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Utility Locating Handbook

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Introduction

This Handbook is intended to "de-mystify" the interpretation of RADAR data and help you to get the most out of your utility and soil surveys. It contains basic information on RADAR theory and method of operation that you would need to understand to perform a survey. The ultimate goal of this guide is to help you to collect good data and interpret those data in order to provide your client with usable information. It explains why and how a certain procedure should be used in a specific case. This guide is only a starting point for you and it is not exhaustive. You will certainly run into situations on the jobsite which are not covered in this guide, but as you gain experience, you will begin to feel more comfortable operating in a variety of situations. It is our hope that the combination of effective training and the tools that you will learn in this guide will start you off in the right direction.

The Handbook mostly deals with what is done BEFORE and AFTER the actual data collection:

BEFORE:	decisions concerning the survey layout, depending on the surveyed structure characteristics, purpose of the survey and equipment capabilities;
AFTER:	data interpretation and decisions concerning data processing.

Utility locating is defined here as any application aimed at position or depth determination of man-made objects embedded within the earth. This includes target location of electrical, water, and gas lines. Other uses include measuring the thickness of shallow soil layers, determining depth to bedrock or water tables and locating voids that are large enough to be directly detected by a 900, 400, 270, 200, or 300/800 MHz antenna. The principal objectives are target identification and accurate measurement of its position and depth.

We assume here that you are using a GSSI UtilityScan® system with a 900, 400, 270, or 200 MHz antenna for your data collection or a GSSI UtilityScan DF® system, and RADAN® (RAdar Data ANalyzer) processing software for data processing and interpretation.

Chapter 1: Antenna Characteristics

The antenna is the crucial element of a RADAR system. It determines data quality, range resolution, maximum depth of penetration, etc. The 900, 400, 270, and 200 MHz and 300/800 MHz antennas used in UtilityScan and UtilityScan DF represent the state of the art in high-resolution, ground-based antennas. They possess the best combination of depth and resolution for ground inspection. The basic principles explained below apply to most other bi-static antennas as well. Bi-static refers to the fact that the transmitter and receiver are two separate antenna elements even though they exist within the same enclosure. This differs from a mono-static antenna in that a mono-static uses the same antenna element to transmit and receive signals.

Antenna – Ground Interaction

When you hold your antenna up in the air, it radiates energy within a very wide cone, almost a hemisphere. However, the 400 MHz and most other GPR antennas are designed to work in contact with or in close proximity to the surface of the ground. When your antenna is on the ground, the ground "pulls" in the antenna's energy and the antenna becomes *coupled* to the surface. To get the best performance, the antenna must stay within 1/10 of the wavelength from the surface – roughly *two inches* for the 900, 400 and 270. You can have a larger gap for the lower frequencies (200, and 300/800 MHz) but it is still best to keep the gap as small as practical. Increasing the air gap should be avoided because a big air gap will cause most of the RADAR energy to be reflected off of the surface rather than penetrate.

The direction of the RADAR energy as it moves into the ground is mainly determined by the surface. The signal normally moves perpendicular to the surface, independent of the antenna position. The angle that you hold the antenna over the ground doesn't matter. The energy will still enter perpendicular to the surface.

Transmitter – Receiver (T-R) Offset

The antenna housing contains two elements, one of them transmitting the signal and the other receiving the reflections. The offset (distance) between transmitter and receiver (T-R offset) will not have a great effect on UtilityScan data, but it is still a parameter to be aware of. The T-R offset in the 400 MHz antenna is 6.3" (16 cm), and it is certainly possible for you to have objects of interest located in the first 6.3" (16 cm) of soil. This value is taken into account for depth calculations in RADAN and velocity calculations with Migration (explained later). This spacing is important to know because it is equivalent to the "fuzzy" zone in your data. Targets in the top 6.3" (16 cm) may appear fuzzy in raw data, but will likely show up fine after applying filters on the unit and in post-processing. These processes are explained later in this guide.

One other concern with objects in the top 6.3" (16 cm) of the ground is that the depth may be off in raw data. When we think of depth to target, we imagine a straight line down from the bottom of the antenna. This is essentially true for targets deeper that 6.3" (16 cm), but for objects shallower than that, the RADAR signal actually has a relatively long distance to travel. Since the energy must move at an angle rather than straight down and back from the center of the antenna, it may appear slightly deeper in the raw data. RADAN corrects this issue in processing the data.

- For the 300/800 MHz DF antenna, this T-R offset is 8.5" and 2.5" (21.5 cm and 7.2 cm), respectively.
- For the 900 MHz: 4.3" (11 cm).
- For the 270 MHz: 9.4" (24 cm).
- For the 200 MHz: 13" (33.2 cm).

Figure 1 shows an antenna over a reflecting utility.

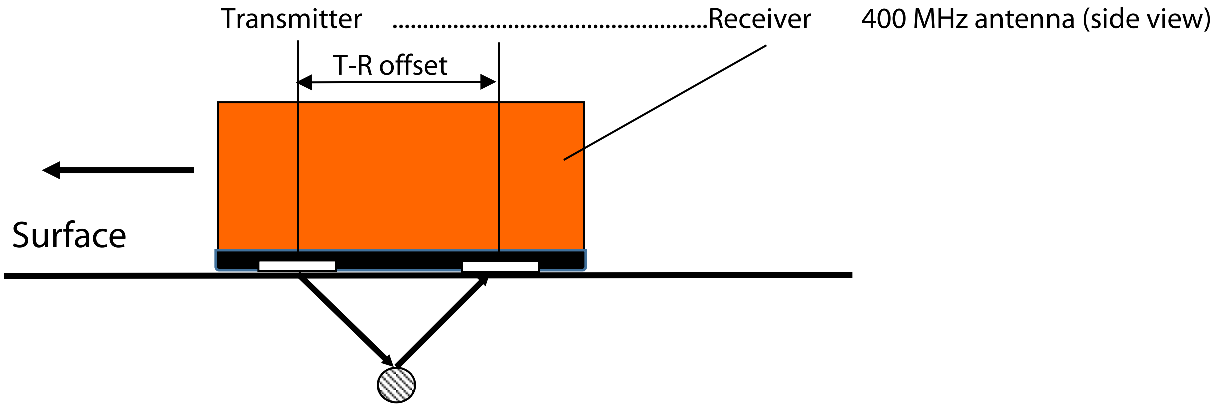


Figure 1: Antenna configuration.

Polarization Effects (Antenna Orientation)

Target Detection: When detecting linear metal targets, antenna orientation relative to the target becomes important. Antenna dipoles (transmitter and receiver) are most sensitive to the *metal* targets that are *parallel* to them. In other words, if you are scanning over a surface with the antenna in its cart in the normal orientation (Figure 1), it is sensitive to targets that are running perpendicular to the direction you are moving (parallel to the antenna dipoles).

If you turn the antenna 90 degrees in the cart (the direction of rotation doesn't matter), the antenna signal is considered cross-polarized. If you scan over a metal target that is again perpendicular to your direction of travel, the antenna is not as sensitive to it.

Cross-polarization can be done with UtilityScan antennas, but it is not recommended for this application. It can be useful in concrete and structure scanning, as those applications can have busier areas with many metal reflectors. Sometimes you are better able to see past those metal reflectors by cross-polarizing your antenna. However, in utility scanning, you are generally only searching for a few targets in a survey. You have a better chance of seeing those targets by having their antenna polarized normally

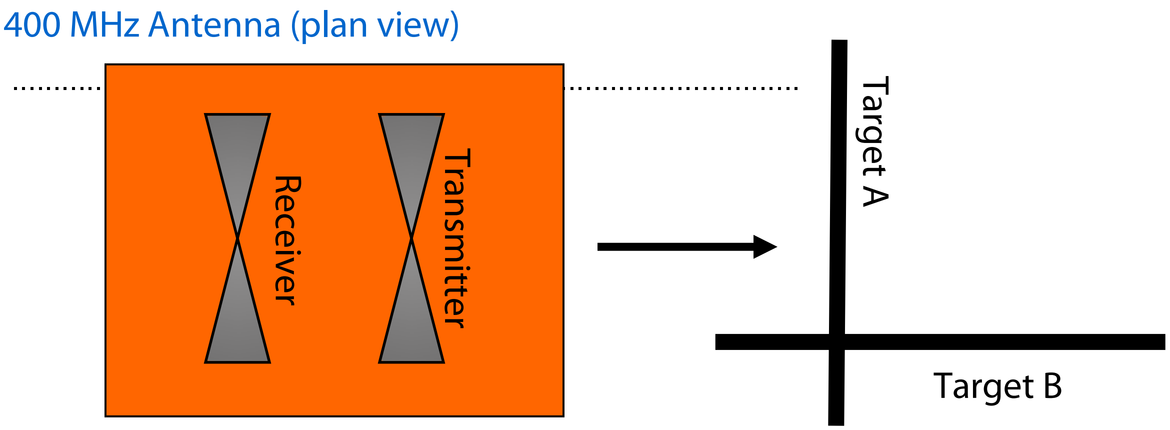


Figure 2: With this orientation, antenna is more sensitive to Target A than to Target B.

In Figure 2, the antenna is highly sensitive to Target A, which is parallel to the transmitter and receiver dipoles, and less (or minimally) sensitive to Target B. When scanning in the indicated direction, it will mostly detect objects that are roughly perpendicular to the survey line (parallel to the dipoles). This is the standard and recommended survey configuration.

Chapter 2: Understanding RADAR Data

Material Properties

RADAR energy responds to different materials in different ways. The way that it responds to each material is governed by two physical properties of the material. The first one is ***electrical conductivity***. Since GPR is EM energy, it is subject to attenuation (natural absorption) as it moves through a material. If the energy is moving through a resistive (low conductivity) material such as dry sand, ice, or dry concrete, the signal is able to penetrate a great deal of material. This is because the signal stays intact longer and is thus able to go further into the material. If a material is conductive (salt water, clay, wet concrete), the GPR energy will get absorbed before it has had the chance to go very far into the material. As a result, RADAR is suitable for inspection of any material with low electrical conductivity (concrete, sand, wood, asphalt, etc.). As a rule of thumb, the greater the water content of the material, the greater the conductivity. In a practical sense, what this means is that you will see deeper in dry, sandy soils than you will in wet clays.

The other important physical property is the ***dielectric constant.*** The dielectric contrast is a descriptive number that indicates, among other things, how fast RADAR energy travels through a material. RADAR energy will always move as quickly as possible through a material, but certain materials slow the energy more than others. If we know the dielectric of the ground, we can figure out how deep something is because the dielectric tells us how fast the GPR energy is moving. The RADAR system is measuring how long it took to get the reflection, so if you know the speed of the energy, you can multiply the two-way travel time and speed to get depth. The higher the dielectric, the slower the RADAR wave moves through the medium, and vice versa. The range of values goes from 1 (air) to 81 (water). GPR energy moves through air at almost the speed of light. It moves though water at about 1/9 the speed of light. A dielectric of 5 to 20, typical for most utility surveys, corresponds to RADAR velocities from 5.3 to 2.6 inches per nanosecond (or 13.5 to 6.6 cm per nanosecond), respectively. Wet materials will slow down the signal because the presence of the water will raise the overall dielectric of the material.

The other important reason we focus on dielectrics is that for a reflection to be produced, there must be a contrast in the dielectric value of the material that the signal is going through and the dielectric of the target. In other words, a reflection is produced at a boundary between two different materials, where the dielectric (and the signal velocity) suddenly changes. A higher dielectric contrast, or difference in dielectric between the two materials, results in a stronger reflection.

Additionally, the contrast in electrical conductivity between the material you are scanning through and the target will affect the brightness of the reflection. Metal targets show as very bright reflections because they are conductive. In addition to the reflected RADAR wave, metal targets will return a small extra signal that results from them becoming charged. Non-metal, non-conductive targets will only return the reflected energy.

Metal, even as thin as aluminum foil, is a complete reflector of RADAR energy. The reflection from it is clearly visible, but the targets behind it will not be detected. A fine wire mesh (2x2", 5x5 cm or smaller) acts like sheet metal and is impenetrable. You will not see targets beneath such a tight mesh.

The strength (brightness) of a reflection is proportional to the dielectric contrast between the two materials. The greater the contrast, the brighter the reflection (examples follow):

Table 1.

Boundary	Dielectric Constrast	Reflection Strength
Sand – Soil	Medium	Medium
Soil – Damp Sand	Low	Weak
Clay – Air	High, phase reversal	Strong
Dry Sand – Granite	None	No Reflection
Soil – Metal	High	Strong
Soil – Water	High	Strong
Soil – Empty PVC	Low to Medium, phase refersal	Weak

Reflection Polarity will tell you a great deal about the type of material a reflection comes from. They come in two forms: Positive and Negative (White and Black in the default color table). This color will be distinguished by whatever the first <u>most dominant</u> band is in your hyperbola. There will usually be a weaker band of the opposite color on top of the first <u>dominant</u> band. There will also be a strong band of the opposite color below the first <u>dominant</u> band. This “halo” effect is just an imperfection in the received signal.

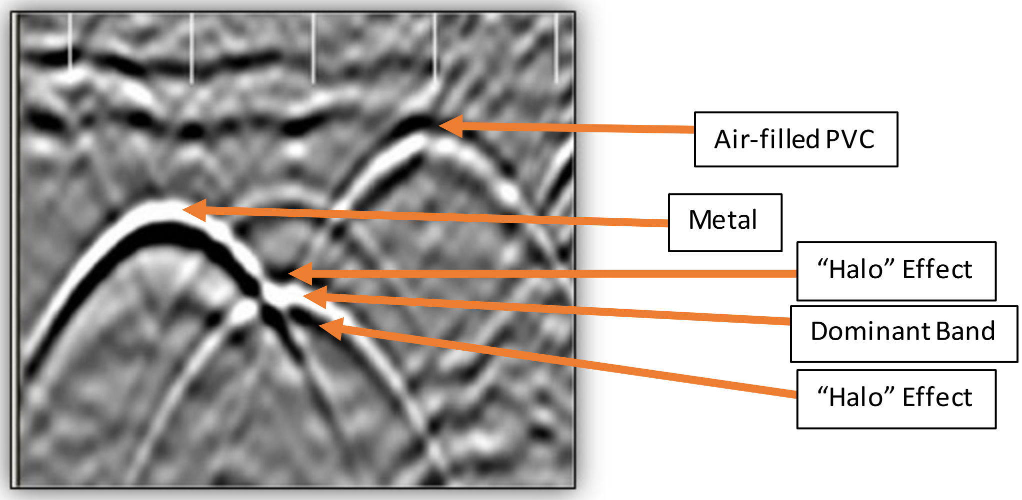


Figure 3: Metal and PVC targets. Reflection polarity.

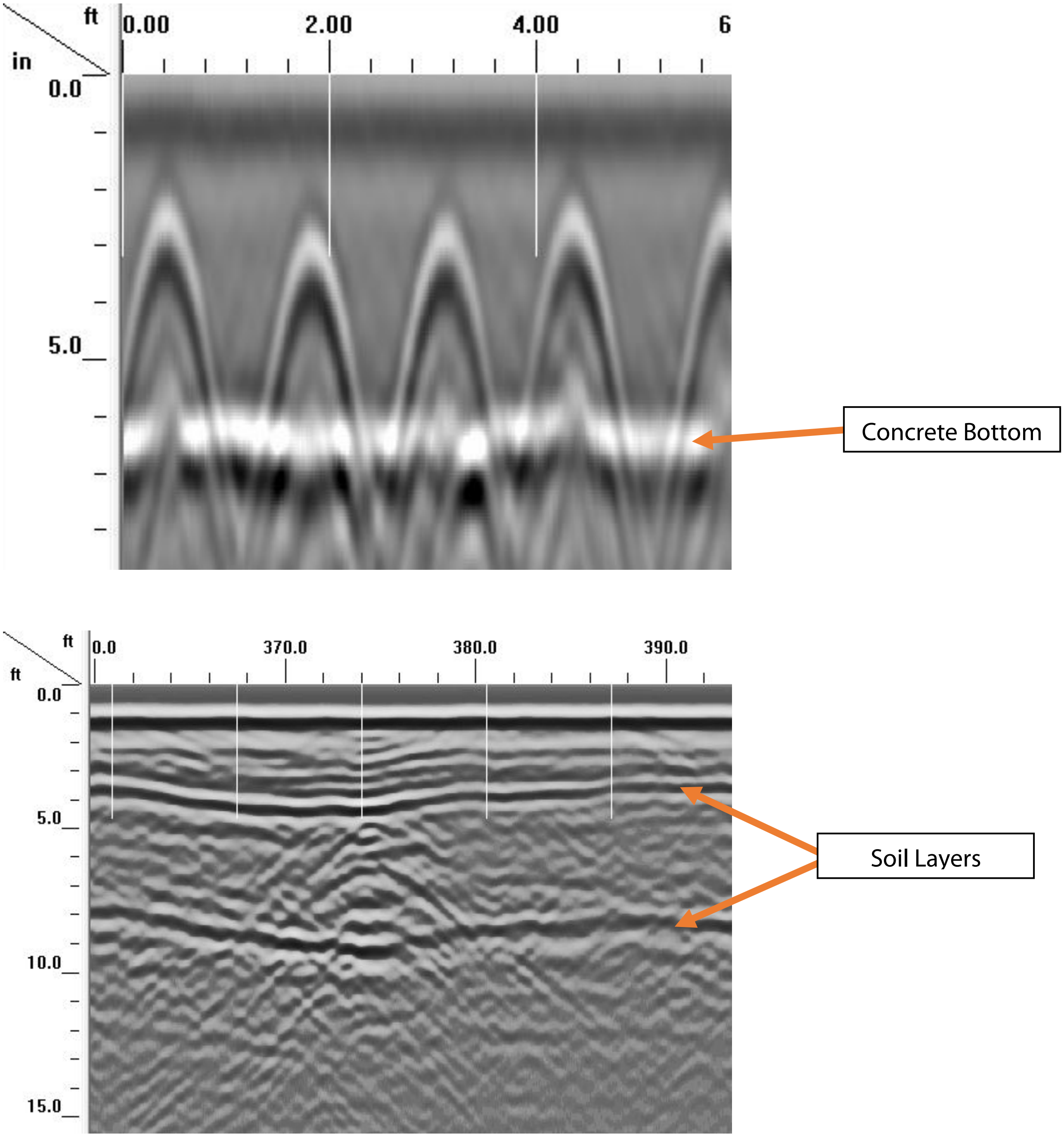
A negative reflection tells you that the RADAR wave sped up when it reached an object. Often in a utility survey this means that your hyperbola has reflected off of an air filled PVC or an air void. A RADAR wave will travel fastest through air.

A positive reflection tells you that the RADAR wave has slowed down. In a utility survey, this usually means that you received a reflection off of a metal object. This metal object could be an electrical wire, water main, gas line, etc. A single reflection won’t tell you exactly what the object is, just a general idea of what the object may be. From here, you have to bring in your own knowledge about the area.

Layer Reflection

When scanning over a continuous layer boundary (soil - clay, concrete - subgrade, etc.), the antenna repeatedly receives reflections from sections of that boundary within the antenna footprint. They form a layer reflection that resembles the reflecting boundary.

Figure 4: Layer Reflections.



Target Reflection (Hyperbola)

When the antenna crosses a pipe-like target at a right angle, the resulting image looks like an inverted U or V – a *hyperbola* is the descriptive term for its shape (note them in Figure 3). This happens because the radiated antenna beam has the shape of a wide cone, thus the RADAR can see the target not only when on top of it, but also in several scans before and after that position. The hyperbola shape reveals the antenna approaching the target and then going away from it. Its summit is exactly where the target is located. The groove/painted line at midpoint between transmitter and receiver on the 900, 400, 270, 200, and 300/800 MHz antenna housings indicate the target position (see Figure 5). Some carts that house each antenna also have markings which indicate the target position. Hyperbolic reflections may sometimes seem a nuisance, but in fact they help the analyst by making even small targets readily visible.

The shape of a hyperbola depends on two parameters:

- **Scan Density:** smaller scan density (more scans per foot/m) produces wider hyperbolas;
- **RADAR wave velocity:** higher velocity (lower dielectric) produces wider hyperbolas and vice versa.

Scan density is controlled by the operator, so it is known from the survey data. This allows the velocity to be derived from the shape of a hyperbola using the Migration function in the RADAN post-processing software and on the SIR®-4000 and DF tablet. This will be discussed in detail later, along with other methods of determining velocity (see Depth Measurement).

The brightness (amplitude) of a single hyperbolic reflection follows the same rules as the examples given in Table 1. Metal objects produce strong clear reflections. In contrast, a PVC pipe reflection will have the same shape, but with a much lower amplitude. Therefore its image will be weaker (dimmer). You can see this in Figure 3.

Remember: A reflection always comes from the very top of the target.

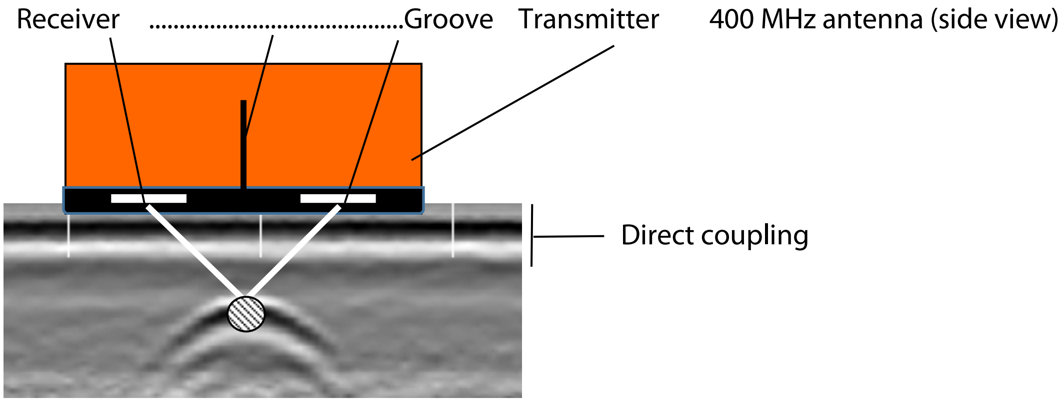


Figure 5: Locating a target.

The shape of a hyperbola does not change significantly with target size for any diameter less than the spacing between the transmitting and receiving elements – all such targets are point-like for the RADAR. This means that any targets under 6.3" (16 cm) in diameter will produce hyperbolas of the same size and shape with a 400 MHz antenna. Relative sizing is possible for targets of a diameter greater than 6.3" (16 cm) as long as they are located the same depth, are crossed at the same orientation, and are surrounded by the same material.

- For the 300/800 MHz DF antenna, this T-R offset is 8.5” and 2.5” (21.5 cm and 7.2 cm), respectively.
- For the 900 MHz: 4.3” (11 cm).
- For the 270 MHz: 9.4” (24 cm).
- For the 200 MHz: 13” (33.2 cm).

Composite targets like a PVC conduit with electric wires inside can produce hyperbolic reflections that do not always have the perfect shape of the hyperbola from a round pipe or rod. There are several reflections within each of them which results in a somewhat distorted hyperbola.

A hyperbola may also appear distorted or incomplete when the survey line crosses the target diagonally. As the survey line direction becomes nearly parallel to the linear target, the reflection appears as a slightly curved line. If the antenna moves parallel to it, the target looks like a continuous layer. The best way to verify its nature and to locate it is to scan in the transverse direction (across the suspected target) to see if a hyperbolic reflection appears. The polarization issues discussed above have to be taken into account.

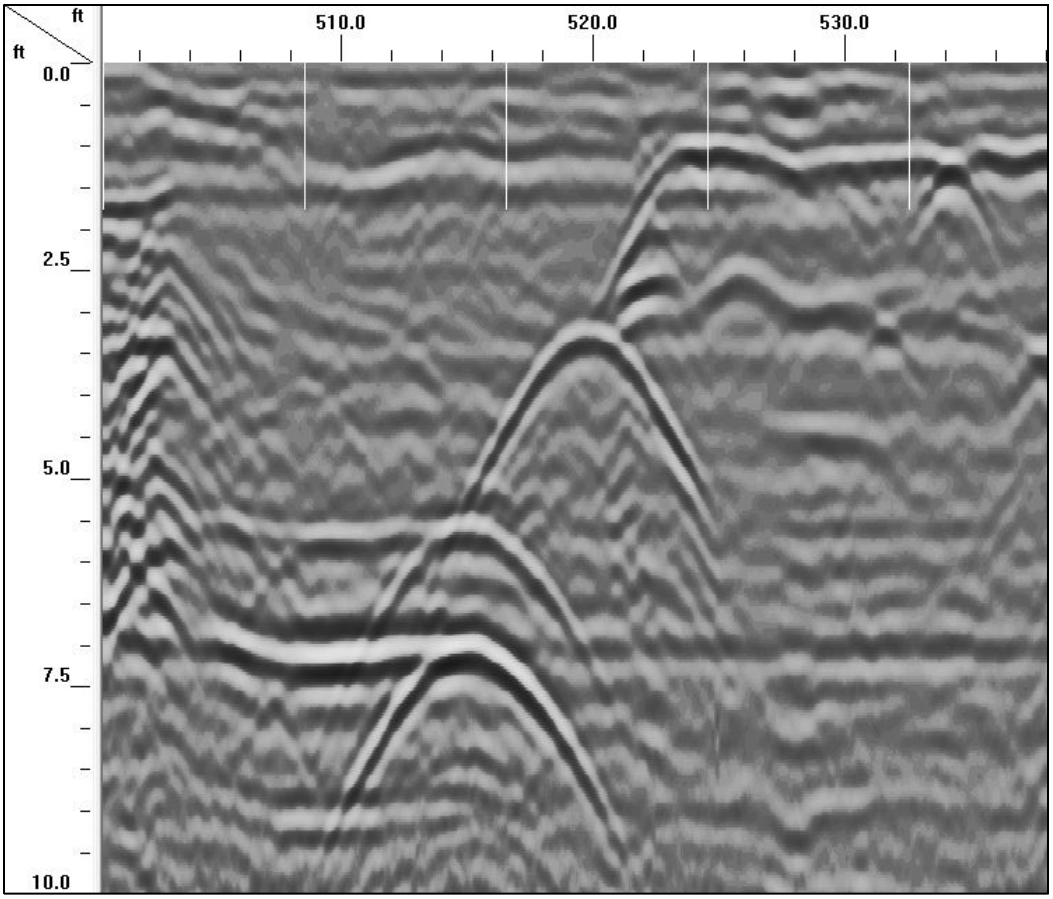


Figure 6: Hyperbolic reflections. Note the bottom two – the layer reflection coming off of the left of the peak is due to the fact that both pipes are bent at 90 degrees. The layer reflection is from running parallel, and the hyperbola is from running perpendicular over the pipe after it bends.

Target Detection Accuracy

Horizontal Accuracy and Resolution

The accuracy with which we can locate a target depends on the antenna pattern and scan density. If the antenna were radiating a narrow vertical beam, we would see a small dot-like image of the target right where it is located. Instead, it radiates in a cone, the angle of which varies with the dielectric of the soil/sediment. The antenna starts sensing the target when approaching it, continues to receive reflections as it passes over and for some distance past the target. The range between antenna and target changes as it moves, which explains the hyperbolic shape of the reflection.

The target is located at the peak of the hyperbola (see Figure 5). Thus it is critical how accurately the hyperbola summit can be located. The positioning accuracy is approximately equal to the scan density, but does not get finer than 1” (2.5 cm) under any conditions.

Note: Use bright paint or tape to highlight the antenna center position on the antenna or survey wheel housing.

Lateral (spatial) resolution, or the ability of the antenna to see two closely spaced targets separately, is determined by the wavelength. The wavelength of the 400 MHz antenna in average soil (dielectric of 10) is 9.3” (23.7 cm). For the 900 MHz, this is 4.1” (10.5 cm). For the 270 MHz, this is 13.8”, (35 cm). For the 200 MHz, this is 18.6” (47.4 cm). For the 300/800 MHz, this is 12.4/4.7” (31.6/11.9 cm). In most cases, two targets at the same depth with a lateral separation of less than 4-5" (10-13 cm) appear as one object.

The ability of the signal to pass through a mesh of conductive material is a related issue. As a rule of thumb, RADAR signal will penetrate a metal mesh with a spacing larger than the wavelength – say, through a 6" (15 cm) wire mesh with a 900 MHz. A fine metal mesh (spacing 2-3" or 5-7.5 cm) may appear as a reflecting layer and may completely disguise targets beneath it.

Range (Depth) Accuracy and Resolution

UtilityScan and UtilityScan DF are capable of measuring depth to a target in ½” (12 mm) increments – this is its absolute accuracy. The resulting depth readout will be accurate to 1” (2.5 cm or 5% of the depth, whichever is greater) if a depth calibration procedure has been correctly performed prior to the measurement AND the material through which you are scanning is homogenous in terms of dielectric. When an assumed Soil Type is used, the measured depth can be off by as much as 20%. Always exercise care when assuming depth to target as many factors can affect the accuracy.

Vertically, a distance of ¼ of the wavelength between two targets is sufficient to see them separately which yields a range resolution of approximately 2.5” (6.4 cm) with a 400 MHz. The deeper target can still be invisible if it is directly beneath the top target or in close proximity (less than 1" or 2.5 cm horizontal separation).

In short, a target located beneath another target may or may not be seen, depending on its position relative to the top target and properties of the subsurface. Never promise seeing two parallel utility lines before you actually see the data.

Feature Identification

Surface Reflection

The very first signal in a scan is often called “direct coupling” between the transmitter and receiver. It is used to identify the surface position in a scan. With the UtilityScan and UtilityScan DF antennas, the surface is located at the first positive (white) peak within the direct coupling (see Figure 7).

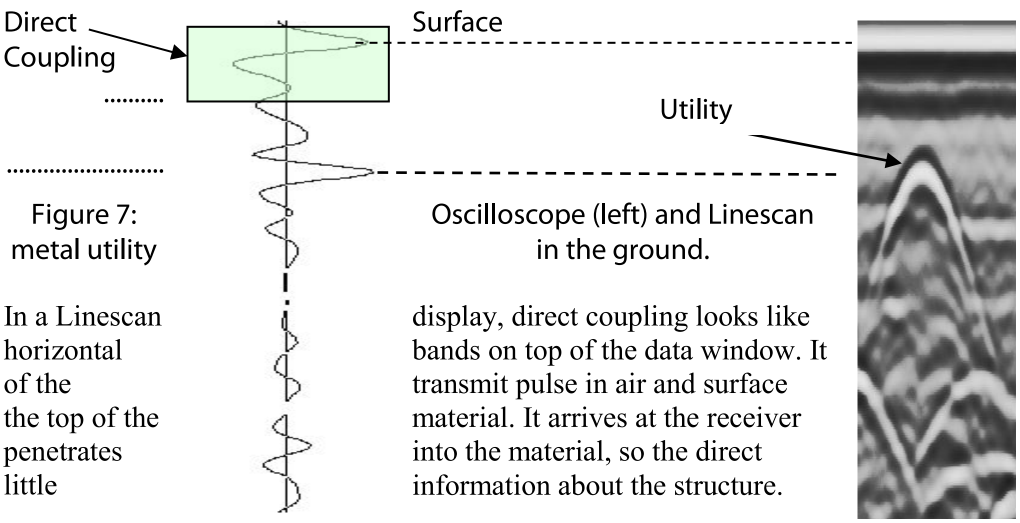


Figure 7: Oscilloscope (left) and Linescan displays of a metal utility in the ground.

In a Linescan display, direct coupling looks like straight horizontal bands on top of the data window. It is a combination of the transmit pulse in air and surface reflection from the top of the material. It arrives at the receiver before the signal penetrates into the material, so the direct coupling carries little information about the structure. Yet its amplitude depends on the dielectric of the material (see below). Variations in amplitude may indicate change in properties (increased moisture, for instance).

Direct coupling disguises the beginning of the scan. Making it as short as possible is a major design goal. The 400 MHz antenna has an extremely short direct coupling that allows it to detect targets from 1.5" (3.75 cm) below surface. Targets within the first 1.5" from the surface may indicate their presence by changing the appearance of the direct coupling, but their position and depth cannot always be accurately determined. This depth is roughly the same in the additional UtilityScan and UtilityScan DF antennas.

The negative peak (a straight horizontal black line in the Linescan display) immediately below the surface is a part of the direct coupling. The first positive peak doesn’t show any visible variations, though its amplitude may vary along the profile. Some variations may be seen within the negative peak. They usually indicate changes in subsurface properties within the top inch of material, though their accurate interpretation is difficult.

Common Metal Targets: Pipes and Utility Lines

Pipes and utility lines are the most common metal targets in a utility survey. Lines that are oriented perpendicular to the survey line will produce clean and strong hyperbolas. The strength (amplitude) of a metal reflection increases with pipe size. On the other hand, it decreases with depth and/or presence of corrosion. It will also decrease when surrounded by material with a high dielectric constant. Pipe size can be estimated from reflection strength on a comparative basis, but cannot be accurately measured. This means if two pipes are located at exactly the same depth and in exactly the same material, and one is brighter than the other, the brighter one may be larger. How much larger is impossible to determine.

A steel pipe (conduit, for instance) looks exactly the same as a steel rod of the same diameter. The RADAR signal does not penetrate metal, so there is no difference between reflections from a solid rod or a hollow metallic pipe. A large diameter conduit, duct or pipe (over 2" or 5 cm) will have a noticeable horizontal size in the profile, but it is still unwise to attempt to find the size of the target from your RADAR data.

Making the distinction between one line and another usually requires outside information about the area. They must ask where it would make sense to see one utility over another. Using above ground objects (water and gas valves, manhole covers, etc.) and the knowledge of the history of a survey area will make interpretations more accurate.

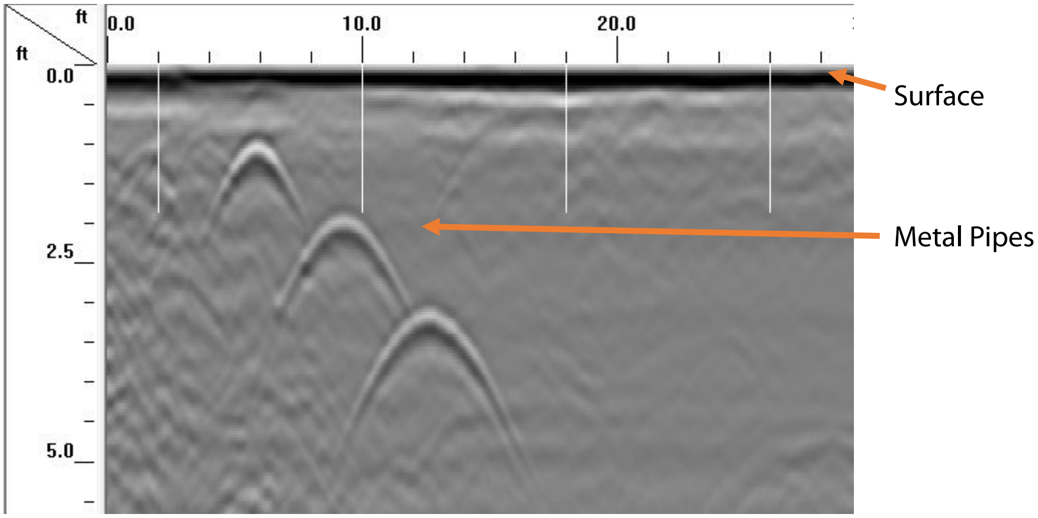


Figure 8: Three metal targets of the same diameter.
Note how the deeper the target is, the larger the hyperbola is.

PVC Targets

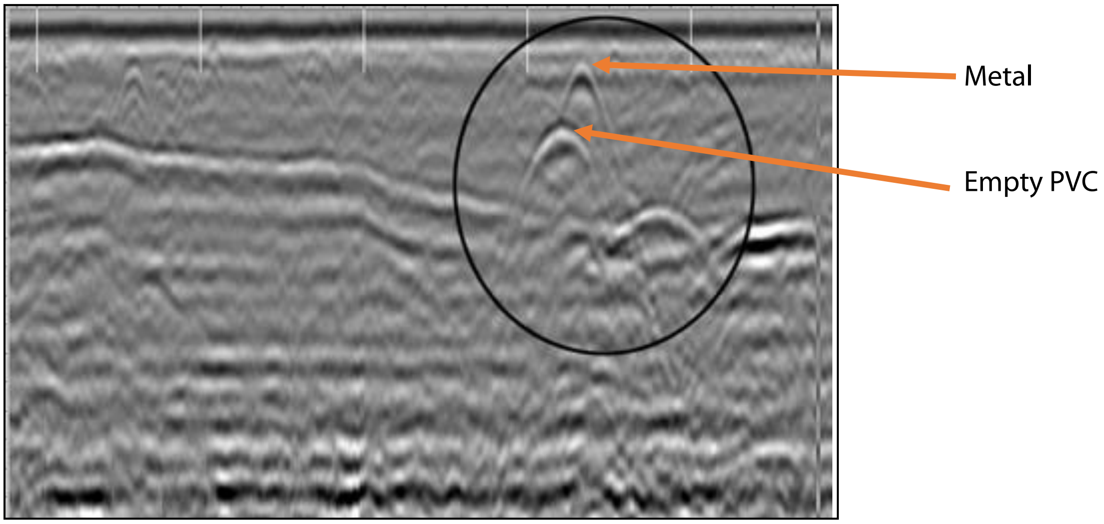


Figure 9: A metal and PVC pipe.

A PVC pipe or non-metallic conduit in soil produces low-amplitude hyperbolas of the same shape as hyperbolas from metal targets. PVC is nearly transparent for RADAR, so targets inside or underneath a PVC pipe can still be visible. This means that we do not directly detect the PVC, we detect whatever is inside of the PVC.

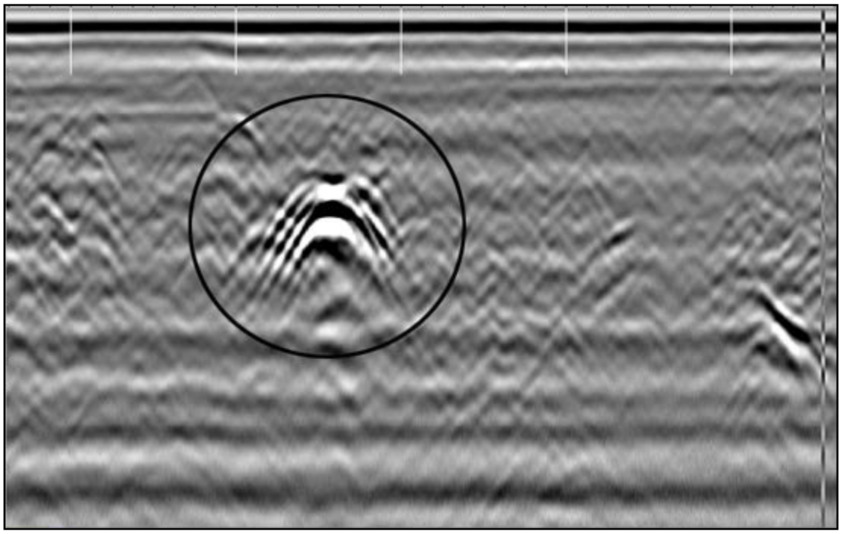


Figure 10: A bank of conduits feeding into an industrial building. Note the dipping edge of a trench cut to the upper left of the conduits.

A PVC conduit with several wires inside can have a distinct appearance of several hyperbolas “mixed” together. It looks like a “broken up” hyperbola that doesn’t have the regular shape of the reflection from a single bar or pipe.

Voids and Fractures

Voids in concrete or under soil layers, either air or water filled, are high-contrast targets. However, even an easy target - a planar fracture parallel to the surface - would have to be at least 1" or 2.5 cm thick to produce a reflection. Thinner fractures in most cases cannot be detected directly. Thin vertical or near-vertical fractures are also not detected.

An air filled void will be a strong reflection, but will show as a strong negative (black) reflection. This is because the RADAR energy is moving into a material with a lower dielectric than the surrounding material and therefore speeds up. Air has a dielectric of 1.

If the void is water filled, the reflection will still be strong but it will be a positive (white) reflection. This is because the RADAR energy moved into a material with a higher dielectric value and therefore slows down. Water has a dielectric of 81.

A large void typically looks like a strong reflection with no definite shape. An example of a void in concrete is shown in Figure 11.

Water culverts and tunnels may appear similar to PVC targets if they are empty (air-filled). They will simply appear much larger than your average PVC pipe.

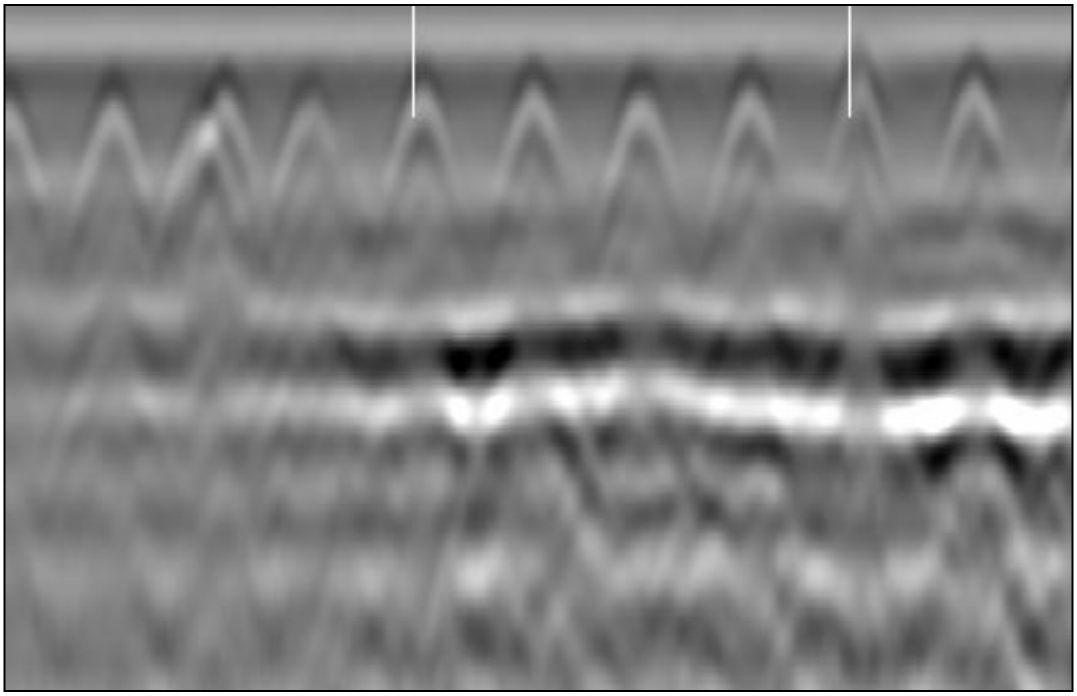


Figure 11: Example of void in concrete.

Noise & Interference

It is important to be able to tell real reflections from noise or interference. Noise is any unwanted signal generated within the system; interference is a signal originating from a target or some external source, but appearing away from it in the data (for example, crossing hyperbola tails). RADAR clutter, the mix of reflections from numerous targets, can be sometimes considered noise as well. Typical examples are:

- Horizontal ringing bands in the linescan display.
- Multiple reflections from layers.
- Hyperbola tails extending far from the target and overlapping with tails from adjacent hyperbolas.
- Ringing from metal directly on or close to the surface.
- Cell phone or two-way radio static.

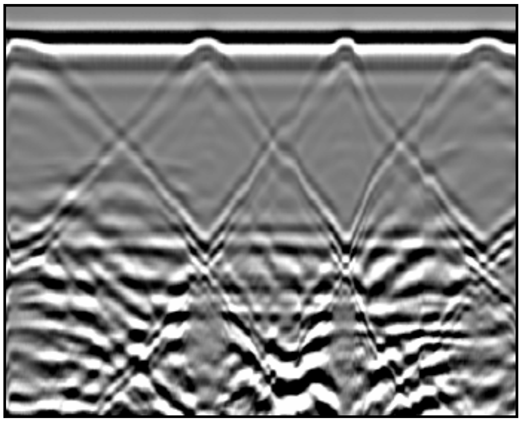


Figure 12: Interference patterns in RADAR data collected on a hollow wall with steel studs.

Figure 12 shows a spectacular display of interference. The antenna was moved across a thick hollow wall of a high-rise building. Inside the wall, large steel studs created a zig-zag pattern of side reflections. The studs themselves are perpendicular to the wall surface and are only visible by their side reflections. Behind the wall, reflections from various targets in air create clutter that cannot be interpreted.

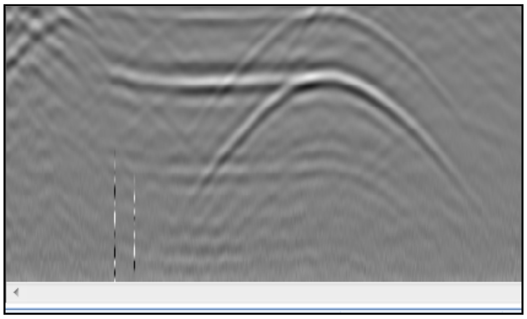


Figure 13: Cell Phone Interference.

Figure 13 displays the most common form of interference in RADAR data. Cell phone interference usually displays as a distinct line originating from the bottom of a linescan and vanishing as it approaches the top. To prevent this from occurring, it is best to either leave one’s cell phone off or in airplane mode, or have all cellular devices at least 10 ft (3 m) from the survey area. When performing a survey near a cell tower, it's best to try and stay 50-100 feet (15-30 m) away. Because different call towers may emit at different rates, this number could be greater or smaller. Two-way radios will produce noise similar to that of a cell phone, but on a greater scale. Instead of one distinct line, it will appear more as a large chunk of lines, similar to static. The same rules apply here: to limit the amount of noise created, either turn the device off or try to remain as far away from it as possible.

Penetration Depth

Attenuation causes the signal strength to fall off with depth. At a certain depth, the maximum reflection amplitude decreases to the level of system noise and becomes undetectable. From this level down, data contains no usable signal. This level is referred to as *maximum penetration depth,* or *noise floor*.

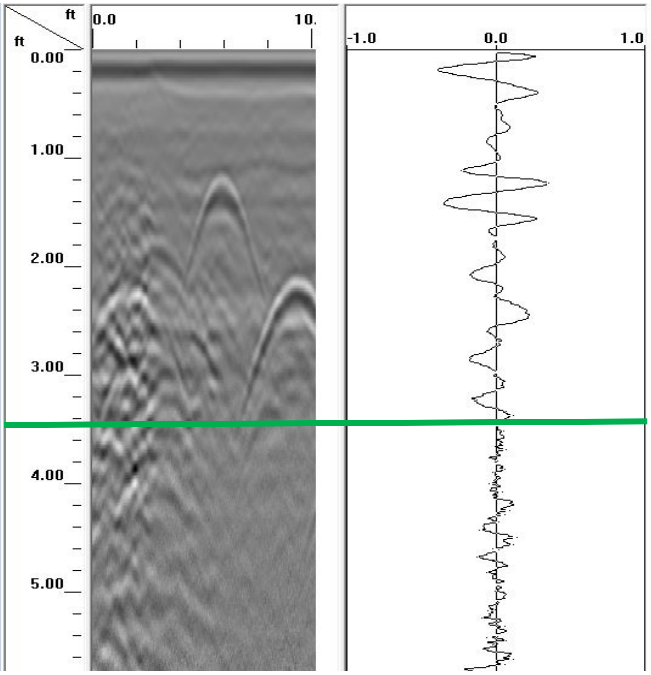


Figure 14: Linescan and O-scope of the same profile showing the penetration depth (green).

In the oscilloscope display during setup, this is the depth where the signal becomes jittery and moves randomly when antenna is not moving. In the Linescan display, it corresponds to a textural change below which reflections are no longer visible and only snow-like high frequency noise as well as horizontal ringing bands are seen.

- The normal penetration depth for a 900 MHz is 30" or 76 cm.
- For 400 MHz, this is 8 ft or 2.5 m.
- For 270 MHz, this is 12 ft or 3.5 m.
- For 200 MHz, this is 25 ft or 7.5 m.
- For the 300/800 MHz DF, this is 10 ft or 3 m.
- In very conductive materials, like wet clay, it can be reduced to 4 ft (1.2 m) or less with a 400 MHz antenna. However, in low dielectric and low conductivity materials, like dry sand, it can be increased to 15 ft (4.5 m) with a 400 MHz antenna. Therefore, penetration depth is dependent upon the material type.

Survey Grid Layout

Line Direction and Spacing

The position and number of survey lines on a particular structure depends on the purpose of the survey, structure type and size, operator's experience and some other factors. Surveys vary from a single line intended to locate a conduit or cable, to a dense 50 x 50 ft (15 x 15 m) grid for 3D viewing of a busy area.

The general guidelines are as follows:

- Plan survey lines so they cross perpendicularly to the features you intend to detect.
- A line spacing of 2 ft (30 cm) is required for complete coverage with most UtilityScan antennas. This is the maximum practicable survey density that may be used for a detailed 3D mapping.
- Linear targets that cross the survey lines at an angle of 45 to 90 degrees, will be resolved with good accuracy. A complete survey of the area requires a survey in two perpendicular directions unless all targets are known to run parallel to one another.

It may be useful to do a couple of preliminary scans to determine the position of some targets. Mark them on the surface and then lay out the grid accordingly.

Position (Distance) Control

The antenna position along each survey line (distance scale) is controlled either with a survey wheel or by manual marking. The survey wheel has an encoder that sends a fixed number of pulses per revolution to the control unit. The control unit then uses these pulses to trigger the antenna at equal distance intervals (scan density). In UtilityScan and UtilityScan DF, these intervals are dependent on the scans per unit setting selected by the operator.

The survey wheel is the recommended method of distance control. When a survey wheel is not available or cannot be used for some reason, the only way of maintaining high resolution distance control is to mark the surface at even intervals (or use existing visible marks such as tile edges) and then enter user marks at these locations. The scan density will vary along the line and will have to be corrected using Distance Normalization in the RADAN post-processing software. To do this, you need to know the exact distance between markers. A GPS may be used for location control but the data will still need to be distance normalized in order to be displayed in most 3D applications.

Scan Density

The scan density determines how detailed the survey will be along lines. Figure 15 shows the same utility line surveyed with different scan density settings. In UtilityScan, 12 scans/foot (40 scans/meter) must be collected in order to resolve small targets and maintain data integrity. It is always a good idea to collect more scans. The default setting is 18 scans/foot or 60 scans/meter.

Small utilities and voids may require up to 24 scans/foot or 80 scans/meter.

A smaller scan density (more scans per unit) slows down the survey, so the rule of thumb is to collect as many scans as possible while maintaining an acceptable survey speed. The scans/foot and scans/meter settings and corresponding images for a 1" (2.5 cm) wire mesh are shown in Figure 15 below.

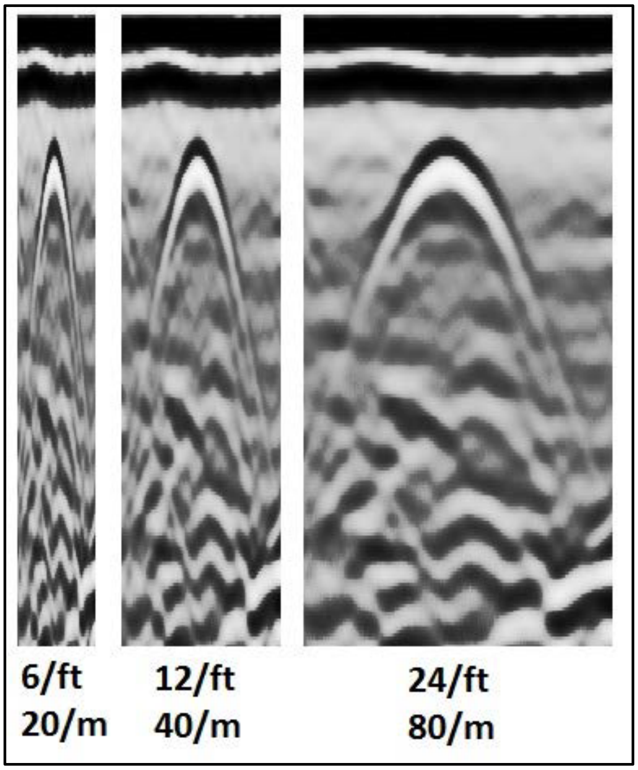


Figure 15: Scan density effects.

Survey Wheel Accuracy

Under optimal conditions (smooth surface, proper calibration, no slippage) survey wheel distance error does not exceed ±1% (±1 ft or 30 cm over a 100 ft or 30 m distance). If a better accuracy is desired, we recommend inserting a user mark at the end of the measured survey line. In RADAN, there are two ways of correcting the distance scale using the start and end marks:

- If the exact scan density does not matter - adjust the scan/unit parameter in the file header so the indicated distance between the marks equals the true distance. Survey wheel accuracy decreases on a rough or dirty surface.
- If a certain scan density should be kept, you will need to use the Distance Normalization procedure using the exact Start - End mark distance and the desired Scan/Unit value. This procedure requires the RADAN software. See the RADAN manual for instructions on this procedure.

Manual Marking

Surveying without a survey wheel is not recommended. However, user markers (vertical dashed lines in the data) help to establish a distance scale when using a survey wheel is impossible or impractical. They can be entered by clicking the marker button on the control unit. Distance Normalization based on properly entered user markers can render a distance scale with an average accuracy as good as the one obtained with a survey wheel. However, individual scan density may be different which causes uncontrolled local position errors.

Mark the surface with chalk or paint at equal intervals prior to surveying. The mark spacing (distance units per mark) should be 10 times the acceptable error or smaller. For example, if 2 inch (5 cm) accuracy is sought, marks should be entered a maximum of every 2 feet (60 cm), while a 10 ft or 10 m mark spacing is sufficient to provide a 1 ft or 1 m accuracy. User markers are entered each time the antenna center crosses a regularly spaced point painted on the ground or on a tape measure.

When surveying without a survey wheel, the operator should move the antenna at a steady speed, avoiding stops and jerks. Also, the scan density depends on the antenna speed and no warning is given if the antenna moves too fast. The optimal speed should be calculated from the desired scan density and known system scan rate:

Speed (ft/sec) = (Scan Density) x (Scan Rate)

A few test lines should be taken to determine optimal speed from the visual appearance of the data (Figure 15).

Depth Scale Calibration

Surface Identification: Accurate surface identification is the first step to a correct depth scale. The control unit (SIR 3000/4000 or DF Tablet) will automatically identify the surface. However, data taken from the SIR 3000 and opened in RADAN will need to have the ground surface re-identified. The time (and depth) scale starts at an arbitrary time-zero, usually above the true surface. This has to be taken into consideration and corrected with a time-zero correction. Please see the RADAN manual for details.

In RADAN and RADAN for UtilityScan DF, this process can be done automatically for data collected with the SIR 4000 and DF antenna. Because data with these control units are collected in a 32 bit format, RADAN is able to perform some pre-processing on your data file once it is opened. RADAN will automatically locate the surface and set time-zero in the data after it is opened in the software, along with a number of other processing steps. Additionally, the SIR 3000/4000 automatically locates the surface and places it at the top of the screen while collecting data. You can manipulate this feature under the Collect > Position menu in the SIR 3000 or the RADAR > Position menu in the SIR 4000. See the SIR 3000/4000 User Manual for details.

Once time-zero (and depth) is set at the surface, depth to a target in utility surveys can be determined using dielectric tables, ground truth (known target depth) or hyperbola shape analysis (migration in RADAN).

Using a Soil Type

This is the simplest, but least accurate method of depth calibration. By selecting a table value, a depth scale that is accurate to within 20% is normally obtained. Because soils and soil types are so varied, it's best to utilize an online database first, such as Web Soil Survey, to determine what the average soil type is in a survey area. After a soil type is known, a more accurate table value can be used. Be careful, because there is no way of assessing how accurate the result is unless another method is used.

Using Ground Truth

Ground truth, or known target depth, is the best way to calibrate the depth scale. Any feature identified in the data can be used if its depth is known from an independent source (like digging to it). Digging is in most cases the only way to measure the exact depth to a particular target.

Once a depth measurement is obtained, the signal velocity and dielectric can be calculated using the two-way travel time (2WTT) from the RADAR data. This can always be done manually (Velocity = 2 x (Depth/ 2WTT), but UtilityScan has an automated Depth Calibration feature that performs the calculations and adjusts the depth scale (soil type will be shown as CUSTOM on the SIR 3000). If several layers are present between the surface and the measured target, the calculated velocity or dielectric is the average of these layers at the calibration point. If the thickness ratio for these layers changes in the profile, the average velocity is no longer accurate.

See your control unit manual (SIR 3000/4000 or DF Tablet) for instructions on this procedure.

A spot calibration can be applied to the entire survey area if it contains roughly the same soil. It is up to the analyst to decide how representative the value is.

The 2D Interactive module of RADAN has an advanced capability of calculating velocities for different layers and sections of the data using multiple known features (targets or layers). These values can be applied to user-selected sections at the operator's discretion. Please see the RADAN manual for details.

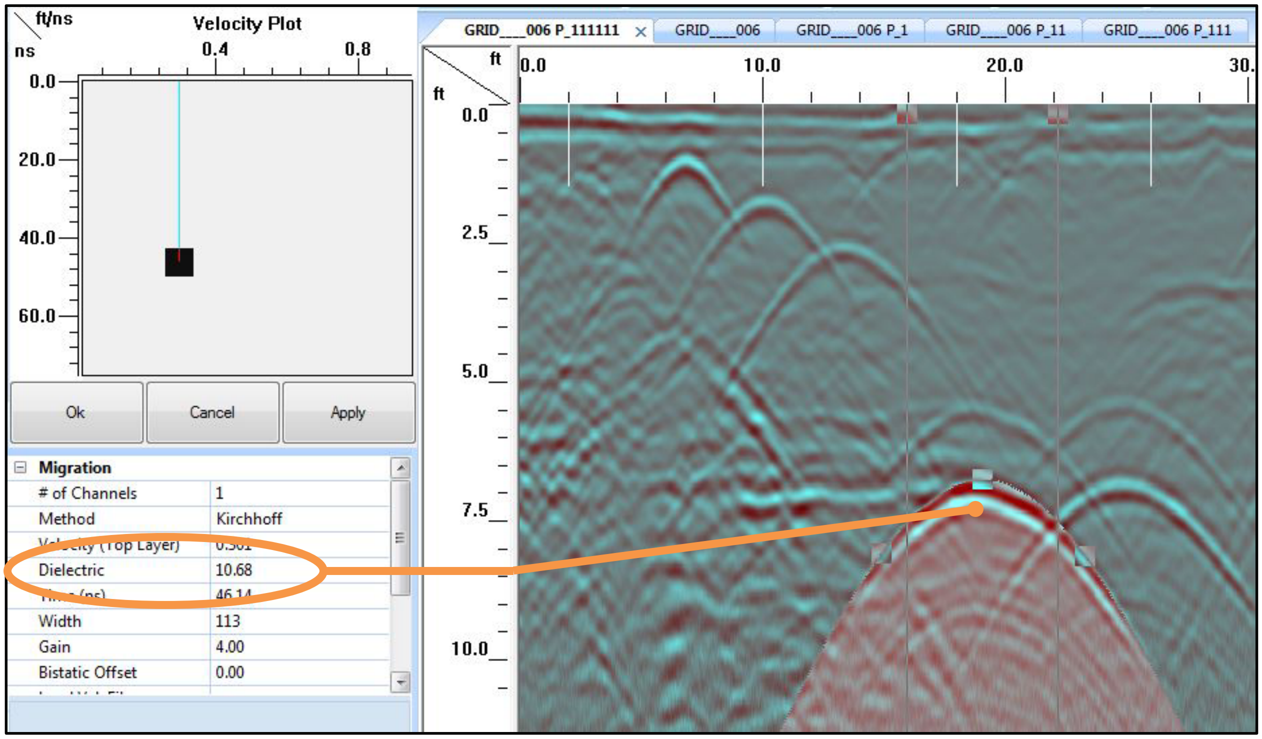
Using Hyperbolic Shape Analysis (Migration)

The RADAR wave velocity in the medium between the surface and the target determines the shape of a hyperbolic reflection. In materials with a high velocity (low dielectric), hyperbolas are wide. A low velocity (high dielectric) results in narrow hyperbolas.

A quick, automated velocity measurement using this principle can be done on the SIR 3000/4000, the UtilityScan DF, and in post-processing.

In post-processing, we make use of the Migration function.

The Migration function in RADAN calculates the signal velocity in the medium from the shape of hyperbolic reflections. To measure velocity, match the shaded hyperbolic overlay to a hyperbola in the data. The calculated velocity and corresponding dielectric will be immediately displayed in their respective boxes to the left. **Note:** Migration is only accurate if you scan perpendicularly across the target.



Migration	
# of Channels	1
Method	Kirchhoff
Velocity (Top Layer)	0.301
Dielectric	10.68
Time (ns)	46.14
Width	113
Gain	4.00
Bistatic Offset	0.00

Figure 16: Velocity measurement in Migration.

This is an accurate method that does not require the user to know the target depth. The only requirement is that the scan density must be known and correctly entered into the file header (done automatically if a survey wheel is used).

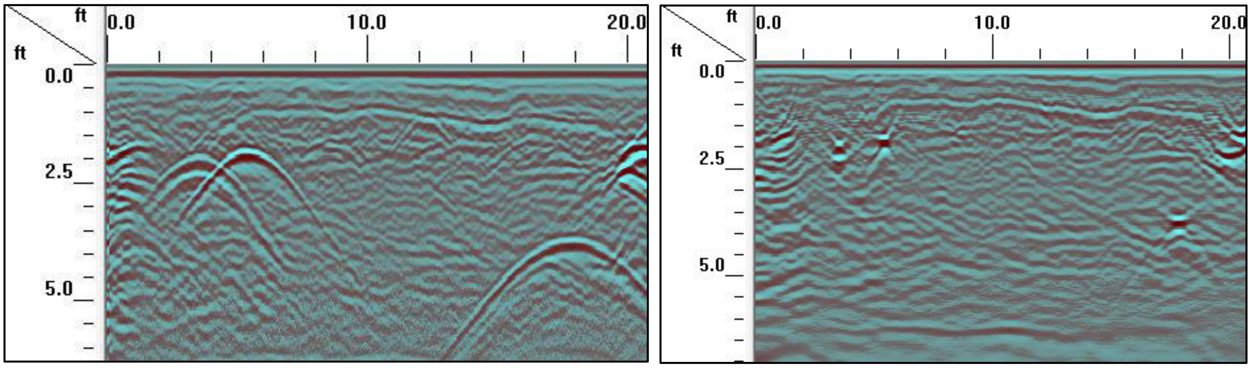


Figure 17: Raw and migrated data.

Migration eliminates hyperbolas by collapsing them into dots representing the actual targets. This can be helpful to make target identification more intuitive. Migration can reduce clutter in the image and make it easier to interpret. This is especially true for 3D representation of RADAR data – data with hyperbolic reflections needs to be migrated in order to achieve a quality 3D display.

In single profiles, there is a risk of missing weak targets after migration, so a migrated profile should be analyzed along with the raw image. In 3D display, it is no longer a problem as even a weak, but continuous linear target is readily visible.

Keep in mind that this process assumes a single velocity and applies that velocity to the entire 2D profile or 3D grid. RADAR waves tend to travel at different speeds throughout a soil, as soils tend to be inhomogeneous. A variable velocity migration may produce a more accurate image of your GPR data (Figure 18). A migration can be performed with multiple targets until it provides an accurate representation of the RADAR wave speed (and thus, the changes in a material's dielectric) over the course of your survey. Please refer to the RADAN manual for details.

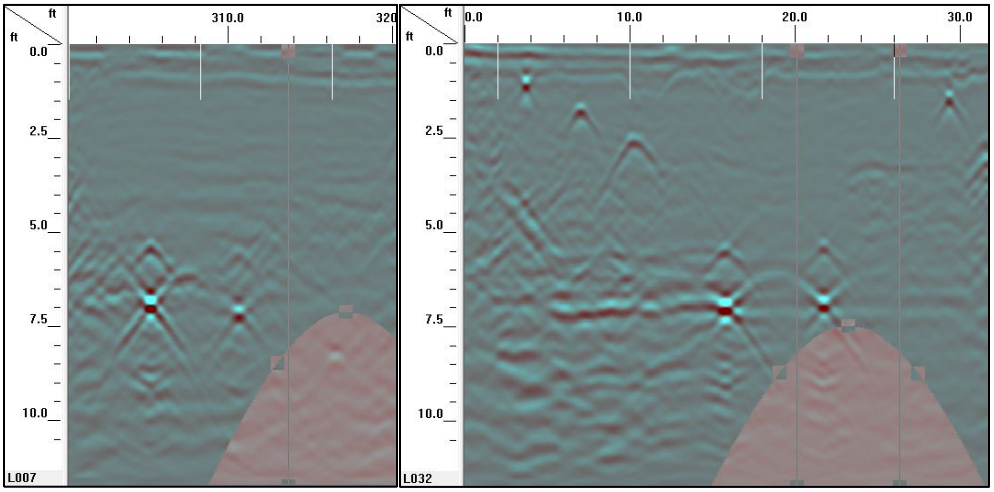


Figure 18: Variable Velocity Migration. A single successful migration on the left, and an unsuccessful single migration on the right. The right image would require a variable migration to process correctly.

In the SIR 3000, Migration is not performed as a visual enhancement. Rather, it is performed as a hyperbolic shape analysis process in order to better determine a material’s dielectric constant. This process is known as the “Test Dielectric” process in the SIR 3000 set-up screen. It is only recommended to use this for concrete surveys as concrete is more homogenous than soil. Please see the SIR 3000 manual for details.

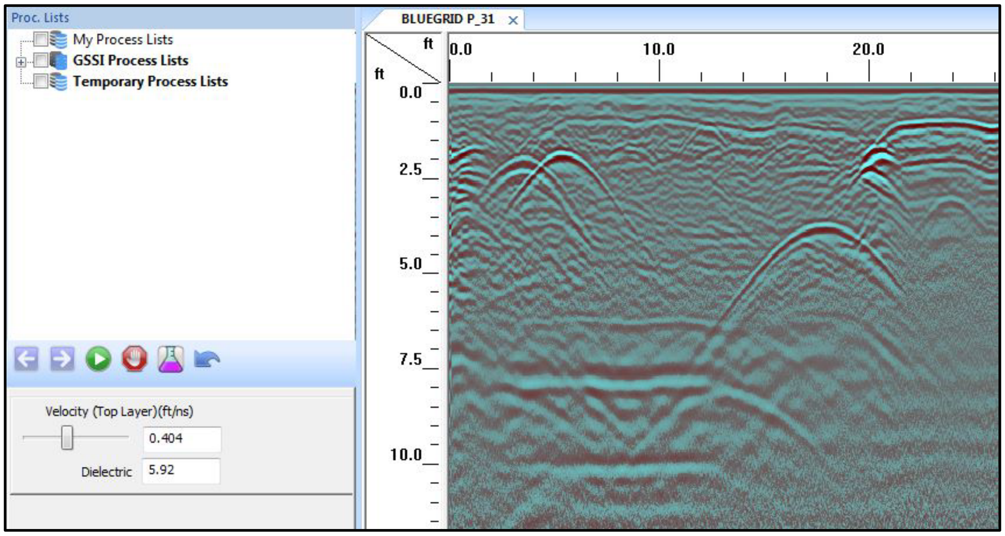
In the SIR 4000, Migration is performed as both a visual enhancement as well as a process in order to better determine a material’s dielectric constant. This process is known as “Focus On/Off” and “Show Hyperbola” in the SIR 4000 collect screen. Please see the SIR 4000 manual for details.

In the UtilityScan DF, Migration is performed as both a visual enhancement as well as a process in order to better determine a material’s dielectric constant.

The visual enhancement exists in the Scan sub-menu under “Filters”. If the user sets the Migration filter on, there will be an option to scroll the filter over your collected data to view it in a “focused” or migrated format. This filter can also be used to better determine a material’s dielectric constant.

Another option to determine the dielectric constant is to make use of the Focus feature. This process can be performed after collecting some data by positioning both the vertical and horizontal cursors over a target and pressing the Focus button along the bottom. Please refer to the UtilityScan DF Quick-Start Guide for details.

In post-processing with RADAN for UtilityScan DF, Migration can still be performed. The Migration process is shown as “Focus” and works by moving a scroll bar left and right to fine-tune the dielectric. Making use of the purple flask button (the test button) will show the user how close to the correct value they are, and pressing the green play button will apply the value (Figure 19). Please refer to the RADAN for UtilityScan DF manual for details.



Velocity (Top Layer)(ft/ns) 0.404

Dielectric 5.92

Figure 19: RADAN for UtilityScan DF.

Chapter 3: Performing a Survey

This section explains what a user will need to bring to a jobsite, in terms of tools and background information. Being well-prepared can save a great deal of time on site and will make your interpretations more accurate.

We will start with a breakdown of the steps and tools needed to do a job, and then move onto each step in greater detail:

- Target Characteristics: What are you looking for?
- Survey Design: 2D vs. 3D
- Choosing the Right Tool
- Research and Additional Tools

Target Characteristics

First, you need to ask yourself: What are you looking for? What is the purpose of the survey? Are you looking for metal targets/utility lines, plastic pipes, a concrete culvert, or bedrock? Once you've answered this, you can begin to prepare for the survey.

Understanding the electrical properties of your target(s) and soils will allow you to move forward. This includes the ***dielectric constant***, and the surrounding material's ***conductivity***. Will the target reflect brightly, or will it be faint? Is the antenna used even capable of reaching the depth of interest? These are questions you need to ask yourself to prepare. Keep in mind that the depth of penetration of your antenna will decrease as the material's conductivity increases. With a 400 MHz antenna, you may get 8 ft (2.5 m) down in dry sand but maybe only 4-5 ft (1 – 1.5 m) in wet clays.

You will also need to have an idea of the dimensions of your target. If this is unknown, then the dimensions of where you (or your client) ***expect*** to find it will have to suffice. These dimensions will affect your 2D transects and possibly the shape and size of a 3D survey if required.

Survey Design: 2D vs. 3D

Once you have an idea of what targets you may be searching for – you can begin to design the survey. If the targets are utility lines or cables and they are in a known direction – it may make sense to do 2D transects and mark them on the ground. If the targets move in unknown directions, then perhaps a bi-directional 3D grid would be more effective. 3D grids are generally a better idea if you need 100% confidence in a targets location, or if your client wants a good image of the area for a report. These are especially recommended if there is anything potentially dangerous to hit in the site that you are looking to avoid. 2D surveys, on the other hand, are much quicker and easier, especially if you are surveying for one or two lines. They are also more effective if the survey is meant to locate geologic layers, like bedrock or water tables.

Choosing the Right Tool

This step focuses on choosing the correct antenna for your survey goals. With an idea of your target(s) properties and a survey site in mind, you can now choose the right antenna to collect the necessary data. You want to consider two things here:

- How large are the targets?
- How deep do I need to survey?

You cannot do much about the surrounding materials or target properties, but the antenna is one factor you do have control over.

As you look over your antennas, take note of their depth range:

Depth Range	Primary Antenna	Secondary Antenna
0 – 3 ft (0 – 1 m)	900 MHz	400 MHz
0 – 8 ft (0 – 2.5 m)	400 MHz	300/800 MHZ (DF) or 270 MHz
0 – 15 ft (0 – 4.5 m)	300/800 MHZ (DF) or 270 MHz	200 MHz
0 – 30 ft (0 – 9 m)	200 MHz	

While it may be tempting to always use a 200 MHz to achieve full depth of interest, the targets will need to be larger to appear well. In short:

Lower antenna frequency = deeper signal penetration = larger target size.

Research and Additional Tools

With most of the preliminary steps out of the way, we are now ready to approach the site and begin setting up. When you are on-site (ideally prior to actually performing the survey), you may want to ask the local "experts" of the area. There may be someone on-site that actually placed the utility you are attempting to locate, or could know where it enters the facility. This would give you somewhere to start. Ask for site plans or as-built drawings. You may also be able to take soil samples to determine what material you are surveying through, and have a better idea of the electrical properties.

Be sure to bring any equipment you may need. This includes marking devices (flags, paint, and cones), tape measures, and some small necessary tools, such as tape, wrenches, screwdrivers, etc. And, of course, your GSSI antenna and survey wheel/cart. It is also always a great idea to bring a field notebook. Write down anything you see that could affect your survey data, and anything about your actual survey. Never expect to remember something when you get back to the office.

A pre-survey inspection is always a good idea. This includes looking across the surface for evidence of your targets. Is there anything aboveground that could have an underground utility running to it? Or, is there anything aboveground that could cause you to mistake it for a utility? Often, tree roots and rocks will show as hyperbolas, and may be mistaken for targets. Any of these aboveground objects are good to note in your field notebook. Taking photographs of the site are also useful for making interpretations later, as well as for reports.

Chapter 4: Depth and Position Measurement

This section summarizes the above issues and is a step-by-step guide to the actual mapping procedure. The term “mapping” refers to the determination of target position and depth in RADAR data. Several approaches are to be considered:

- Field measurement using the system screen or a paper printout.
- Manual measurement using post-processing software (RADAN).
- Automated measurement using specialized post-processing software.

On sites where multiple targets exist and overlap, it is strongly recommended to use post-processing software.

Field Measurement

Distance Mode - PROJECT697 - PROJECT697__002

Distance: 6.16 m
Cursor Depth: 1.09 m

Figure 20: Data Collection screen in SIR 4000.

When collecting, simply dragging the antenna back along the survey line will help identify target positions on the surface using the backup cursor feature (see the UtilityScan and UtilityScan DF Quick-Start Guide). If you stop data collection (in the SIR 3000), you can also use the cross-hairs cursor to measure position and depth of targets. The corresponding X (distance) and Y (depth), coordinates are shown in the bottom right corner. With the SIR 4000, this is achieved with the H Cursor button, displaying a horizontal cursor. With the UtilityScan DF, pressing on the screen with the stylus will make the horizontal cursor appear.

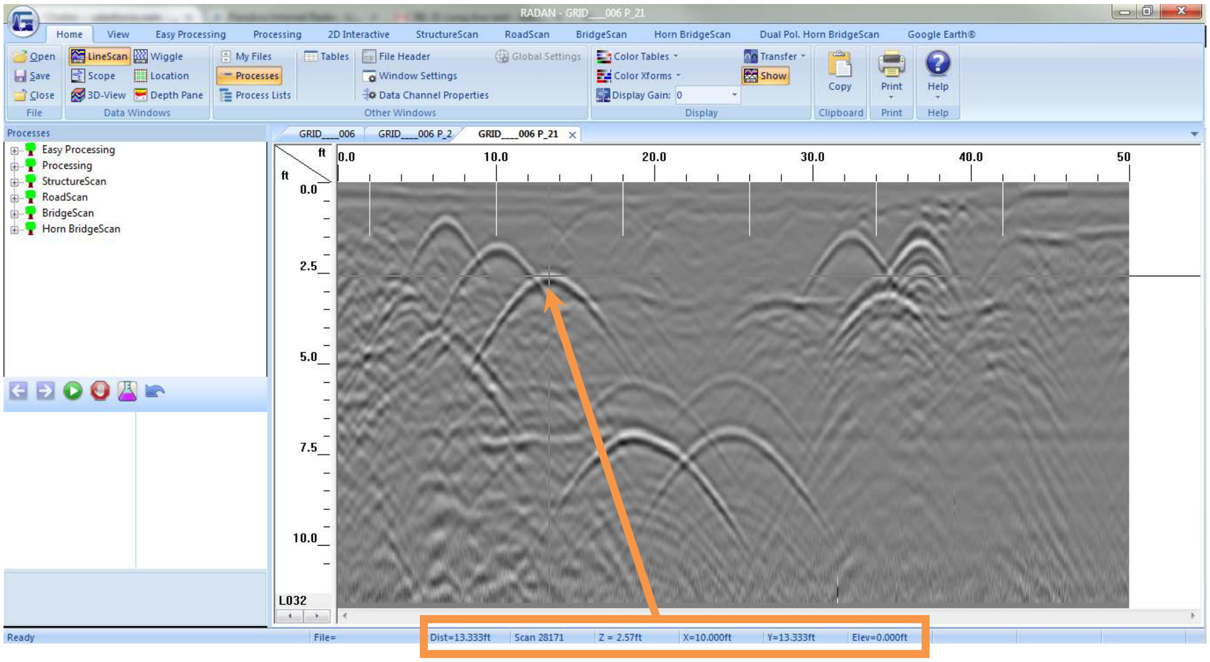
Manual Measurement Using Post-Processing Software

Alternatively, the survey data can be transferred to a PC and analyzed using the computer monitor. The graphic capabilities of modern computers, combined with the power of RADAN post-processing software, makes the analysis much more accurate and reliable.

The main advantages of this approach are:

- multiple file display;
- advanced processing capabilities;
- accurate velocity determination with Migration;
- printable output (report);
- fast point-and-click coordinate measurement.

With all the above features, the data is interpreted visually and position information still has to be manually copied.



Dist=13.333ft Scan 28171 Z = 2.57ft X=10.000ft Y=13.333ft Elev=0.000ft

Figure 21: Data display in RADAN.

Automated Measurement

Using specialized features in RADAN can make mapping a large number of features much more feasible. The surface is automatically located prior to depth calculations. Using some operator input and visual control, the software locates points of maximum amplitude within specified features (layers or targets), places a colored dot (pick) over them and extracts coordinate and amplitude information into a numeric database. Automated depth calculations are performed using other data sources or ground truth. Horizontal and vertical velocity differences can be taken into account. Picks can also be filtered according to depth or amplitude statistics.

Layer boundaries are traced using positive or negative amplitude peaks using EZ Tracker. A hyperbolic search algorithm locates targets using their hyperbolic signature and tags them with the Auto Target function. On files that have been migrated prior to analysis, the dot-like targets will be identified instead. Please refer to the RADAN manual for more details.

Remember: You will always want to double-check the output of any automated processing and target picking done in RADAN. The interactive nature of RADAN modules helps avoid mistakes by allowing you to visually check the results of automatic procedures. Any missed or mislabeled targets should be corrected manually in 2D Interactive using the Pick Tools

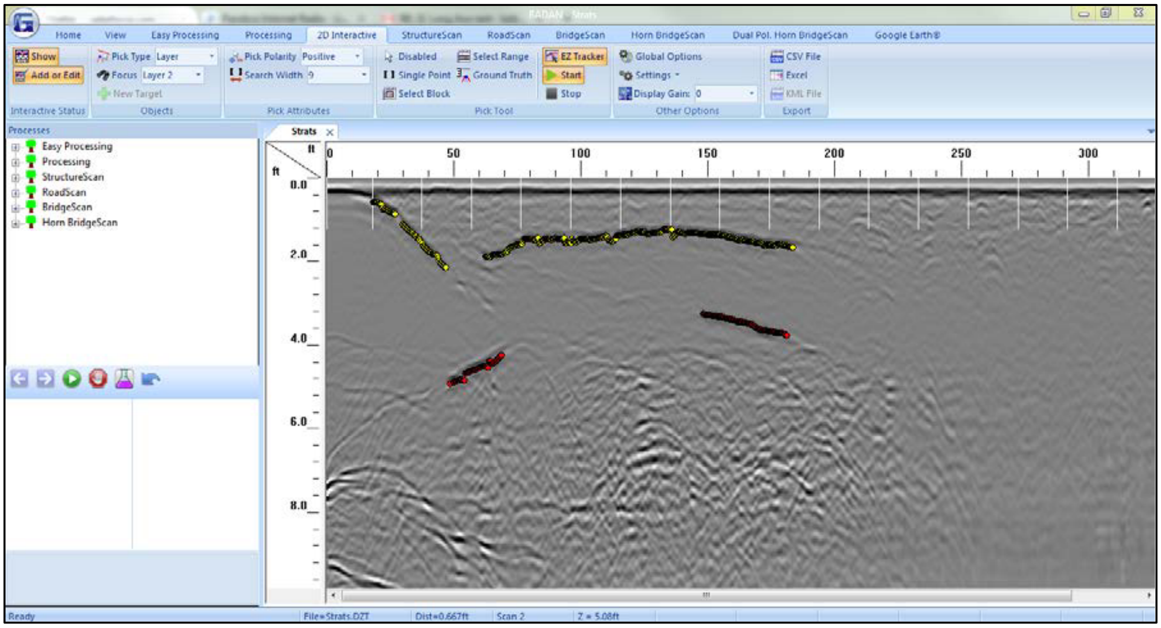


Figure 22: Data display using EZ Tracker 2D Interactive feature to mark layers.

Automated interpretation can be carried out on individual profiles or on the entire site at once. Processing of a single file outputs X and Z coordinates of targets as well as their amplitudes. Alternatively, the whole dataset can be assembled into a 3D grid and processed at once. The Y coordinate of targets will be added to the output table.

The output from all automated modules is an ASCII table that can be reopened in other software programs capable of importing a text file, for example Microsoft EXCEL or Golden Software SURFER. It can be plotted, transferred into other documents or used in calculations.

Chapter 5: 3D Display of RADAR Data

3D display of RADAR data is one of the most important innovations in GPR. It greatly simplifies data interpretation and allows one to identify targets with confidence. 3D viewing is more intuitive than single-line analysis and allows the identification of subtle features that are easily missed in single profiles. Identification of targets is simplified because their true shape and spatial relationship to other objects becomes visible.

It must be understood that we're talking about "simulated 3D". A three-dimensional image is created by simultaneously displaying several "conventional" RADAR lines parallel to each other. Interpolation between these lines gives the impression of a continuous image of the entire survey area.

3D display is most efficient for linear targets. The human eye easily recognizes linear features, even very weak or intermittent. A plan view is the most practical way of looking at 3D datasets. Utility lines, conduits, etc. can be quickly mapped from a plan view.

We will focus on using the 3D-View data window in RADAN and RADAN for UtilityScan DF.

3D-View and Super 3D

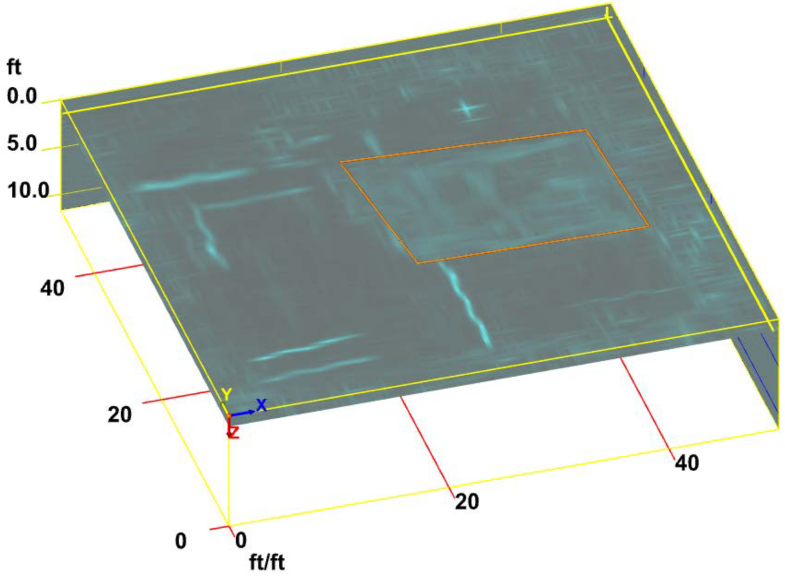


Figure 23: Data display in 3D-View. A 50×50 ft (15.25 x 15.25 m) testing area with metal lines and a rectangular clay layer (outlined in orange).

3D-View adds the three-dimensional cube/slice viewing capability to RADAN as well as the ability for the user to add their own interpretations of what the data displays (Figure 23). This shows the entire site at once in a plan view or as a user-selected perspective view of the data "cube". There is no limit to the dimensions of the survey area.

Note: 3D views are an excellent tool for feature identification. It is best to use them in combination with the regular vertical profiles (the 2D transects) comprising the 3D view. Individual profiles contain information about the depth and nature of targets that can efficiently complement the 3D display. Use the variety of approaches described in this manual to get the most out of your data.

In 3D-View the user can add interpretations using a variety of different methods. Please refer to the RADAN manual for details on using 3D and 2D Interactive tools.

After you have made your interpretations, you have the power to export this information to a variety of other programs for further analysis or report writing. There are a number of image export options, as well as CAD and Shape file extensions. If your data has GPS information applied, you can export a KML file that can open within Google Earth. There are many different avenues available to you after your GPR information has been processed in RADAN.

Super 3D

Super 3D combines multiple 3D GPR files. This feature can mesh together many separate 3D files collected next to one another on the same survey and can make surveying a large area more manageable. Please see the Super 3D section of the RADAN manual for details.

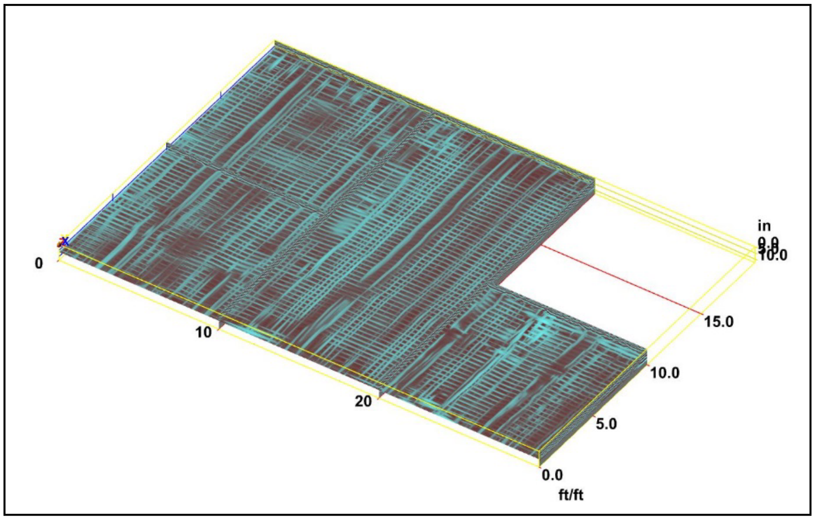


Figure 24: Super 3D file of 4 different 3D grids.