll have to enter an estimated dielectric or collect a file and migrate in RADAN (and then enter the value).
        - Scn/Unit: Scans per unit. A typical value is 50 scans/meter or 18scans/ft.
        - Gain (dB): Linear gain amplification. If your Gain curve looks OK, but is a little washed out, change this value to 6 to add contrast.
    - **Gain Submenu:**
        - Mode: Manual
        - Points: 3 to 4. For a 400MHz antenna I find that shallower time ranges are best optimized with more gain points (4 to 5), and deeper time ranges are better with fewer gain points (3 to 4). In Manual Gain mode you'll select individual gain points (GP1, GP2, etc.) and increase or decrease the gain value. The goal is to make all of the O-Scope peaks roughly the same size from top to bottom. This will create an even gain curve.

  - **Position Submenu:**
    - Mode: Manual (the user sets the position of the direct wave). In most situations you can select Auto mode and the system will auto-configure the time zero position. You can then switch to Manual mode. This will lock in the position correction and it will not change after swapping batteries or powering off the system.
  - **Filters Submenu:**
    - LP_IIR: IIR (vertical) low pass filter. All frequencies above this value are discarded. A good rule of thumb is to use a value of 2x the antenna's central frequency.
    - HP_IIR: IIR (vertical) high pass filter. All frequencies below this value are discarded. A good rule of thumb is to use a value of ¼ of the antenna's central frequency.
    - LP_FIR: FIR (vertical) low pass filter. Avoid this filter.
    - HP_FIR: FIR (vertical) high pass filter. Avoid this filter.
    - STACKING: Smooths data and downplays sporadic noise. Avoid this filter.
    - BGR_RMVL: Scan-based background removal that attempts to remove horizontal noise bands from continuous EM interference. Avoid this filter unless required for real-time interpretation.
- **Playback Menu:**
  - I see no benefits to using Playback settings in the field.
- **Output Menu:**
  - **Display Submenu:**
    - Mode: Line
    - C_TABLE: 4
    - C_XFORM: 2
    - GAIN (dB): Linear gain amplification. If your Gain curve looks OK, but is a little washed out, change this value to 6 to add contrast.
  - **Transfer Submenu:**
    - PC: Transfers data to using USB cable. Doesn't work with Windows 10.
    - Flash: Transfers data from internal storage to Compact Flash card.
    - HD: Transfers data from internal storage to USB flash drive.
    - Delete: Select and delete saved files.

- **System Menu:**
    - **Units Submenu:**
        - Depth: Set vertical units.
        - Distance: Set horizontal units
        - VScale: choose display format for vertical scale (depth, time, or height)
    - **Setup Submenu:**
        - Recall: Select cart/encoder and antenna configuration to recall GSSI-recommended default values. A good place to start for every new survey. This option will also recall default encoder calibration values, so you should calibrate the encoder after recalling default settings.
        - Save: Save a custom configuration that can be recalled later.
    - **Path Submenu:**
        - Choose an existing project or create a new project name.
    - **Backlight Submenu:**
        - I recommend the highest backlight setting.
    - **Data/Time Submenu:**
        - Set time and date if needed.
    - **Battery Submenu:**
        - Check battery power status without removing the battery.
    - **Language Submenu:**
        - GPR surveys are not the best time to learn a foreign language.
    - **Version Submenu:**
        - View current firmware version. For 1100 series there could be an update. For 2100 series there probably will not be a newer version available.

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Appendix A: **GSSI File Header Information**

Field acquisition and display parameters are stored in each GPR profile. RADAN 7 can display this information using the File Header button on the Home tab. For 32-bit systems (SIR4000, UtilityScan) there are at least two files associated with each file name. For general GPR profiles there will be a .DZT file that stores all of the raw data (unprocessed/ no filters) and critical acquisition settings like scans/unit, dielectric, time range, and samples/scan. A related .DZX file will contain all field processing parameters, such as any filters applied (stacking, background removal, bandpass) and any range gain or linear gain information. The file header for the raw GPR data (.DZT only) will look different than the field processed data (.DZT and .DZX). When opened in RADAN 7 you'll see a raw profile window (.DZT only) as well as a "pre-processed' file window (.DZT and .DZX) where for better or worse profiles will look like they did during acquisition. Raw data will usually show one processing stage (position correction), while 'pre-processed' data (.DZT and .DZX) will display all applied filters and range gain settings. When a GPS is integrated into the system there will be a .DZG file that stores the NMEA sentences from the GPS along with specific GPR scan numbers for linking the two datasets. You'll also have a .DZA file for LineTrac accessory data. For 16-bit and control units (SIR3000 and earlier) there will only be a .DZT file and it will store acquisition and display parameters because SIR3000 data are not raw; they inherit field parameters. If a GPS is connected through a Serial Data Recorder there will also be .TMF and .PLT files.

The file header will be similar for 32-bit and 16-bit systems. The major difference will be seen with older analog antennas that do not have a Smart chip; for these there will be no antenna model listed unless it was set on the control unit. Other minor changes include the use of accessories with newer digital antennas and the Signal Floor option on 32-bit control units.

File Header Parameters

Original File: Name of the original file. This will display the name of the original file even if a processed file is open.
Created: Date the original file was created.
Modified: Date the file was last modified.
Number of Channels: Number of channels. Most data have one channel (except DF antenna).

<u>Horizontal Parameters</u>
Scans/Sec: Number of scans collected per second in the open file.
Scans/Unit: Number of scans collected per unit (meters, feet, etc.) in the open file. This number can be modified.
Units/Mark: Number of units (meters, feet, etc.) collected per mark. This number can be modified.

<u>Vertical Parameters</u>
Samples/Scan: Number of samples collected per scan. This is typically 512 samples for archaeology and forensics applications.
Bits/Sample: Number of bits per sample.

Dielectric Constant: Dielectric value entered when the data were collected. This number can be modified and controls the calculated vertical depth scale in the linescan and wiggle windows. This number can be manually edited as well (see Section 2.5).

Channel Information

Channel: Which channel to display in Header Information. Important for 300/800MHz DF antenna
Antenna Type: Antenna central frequency used to collect the data.
Antenna Serial #: Serial number of the antenna used to collect the data (if available).
Position (ns): Position of the start of the scan (Time-Zero) used when collecting the data.
Range (ns): Vertical range of the data in nanoseconds of two-way travel time.
Top Surface: Height of the scan above the direct wave, i.e. above ground surface, from when the data were collected. This will typically be a negative number.
Depth: Maximum depth range calculated based on the Range and Dielectric.

Processing History

Processing steps and the order in which they occurred. This includes newly-opened data and post-processed files. Below are examples processing steps.

- IIR Filters: IIR filters applied to the data with high pass and low pass values.
- FIR Filter: FIR filters applied to the data with high and low pass values.
- Position Correction: Time Zero processing.
- Range Gain: Any Gain modifications.
- Background Removal: Background Removal applied.

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