A Low-Cost GPR Gas Pipe & Leak Detector

DE-FC26-01NT41317

Final Report

Reporting period Start Date:	30 October	2001
Reporting period End Date:	30 November	2004
Date report issued	30 March	2005
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DOE award number	**DE-FC26-01NT41317**	

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ABSTRACT

A light-weight, easy to use ground penetrating radar (GPR) system for tracking metal/non-metal pipes has been developed. A pre-production prototype instrument has been developed whose production cost and ease of use should fit important market niches. It is a portable tool which is swept back and forth like a metal detector and which indicates when it goes over a target (metal, plastic, concrete, etc.) and how deep it is. The innovation of real time target detection frees the user from having to interpret geophysical data and instead presents targets as dots on the screen. Target depth is also interpreted automatically, relieving the user of having to do migration analysis. In this way the user can simply walk around looking for targets and, by "connecting the dots" on the GPS screen, locate and follow pipes in real time. This is the first tool known to locate metal and non-metal pipes in real time and map their location.

This prototype design is similar to a metal detector one might use at the beach since it involves sliding a lightweight antenna back and forth over the ground surface. The antenna is affixed to the end of an extension that is either clipped to or held by the user. This allows him to walk around in any direction, either looking for or following pipes with the antenna location being constantly recorded by the positioning system. Once a target appears on the screen, the user can locate by swinging the unit to align the cursor over the dot.

Leak detection was also a central part of this project, and although much effort was invested into its development, conclusive results are not available at the time of the writing of this document. Details of the efforts that were made as a part of this cooperative agreement are presented.

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1 INTRODUCTION

This collaboration has developed a light-weight, easy to use ground penetrating radar (GPR) system for tracking metal/non-metal pipes. That gas leaks can also be detected using this new tool awaits confirmation through digging. A pre-production prototype instrument has been developed whose production cost and ease of use should fit important market niches. It is a portable tool which is swept back and forth like a metal detector and which indicates when it goes over a target (metal, plastic, concrete, etc.) and how deep it is. In this way the user can simply walk around looking for targets and, by “connecting the dots”, follow pipes in real time. This is the first tool known to locate metal and non-metal pipes in real time and map their location.

Figure 1: The Util-Lite deployment looking for natural gas leaks.

As is commonly known, GPR is no silver bullet; in heavy clay soils, small deep pipes are often impossible to see. The laws of physics limit the penetration depths based on soil conductivity. But since, in most soils, pipes can be successfully locate regardless of pipe composition and crossing angle, this could be an important addition to the arsenal of pipe locators. Typically, a 10 cm pipe 1m down is easily tracked using this device. In the best Florida soils, a 10 cm pipe can be targeted more than 7m down. In the worst Houston clays, one not might see more than 70cm down.

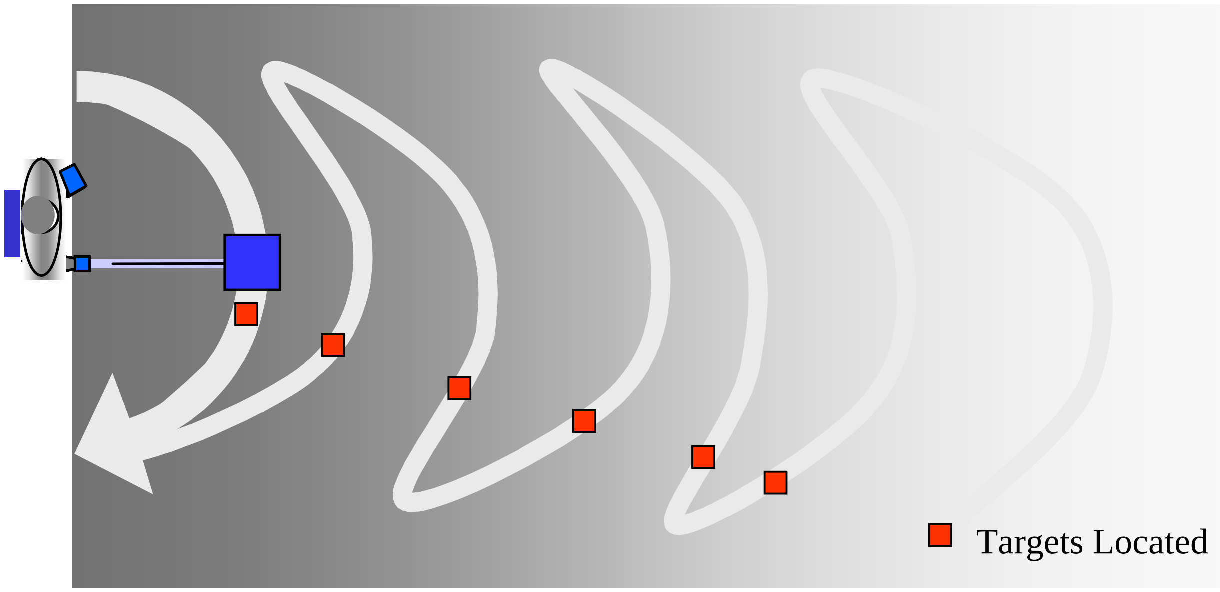


Figure 2: A functional depiction of a portable swept pipe finder/leak detector

The user can follow the pipe as he walks along (Figure 2), distinguishing its depth from other pipes that either cross or are running alongside. He can tell when it bends or branches and, most importantly, locate places where it may be broken.

A lot of work has gone into detecting gas leaks as well. The advantage of using GPR for leak detection is the chance of detecting the leak at the point of the break, rather than at the point it exits the ground. The idea is to exploit GPR's ability to detect subtle changes in soil moisture. At the point where gas leaks from a pipe, the soil overburden will become desiccated. This change produces several measurable changes in the GPR response.

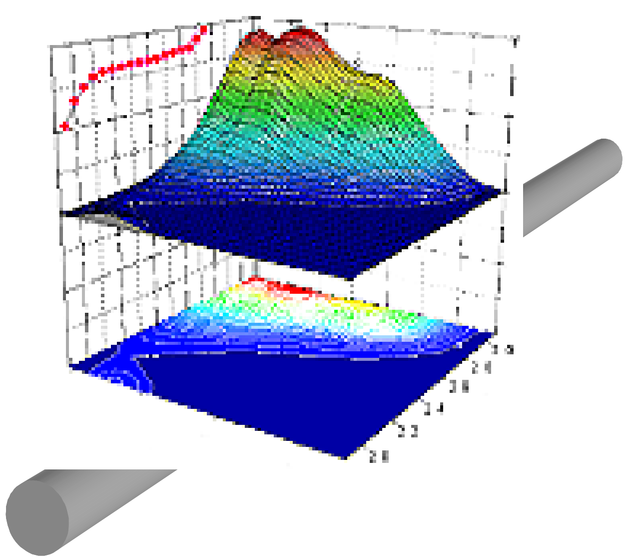


Figure 3: Idealized depiction of signal changes over a gas leak

This Pipe Location/Leak Detection Tool in fact represents an ambitious synthesis of several new developments within GSSI. It combines innovations in both hardware and Software.

Hardware

- lightweight deployment
    - armature
    - antenna
    - backpack
- small, low power system controller
    - compact user interface
    - easy data manipulation
- positioning systems
    - Gyro
    - GPS
    - Accelerometers

Software

- data compression algorithms,
- real-time signal and image processing,
    - audio feedback,
    - feature extraction,
    - target recognition,
    - new graphic data interfaces.
- leak detection

2 EXPERIMENTAL

HARDWARE

2.1 HARDWARE: LIGHTWEIGHT DEPLOYMENT

A new lightweight antenna was created for this project to fit on the end of a pole that would be swept back and forth like a metal detector (Figure 4 and Figure 5). Although the "metal detector" design finds application in many geophysical EM and MAG tools, a lightweight antenna on the end of a pole that could be swept had not been considered until recently. Since "Hard-hat" durability has always be a priority over lightweight antenna designs, this new concept represented a real departure from current methods. One challenging task was to turn a 15 pound 400MHz antenna into one weighting about 2 pounds.

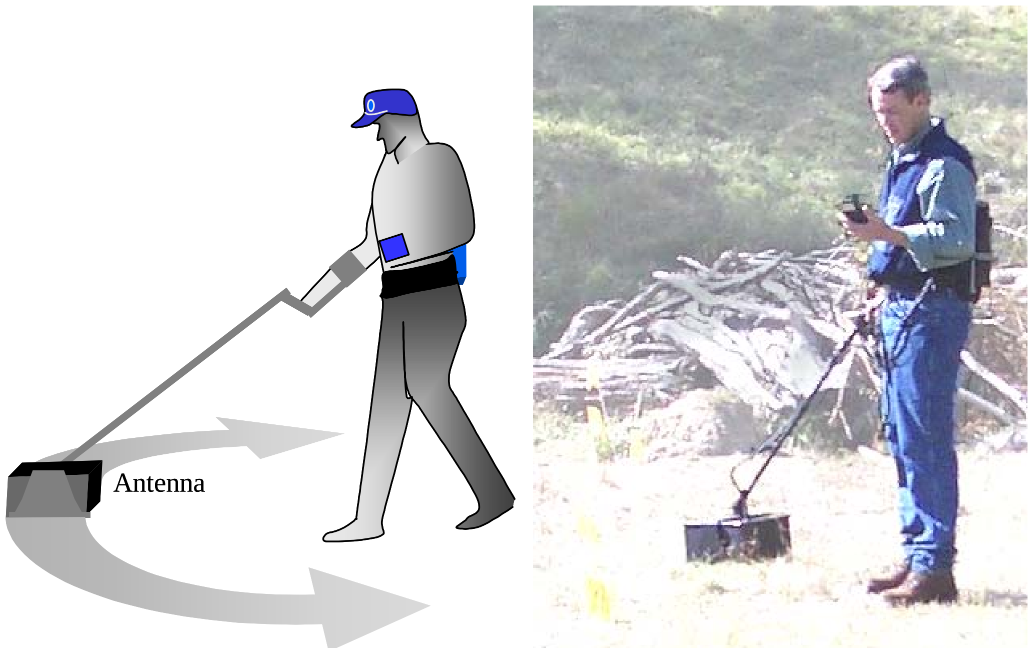


Figure 4: The antenna is light enough to swing comfortably over the ground.

For this design, the handle and boom is simply a modified metal detector design with a holder attached at the end. The antenna slides inside the lightweight holder that doubles as a skid plate. On the end of the boom, a pivot secures the basket in such a way that one can adjust the boom angle without bending over.

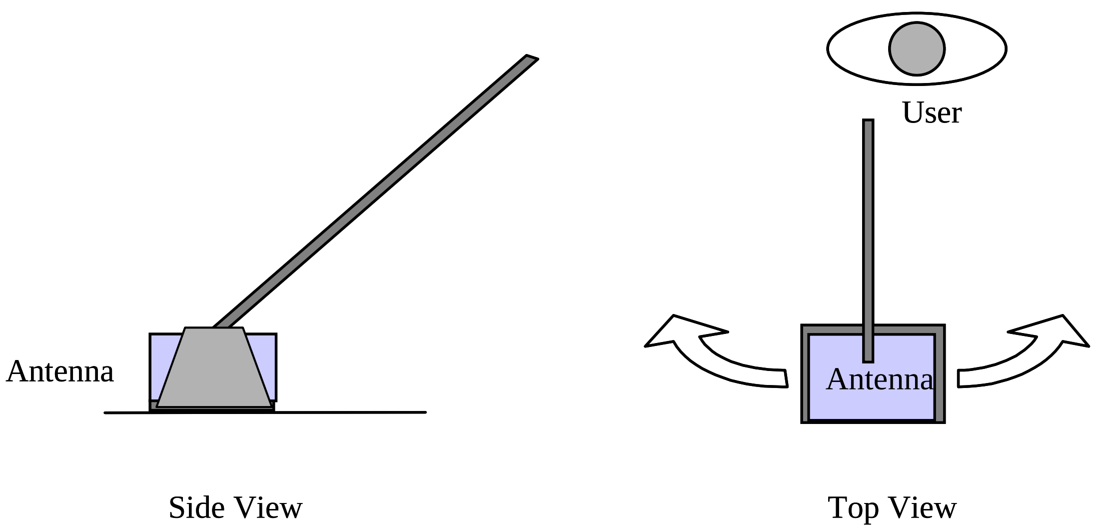


Figure 5: The general deployment concept

The other end of the boom is held either using a standard arm support, or swung from a harness or belt like a gas powered brush cutter. Using the arm support all day is somewhat tiring but bearable.

The box housing the battery and the radar board, which receives and partially processes the antenna signal, is small enough to be worn on a small pack frame or fanny pack. The radar board then sends the data out to a PDA for the user interface.

If one were to view this method as simply a new antenna delivery system (like a cart), one might start to see the several benefits it offers.

1) This “cart” is extremely portable. The entire unit can collapse into a gym bag and weighs less than 15 pounds. This means the user can take the GPR places that would be very inconvenient otherwise. Instead of needing to ship the cart, one might simply take it as luggage.
2) The “cart” is very maneuverable, letting the user swing the unit around trees, hydrants and utility poles, through high grass, over sloped or bumpy terrain, etc.
3) The user can walk at any speed, thus setting the density of the survey intuitively.
4) Unlike a single antenna cart, the user is effectively collecting a swath of 3D data as he walks along.
5) One common challenge associated with identifying pipes using any GPR system, involves locating pipes parallel to the direction of travel. Though pipes perpendicular to the direction of travel trace out a hyperbola that is easily recognized by visual inspection, pipes parallel just look like flat horizontal layers. These pipes are often missed, even when a 3D migrated data set is acquired. However, data collected in an arc will trace out a hyperbolic shape (or nearly so) when it passes over a pipe, making pipe recognition possible.

In sum, the swept concept has several inherent pros and cons over other more conventional GPR “carts”:

Pros:

- Highly portable
- Surveys in tight spaces, uneven or unstable terrain
- Resolution can depend on how slow one goes.
- A swept arc finds pipe hyperbolas regardless of pipe orientation.
- Could also attach a survey wheel and run a conventional straight line survey.

Cons:

- Lightweight sacrifices ruggedness.
- Portability requires redesigning light antennas
- Accurate positioning is more complex
- Portability requires a portable control system (at the expense of functionality).

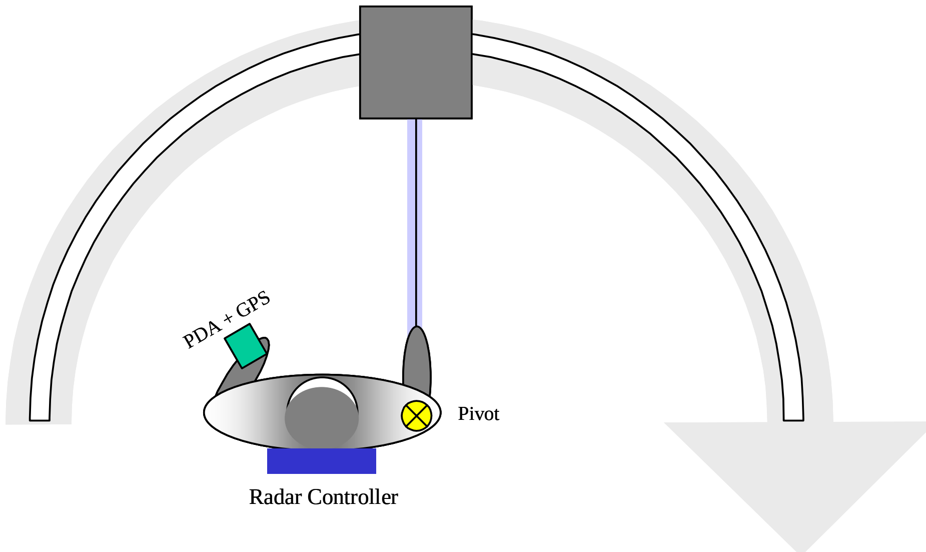


Figure 6: Util-Lite's component locations.

2.1.1 Antenna Design

This antenna was derived from GSSI's most successful utility antenna, the 400 MHz design. It is of manageable size and can typically penetrate about 2m even in difficult soil conditions. However, there is really no reason why several different frequency antennas could not be fit to the same device.

Antenna orientation was another point of decision that needs to be made thoughtfully. For metal pipes, it is best to have the angle of the dipole antenna cross parallel to a pipe.

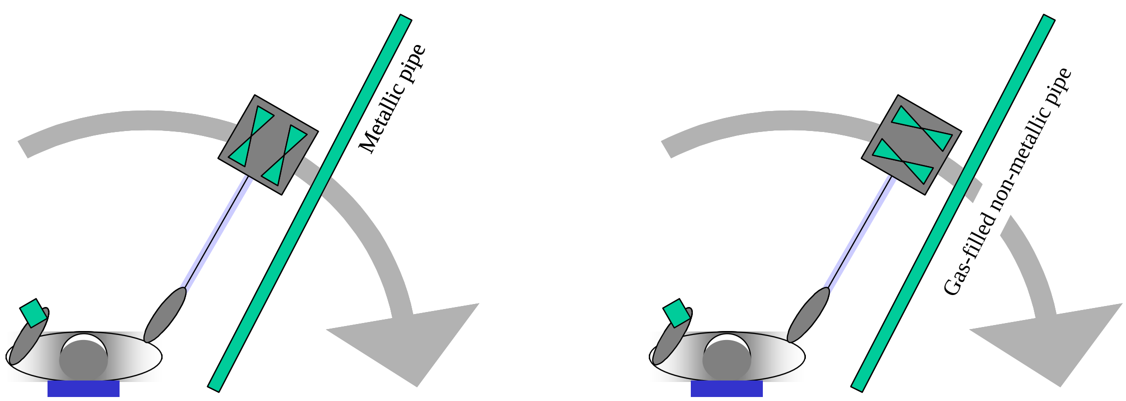


Figure 7: (a) parallel polarization (b) perpendicular-polarization

The orientation of the antenna dipoles affects the ability to see (a) metal vs. (b) gas-filled non-metal pipes (PVC, PE, ceramic etc.).

Multiple antenna polarizations could conceivably be used, including parallel and perpendicularly-polarized configurations. Dual-channel systems were considered for this project (which would add complexity and cost), but found by experience that the perpendicularly-polarized configuration finds both metal and non-metal pipes with reasonable success. In the case when the signal is very weak, and one knows one is only looking for a metal pipe, one can simply rotate the antenna in the cradle to collect in the parallel configuration.

The majority of commercial GPRs use bowtie dipole antennas. For this project slot antennas were experimented with as well as V-shaped antennas which has some air-launched directionality advantages. The traditional design has not yet been improved upon.

Although there is room for much improvement, the antenna housing was made exceedingly light but rigid using a thin plastic. The final result is still probably overkill, as the cradle should provide plenty of protection from damage and abrasion. Inside the housing the antenna is metal and fiberglass and is quite strong. However, it would not survive being run over, as can GSSI's commercial antennas.

Many housing ideas were considered. For example, by designing the antenna more like a pillow than a bomb shelter, the antenna and internal electronics could be still protected. The housing retains its shape while having a light, flexible shell. With a lighter antenna the nylon skid plate on the bottom can now be thinner, since it is not forced to endure so much friction. The housing can be something more akin to fabric than a heavy plastic, reforming its shape after being crushed. The internal chambers might be inflatable bladders lined with EM-reflective Mylar sheet or simply pillow foam that returns to its original shape. The electronics can be printed on the same circuit board on which the antenna pattern is etched. In the end it was kept rather uncomplicated, since the weight issues proved not to be as difficult as first anticipated.

2.2 HARDWARE: THE SYSTEM CONTROLLER

A new radar controller (SIR-2X) was developed partly with funds provided by this cooperative agreement. When configured by the custom firmware and driven with the specialized software it formed the heart of a low cost and low power portable impulse radar system. The performance of the SIR2X Radar Board has been proved and refined on the SIR3000 GPR system recently introduced commercially by GSSI.

Specific improvements and developments on this board include:

- The controller runs from raw battery power and there is no requirement for an additional power supply or supporting circuitry. This alone results in a 67% reduction in the volume of the electronics package over previous generations.
- The board is very low power taking less than 10W while acquiring data with standard GPR antennas. An Ni2020 Lithium-Ion battery pack may run the system for a full day without recharging. This is a 68% reduction in power requirement over systems being shipped just 1 year ago.
- It was designed to be controlled by any general purpose computer system as a USB peripheral. Connection is via a simple USB cable without the need for a massive parallel or custom-designed serial link.
- The on-board DSP now runs at 192MHz, 140% faster than the previous generation's 80MHz. The DSP performance is actually much more improved than that as the input and output data flow is now entirely DMA driven and all memory is internal.

- The controller board weighs about 120gm and the battery required for a full day of operation weighs about 550gm for a total weight of about 670gm. The lightest controller previously designed by GSSI required a large, lead-acid battery and the system weighed over 6000gm. This is an over 88% weight reduction.
- The new controller architecture supports a high speed serial link to the antenna electronics. This allows positioning and other peripheral inputs to be located at the antenna where they are needed and have their data incorporated into the GPR in real time at the controller.

The Sir2X Board was designed to make a complete radar system using an inexpensive hand-held computer for the user interface. The hand held was used for all control and display functions as well as any required data or setup storage. Since this instrument was not intended as a general-purpose GPR, the display capabilities of these devices are certainly sufficient for the application. The audio capabilities can be used to give auditory feedback to the operator so that he does not have to keep his attention on the display.

Major improvements have also been made in the circuitry located at the antenna. A microcontroller has been added to allow for peripherals to be located at the antenna.

- The microcontroller communicates with the radar board over a high speed, bi-directional RS-485 link. The controller has inputs suitable for multiple positioning systems (quadrature encoded survey wheels, PWM encoded accelerometers, marker switches, RS232 serial interfaced sensors, etc.). The controller is fast enough to keep track of these positioning inputs and send processed position information to the radar controller. (e.g. it can tell the radar controller to save scans every 1° of travel)

- Improvements in this area have also been made in the triggering interface. Triggering signals are now low voltage differential signals instead of high voltage pulses. The older high voltage pulses were only needed when there were long cables from the controller to the antenna and this is not the case in this system.

- The antenna and the controller can now be connected with a cable consisting of 4 twisted pairs and a single power pair. In the past 3 coaxial connections plus 9 to 13 additional lines have been used. The new connection is much lighter and more flexible.

2.3 HARDWARE: POSITIONING SYSTEMS

For this project to work, positioning must be able to track the fine scale motion of the antenna as it is swept back and forth, as well as to locate it on a map. Since the data necessary both to locate pipes as well as to locate leaks on a map needs to be generated. And in order to accurately trigger the data collection along an arc, there must be a positioning system that can track the sweep angle. A list of the several positioning options that were considered follows:

1. **None at all**: This could be achieved were there just an audio feedback signal that indicated the location and depth of a target by tones or beeps. This option was rejected for reasons given later.

2. **Rate Gyro**: This option measures angular rate; measuring angle requires an integration, which can introduce drift due to temperature and other factors. The gyro could be stabilized by performing an initial calibration and then by adding a long high pass filter to eliminate the slow variations that might appear due to temperature fluctuations. The result was a stable and repeatable response with drift that was far less than what was needed to track angles from sweep to sweep.
3. **GPS**: A consumer grade GPS makes it easy for the user to track and return to locations if spray paint or some other fiduciary marks were not used or wore off. Of course the user can have all the accuracy he can afford. But since thestated goal was to produce a low-cost system, a consumer grade GPS had to suffice. One that fits directly on the PDA seemed the simplest option. This not only simplifies the interface, but it also allows for an antenna extension if needed. The Fortuna “Xtrack” seemed to have the best combination of price, external control and reliability. It has worked fine.
4. **Accelerometers**: These are built into the antenna but were not actually used due to their high noise response. Initially, there were great plans to use the accelerometers as a tool to correct for both gyro drift and GPS discontinuities. It would be great to use it for dead reckoning indoors where the GPS would not work. And knowing the literature from the rate gyro, and having used GPS extensively in other applications, it was known that a Kalman Filtered synthesis of the three positioning systems was achievable. But since the accelerometers proved to be much less accurate than either the GPS or the gyro, it became clear that they would either not help, or actually degrade the results of both. A feasible solution would require using a military grade inertial system that was out of the scope of this project.
5. Attaching a survey wheel to the antenna was rejected due to slippage errors and awkward use.
6. Camera subtraction options were also considered, similar to an opti-mouse. It was quickly realized that even despite the problems of lenses and dust, one would still be left with the same drift issues as with the rate gyro.

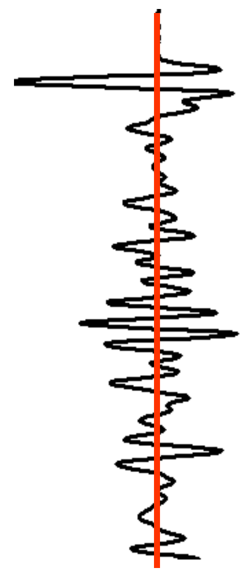
In the end the one-axis rate gyro and the GPS were selected as the best combination.

SOFTWARE

Much of the software development for this project represents a new direction for GSSI on several fronts. GSSI's strength has always been in producing clean, quiet data, but data interpretation has generally been avoided.

Conventionally, after time-consuming "migration" processing, and aligning several parallel profiles, a rather pleasing map of pipes in 3D can be produced. Now much effort has been invested in trying to get the computer to find these pipes for us, without having to "migrate" and without needing to store and manage the large data set. For this project the goal was not only to extract target information in the data, but also to do it automatically and in real-time. This can now be done with sufficient precision to track gas lines in almost any terrain. Here's how

2.4 SOFTWARE: DATA COMPRESSION



The first step in achieving this goal was data compression. Data compression was the key not only to making things fast for real-time processing, but also to identifying (and then extracting) important features in the data. Basically, this step involves keeping only the data essential to good decision-making. Of the many published techniques for doing this, a zero-crossing method was chosen. Although not a concern in this case, all methods compromise the ability to perfectly reconstruct the original waveform.

2.4.1 Zero Crossings

If swung 180 degrees across the body, collecting a scan every degree would collect 180 scans. Instead of storing all the points down the scan, only the position where the signal crosses zero along with its peak-to-peak amplitude is kept. This buys an initial data reduction of a factor of ten.

2.4.2 Feature Extraction

This simplification is used to track coherent lines from scan to scan looking for features, further compressing the data. This fairly complex algorithm predicts feature trajectories and gets the more established features to compete with each other for new zero crossings from each incoming scan. One can then keep only the "interesting" features and throw out most of the "uninteresting" data by looking for clear directions and telltale shapes.

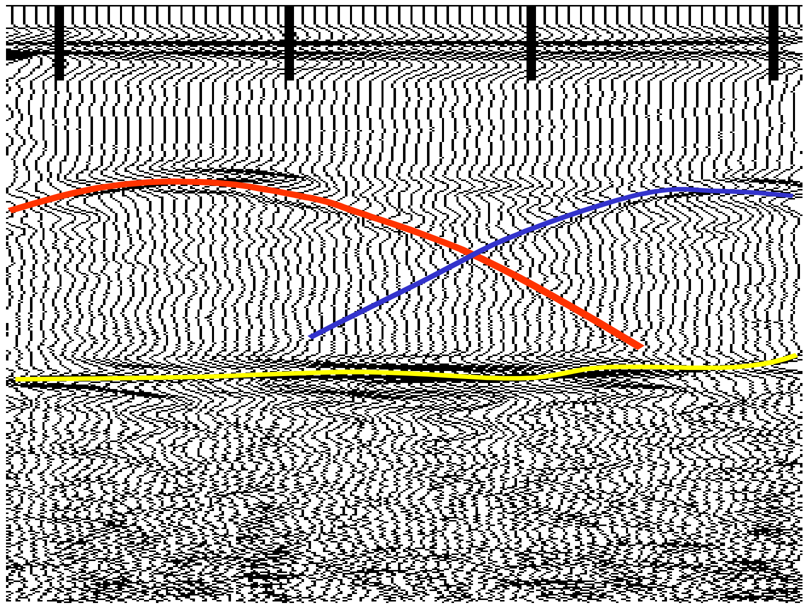


Figure 8: Features in the data can be found by stacking scans next to each other and following continuities. Incoherent information can be filtered out.

This was the core engine behind most of the processing for this project including the tone generation scheme that ended up not being using. NOTE: Tone generation over pipes **is** “feature” extraction, but it relies on the user’s ear to do the extracting. More on this in Section 3.2.

2.4.3 Target Recognition

Pipes produce characteristic hyperbolic patterns (Figure 8), easily recognized by eye in a GPR image, but recognized by computer with some difficulty. There are a few ways to do it

For example, once peaks in the features are identified, one can use amplitude information to recognize symmetric falloff on either side of a peak. One can use shape to evaluate hyperbolic similarity on either side of a peak by plotting x^2 vs t^2 and doing a linear least square fit: ideally two straight lines of equal slope. Or one could approximate the hyperbolic shape by fitting a parabola on either side of the apex. These and other methods, like using shape kernels or modified Hough transforms, etc., can serve to isolate a target hyperbola.

Over the past several years of development all combinations of these have been tried; the algorithm continues to improve. More and more, target recognition is starting to match visual perception (weak targets have low confidence, strong targets show high confidence). Figure 9 shows just one sweep of data. Targets are color-coded by confidence (low = gray, green, blue, red = high), which, for the most part, match visual perception. Notice that even very faint, but well shaped targets can score well, while even strong targets that crisscross can be missed (bottom left). Generally, even in quite complex environments, the algorithm confidently locates the obvious targets and tentatively locates the more obscure targets. On close examination the “false positives” are either low confidence or, on closer examination, really are targets (rocks or debris etc.)

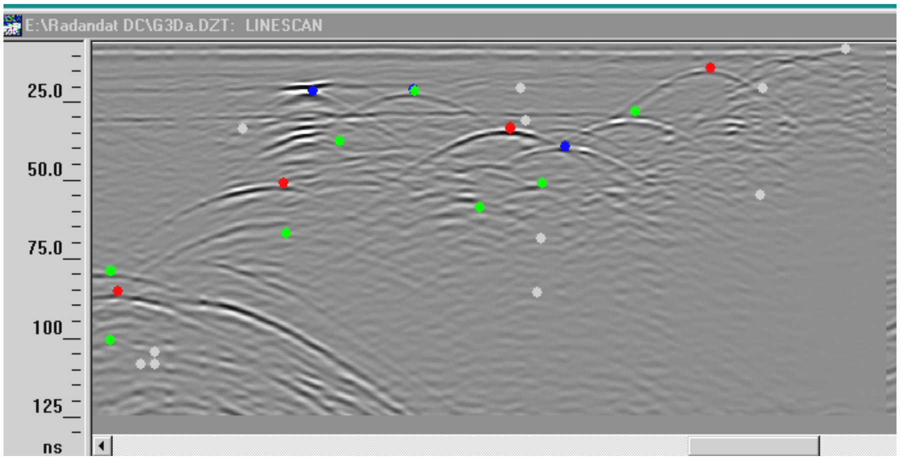


Figure 9: Automatic Feature Recognition example. The red dots mean the target was found with a high degree of confidence (then blue, then green then gray).

2.4.4 Post-Processed Auto Target Recognition

2.5 POST-PROCESSED DISPLAY OPTIONS

Of course most algorithm development was handled inside our RADAN software package, since many development tools are easily available. A few tools in the RADAN software application bear mention, especially since they are important both for data visualization and for leak analysis.

2.5.1 3D Frame Display

Pipe output from target recognition can be displayed in GSSI's 3D Quickdraw program inside RADAN. The data from Util-Lite can also be displayed in 2D.

When several parallel sweeps of data are stacked together, one can assemble a 3D picture of the pipes in a test pit. Figure 10 shows the results in 3D. Generally the red and blue dots mark the pipe locations. Most of the green marks, on re-examination show clear targets that could be rocks or other debris in the pit. The algorithm has been run on scores of other data sets, both shallow and deep, and it seems to hold up well. However, noisy environments may require the addition of a "sensitivity knob" to squelch false positives.

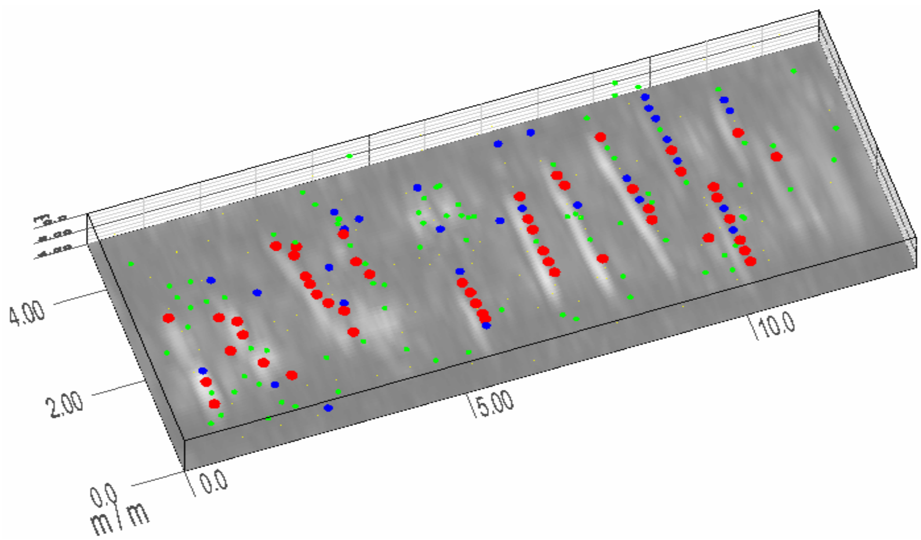


Figure 10: The results of Automatic Hyperbola Recognition shows a strong correlation with the pipes visible in the 3D data.

At least in this example, the leap from Feature Extraction to Target Recognition is a small one. Figure 11shows an estimate of pipe lengths, depths and dip angles based on the results from connected dots. The data shown underneath has been migrated: not the sort of information one could get in real time. The raw data would actually reveal very little in 3D, still less in 2D.

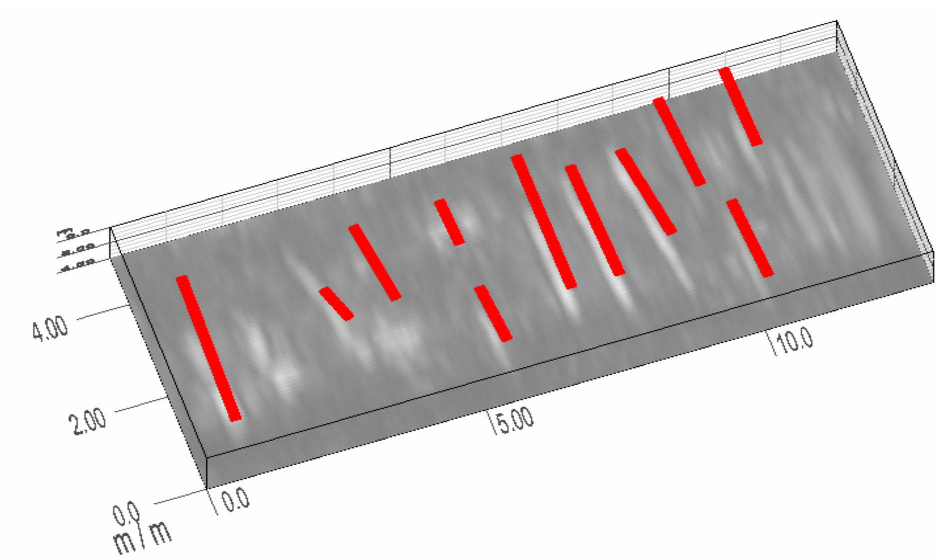


Figure 11 Pipes in 3D based on the features found in Figure 10

One of the goals for future work is to incorporate 3D pipe following into the Util-Lite design so that pipes are recognized from one sweep to the next.

2.5.2 Interactive 3D

A powerful target display and editing routine within RADAN called Interactive 3D Interpretation is now available, into which target locating results get displayed for editing and cleanup (Figure 12). This tool has been indispensable for the development of this prototype and will continue to be important, since now it ca be used to display data as it would appear on the GPS map.

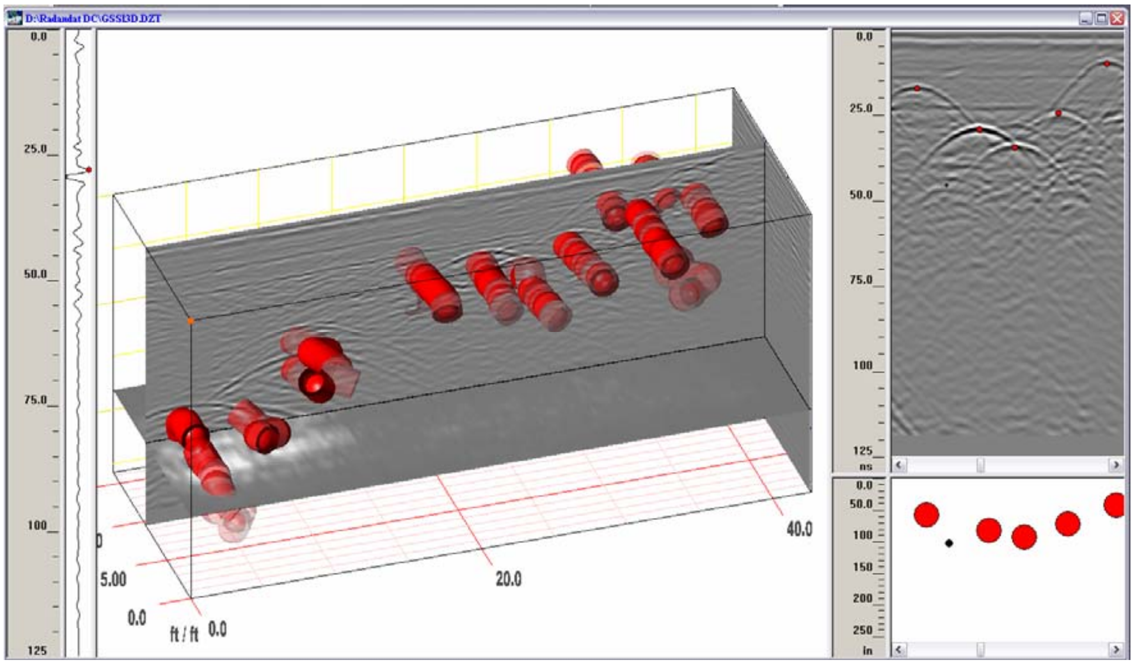


Figure 12: Interactive 3D presentation, showing data in O-scope, LineScan, DepthScan and 3D views. This later version shows the pipes rendered according to their depths based on the average velocity that was determined by auto target.

Development of 3D data display is ongoing and will hopefully be incorporated in the real time analysis of leaks.

2.6 SOFTWARE: REAL-TIME SIGNAL AND IMAGE PROCESSING

Code that was developed in RADAN was then successfully ported into the Util-Lite for real-time target recognition. For the real-time Util-Lite application, the visual cues described above were changed. Recognition confidence was conveyed as dot size instead of color, since colors on a small screen are hard to see. A square (rather than a dot) is displayed to avoid misconstruing size for pipe diameter, which is not determined.

While one collects data by sweeping in one direction, the target recognition results from the previous sweep are being displayed as the cursor sweeps by. So the recognition is actually always one sweep behind. In practice this delay is inconsequential, since one can always swing the cursor back to pinpoint the target location.

In order to make this system simple to use, most decisions regarding setup and image interpretation are being done automatically. Ideally one would want the user just to turn it on and start following pipes and locating leaks. To get there, one needs to make many complex decisions for them and then to present the information in a manner can be used and understood.

There are several ways this can be done. Two were implemented: an Audio feedback method and a graphical feedback option. Although for this prototype it was decided in favor of the graphical feedback method, the audio feedback tool allows for great simplification and truly real-time operation.

2.6.1 Audio Feedback

This implementation creates an audio tone that rises and falls based on the proximity and depth of a target. When the antenna sweeps over a pipe, a hyperbolic pattern appears in GPR data. Using data compression schemes to squelch flat lines and clutter, one can accentuate these rising and falling edges and convert them to sound. By correlating sound frequency with depth, shallow pipes make high-pitched tones and deeper pipes make deeper tones. As a target hyperbola is detected on the way up, the tone starts to rise and then fall as the signal descends on the other side. The peak of a hyperbola can easily be heard as the highest pitch and the location marked on the ground. The result (Figure 13) is an obvious pattern that can be used (either visually or audibly to pinpoint the location and the approximate depth of pipe in real-time.

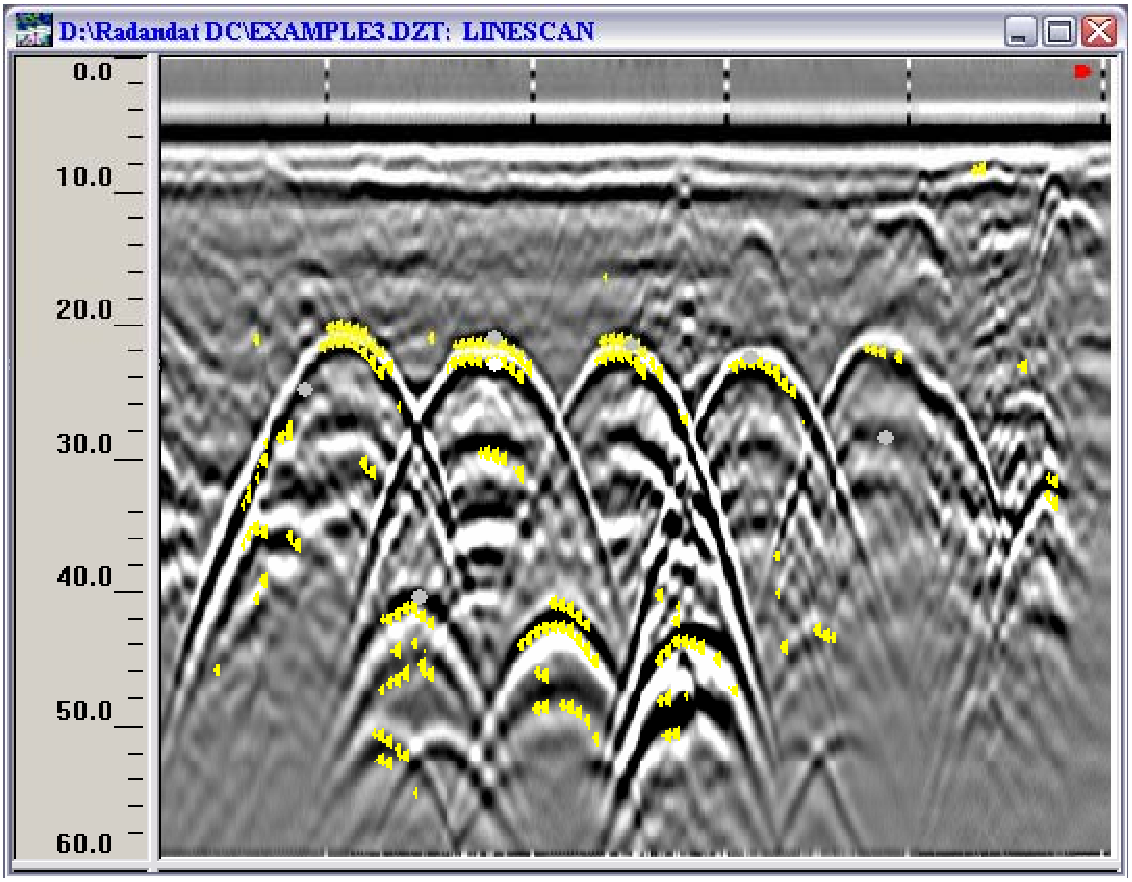


Figure 13: Five shallow pipes and three deeper pipes with places where tones are generated marked in yellow. All the major targets are audibly identifiable.

In this way the user can locate and follow a pipe in real-time. Such a simple method obviates the need for a complex visual user interface; it requires no positioning sensors and relieves the user of having to do any image interpretation. One just sweeps back and forth, listening for the top of the pipe and then mark its location and relative depth with spray paint.

But as a data extraction tool it has several shortcomings. As one might imagine, the important part of the algorithm is what one doesn't hear. Squelching sound and producing silence in heavy regions of clutter is key, especially since no forward information is used to make volume determinations. Figure 14 shows a more difficult example where there are many things that start to look hyperbolic and then fade out. Other difficult problems are found in regions where pipes are located close together or cross. It is assumed that any answers derived will be based on repeated sweeps over the same region, as an aid to interpretation.

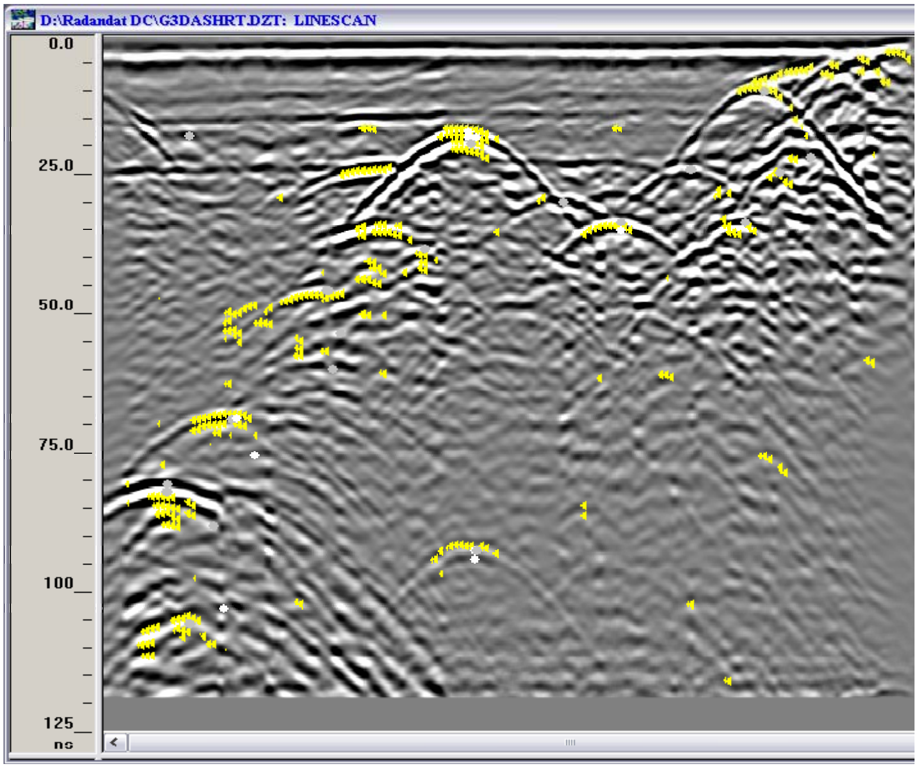


Figure 14: Examples of clutter generating false tones in the lower right side of the image. Tones are correctly generated for all but one of the pipes, but other clutter creates distracting noises

However, a tone is only helpful in real time; it is not an option in noisy environments, nor for the tone deaf, nor if one wants to be able to present or report results, or show someone where to dig on a map. What if one wants a more accurate depth estimate? For this one needs a more complex system with positioning information, soil velocity analysis, and graphical output. More on this later. In the end, it was decided that a more robust and useful interface could be created using a visual display for feedback, by extracting the features automatically, instead of relying on the user's ear to do the job.

2.6.2 Visual Feedback

The final implementation presents two distinct visual feedback displays, split onto the same screen. The top of the screen shows a cursor that sweeps in concert with the antenna. If a target is found, a red dot appears at the right depth and at the angular location at which it was found. The size of the dot corresponds to one's confidence that it is in fact a target.

The bottom of the split screen shows the track log from the GPS. When a confident target is located, a red dot appears in this screen. This allows the user to get a more general feel both for how well the area was covered and for what the general target pattern looks like.

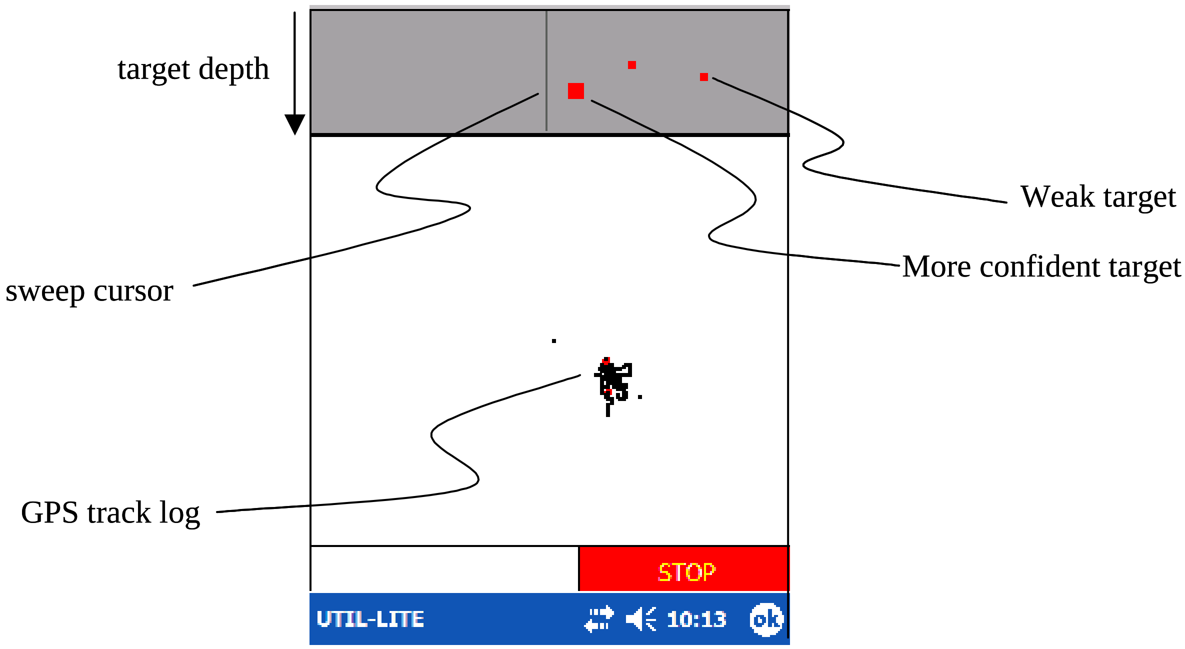


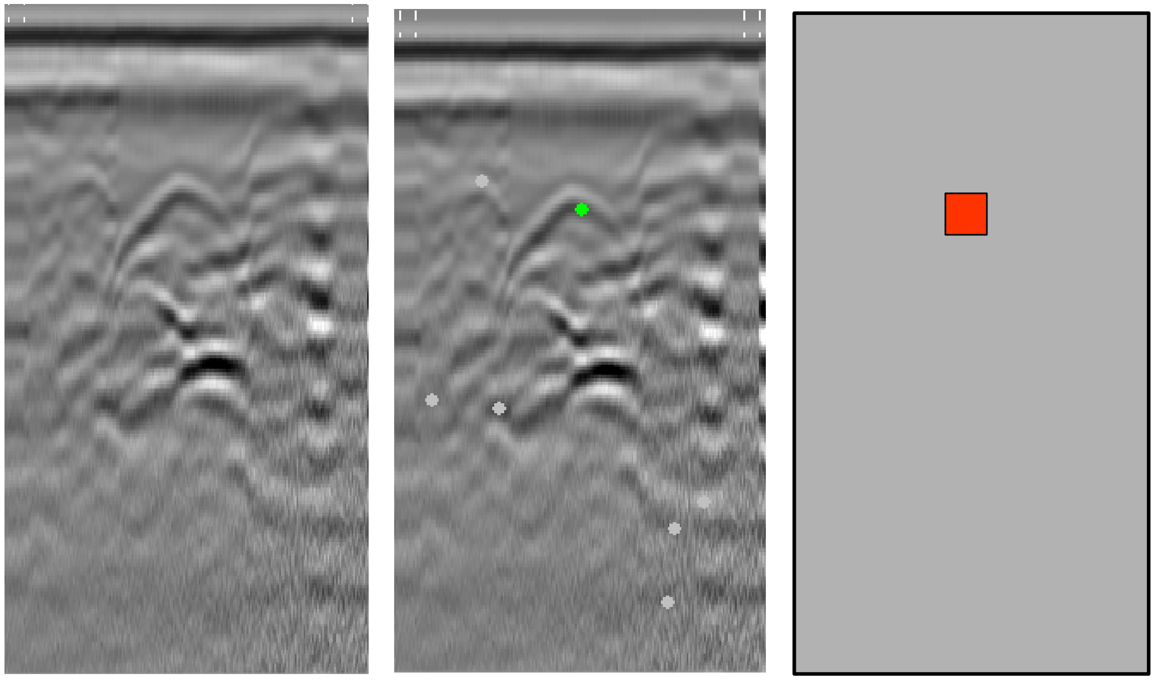
Figure 15:The two display screens. The top screen shows the target locations and depths found during the sweep. The bottom screen shows a cookie trail of your GPS track log along with the locations of significant targets found along the way.

The red square targets are placed so that the top of the square matches the top of the apex of the hyperbola. In Figure 15 the actual results of auto target recognition are shown together with an image of what would get displayed at the top of the screen of the PDA. The green dot represents a recognition that is more confident than the others. The grey dots fall below the threshold and are not displayed. A strong shape beneath the pipe is not recognized because the shape is not sufficiently hyperbolic to qualify, whereas more subtle shapes did. In the end the pipe was correctly identified and could easily be followed along its course.

2.6.3 Target Locating

To locate the target spatially, simply move the antenna back to place the cursor back over the red dot. Then to find a pipe, repeat this process several times along a line. Placing flags or marking the ground with paint will indicate the location of the pipe.

With real-time target recognition, one can locate by aligning the cursor with the red dot. One might also beep a tone directly over a target, or placing a mark physically on the ground as discussed earlier. Spray paint or powder or some other substance can be placed on the ground either by pulling a trigger, or automatically. Since GPR also can give information about target depth and even target material type, the marks could be color-coded. These marking methods are not implemented.



(a) (b) (c)

Figure 16:These pictures compare the actual data (a and b) with a stretched view of what the screen would display (c). Auto target recognition found six targets (b), but five were rejected.

2.7 SOFTWARE: THE USER INTERFACE

A Toshiba Pocket PC e800F was chosen as the interface controller, because of its superior qualities in screen resolution, speed and connectivity. In bright sunlight, the screen is readable only at certain angles and pushing the touchpad with the stylus can be tedious, but otherwise it is quite adequate to the task.

Figure 17: The Pocket PC is a Toshiba e800

Attempts were made to limit the screens necessary for basic operation as much as possible. It got pared down to four (and could probably be fewer) by stuffing the more complex functionality into several other screens. For most pipe location applications the flow (indicated in red) goes like this:

1) Running the application opens the main menu
2) Hit positioning.
3) Hit calibrate, then ok.
4) Hit system init, then run.
5) Start swinging.

The full description of the Menus and options is included in Appendix B.

Ideally one would want to paint a picture on the screen (Figure 18) in such a way that the subsurface "story" becomes increasingly clear.

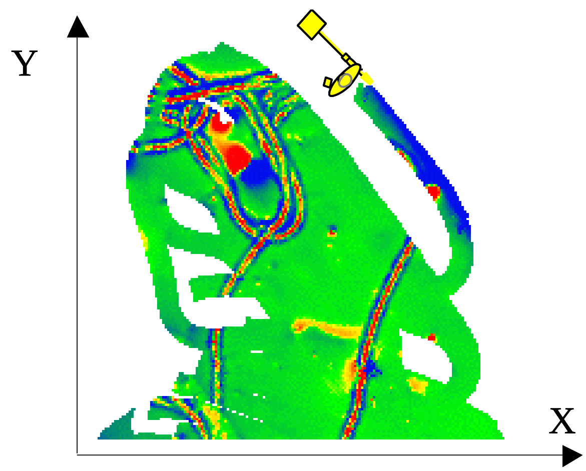
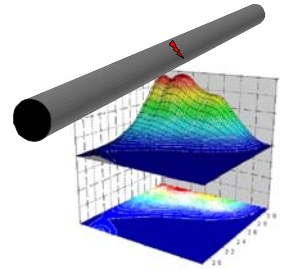


Figure 18: Conceptual idea for displaying data in 3D.

3D displays of the data are constantly being developed, so that the trail of data can be shown. Important work continues to be done on the post-processed/desktop level, since the PDA processing power is not yet up to the job. For now we must content ourselves with dots on a GPS map.

2.8 LEAK DETECTION



Another important aspect of the signal-processing task has been Leak Detection. This section describes both the algorithm as well as efforts for generating and detecting leaks underground. It should be made clear that the implementation of these algorithms is not real-time, but rather operated on post-processed data.

2.8.1 The Theory

When a natural gas pipe leaks, some part of the soil overburden above the pipe should become perfused. Depending on factors like leak rate, soil porosity and water saturation, this soil should become dried out. Typically in leaks beneath grassy soil one can see soil cracking due to dryness as well as a large brown spot where the grass has been asphyxiated.

It turns out that GPR is very sensitive to changes in soil moisture and has been shown to detect subtle differences with high accuracy. When a soil gets dried out above a pipe, one should be able to observe four changes in the signal.

- The decrease in soil conductivity should improve the **penetration depth** of the radar signal. Usually conductivity changes are no friend to GPR since they tend to ruin signal quality and depth penetration. But in this case, one can use this information by constantly observing changes in depth penetration. This could be made especially powerful if a conductivity survey, performed earlier over the same region, could be compared with the current survey. Any changes would be immediately apparent.
- The conductivity decrease should increase **refection strength** of the pipe since more signal is able to actually get to the pipe.
- The decrease in moisture will also lower the bulk dielectric properties which will shorten the travel time of the reflection off the pipe. This will cause a sudden and unnatural **pull-up** of the apparent depth.
- Since the **velocity** of the soil above the pipe will increase, the shape of the hyperbola that is created over the pipe should also **increase**.

2.8.1.1 Max Depth Estimation

Since noise comes in different forms, the maximum signal depth is estimated two ways:

a) phase flips per interval (Vertical)
b) similarity test with previous scan. (Horizontal)

The first method just looks vertically at the data quality down the scan, while the second looks horizontally at signal stability from scan to scan.

The first method looks down each scan, counting the number of times the signal changes direction. As the signal weakens with depth, high-frequency noise starts to get added to the signal, making it look “spikey”. This is an early warning that the signal is starting to degrade.

The second method looks between scans, subtracting two scans and looking for coherence. With good signal, adjacent parts of scans should look similar, while the noisy parts of the scans will show no correlation from scan to scan.

The example below (Figure 19) shows the difference between the two noise measures. Visual inspection shows that not only are they are both generally correct in identifying the maximum penetration depth, but also they tend to compensate for each other. Visual inspection confirms that the minimum of the two is roughly where the true transition lies.

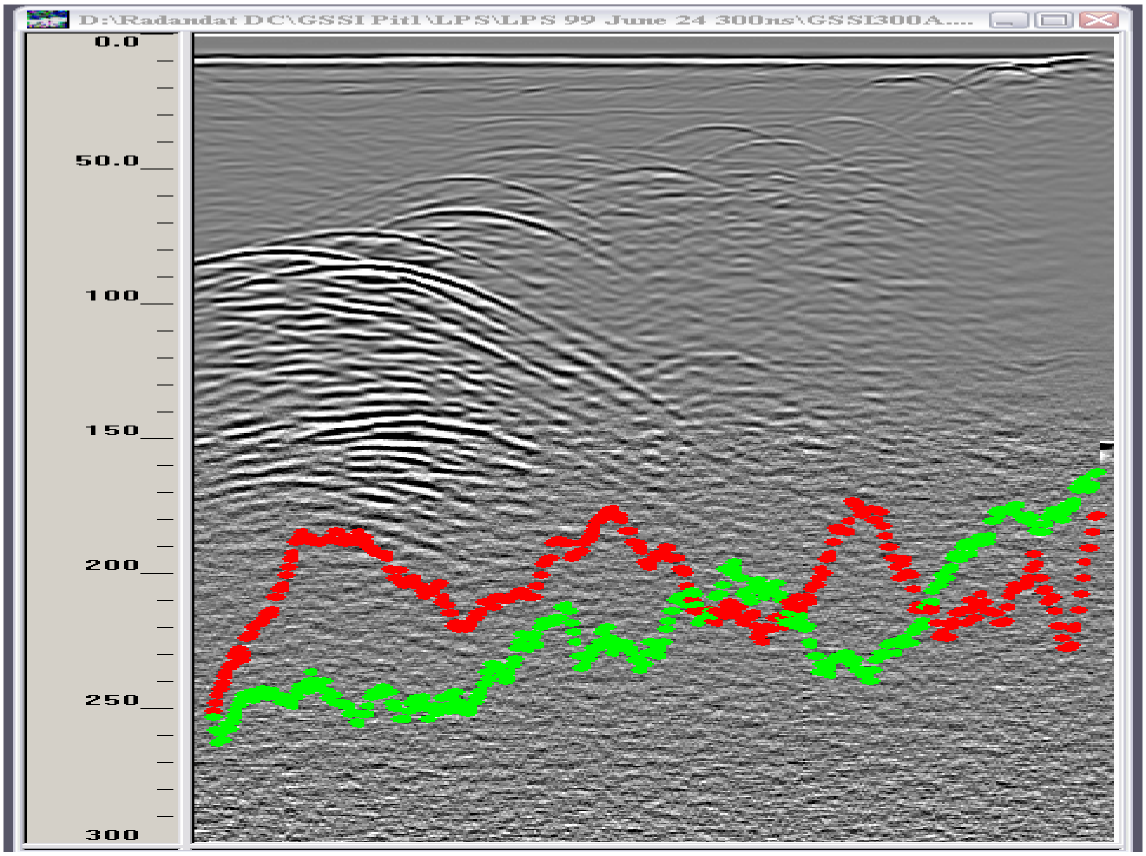
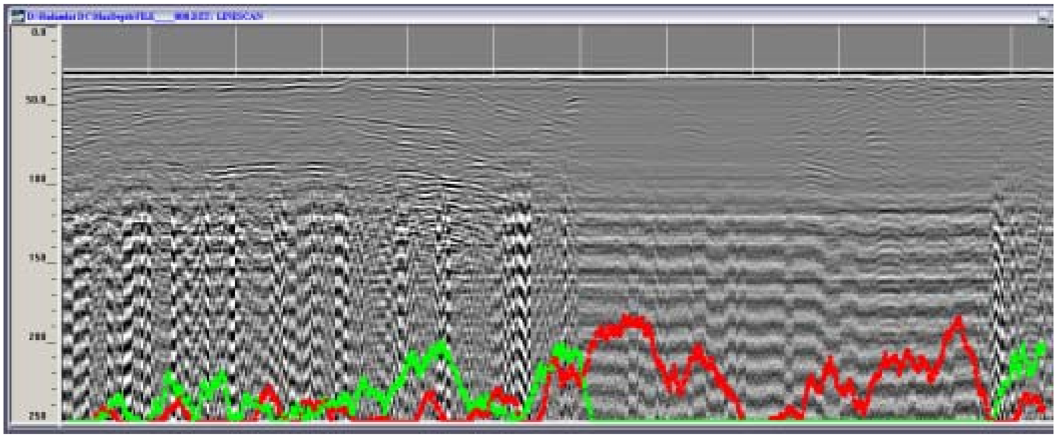
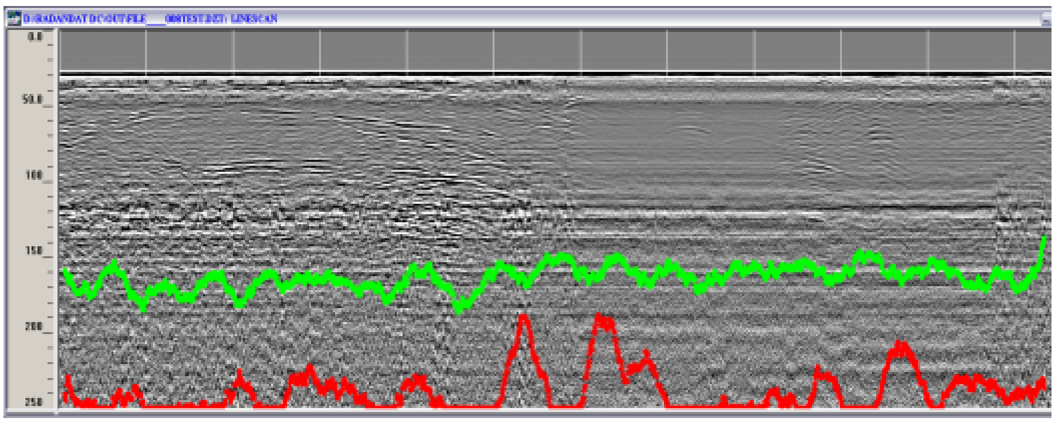


Figure 19: Max Penetration depth measured two different ways. The Vertical method in red (upper) and the horizontal method in green (lower).

There are some situations where some signal processing will need to be performed before a reliable depth is returned. Data with undue ringing looks like (and is in fact) “signal”, but should be discounted somehow, since it is not useful information. This could be performed using “predictive deconvolution” processing to remove the ringing multiples. Conceivably this processing could be done in real time as well. After this the Max Depth scheme (the horizontal part) works reasonably well (Figure 20).



(a)



(b)

Figure 20: Max Penetration depth: (a) Shows results with raw data with a lot of ringing. Neither method is able to get past the ringing to find the maximum penetration depth. (b) Shows results with the data after a deconvolution step to remove the ringing. The Horizontal detection method finds the noise floor reasonably well, while the Vertical method still believes there is plenty of signal at the bottom of the image.

The theory was also nicely confirmed when a 3D data set over one of GSSI's test pits was collected (Figure 21). In the region where the pit had been dug and then backfilled with nice sand, the penetration depth was clearly much better than on either side through the native soil. This basically proved the concept.

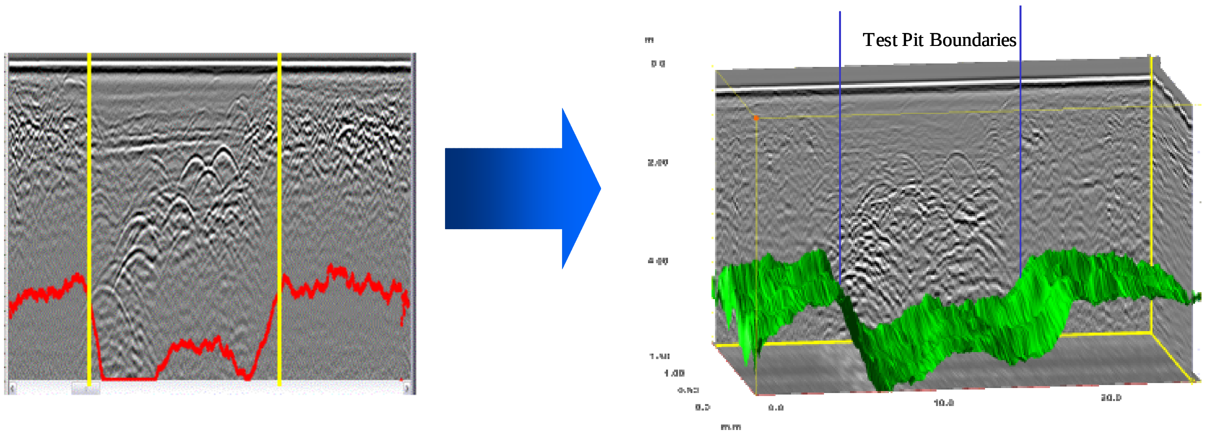


Figure 21: These graphs show the difference in depth penetration as 14 survey profiles went across the test pit. The clean sand in the pit clearly allows better signal penetration, lowering the Max Depth Estimation.

2.8.1.2 Leak Testing

But one important aspect of proving this algorithm is the capability of actually testing the concept in soils with pipes that actually have leaks. Extensive and ultimately futile lengths were taken to simulate this process before giving up and going to gas companies to perform tests in real situations. And whether it works in real situations has yet to be proved.

2.8.1.2.1 LEAK SIMULATIONS

Two leak test areas were created. The first involved drilling five 7m long 0.5 inch schedule 80 npt pipes horizontally under a road. This was done with a jackhammer and then hooked up to an air compressor once in place. In three of them the air came out the end of the pipe, while in the other two the tip was sealed and holes were drilled part way along the pipe. Horizontal drilling can be hard to control the depth of the tip. For three of the pipes, the rock ledge underneath clearly served to guide the tip close beneath the asphalt and limit their effectiveness for this experiment. The other two stayed deep: one 1m deep, the other 0.5m deep.

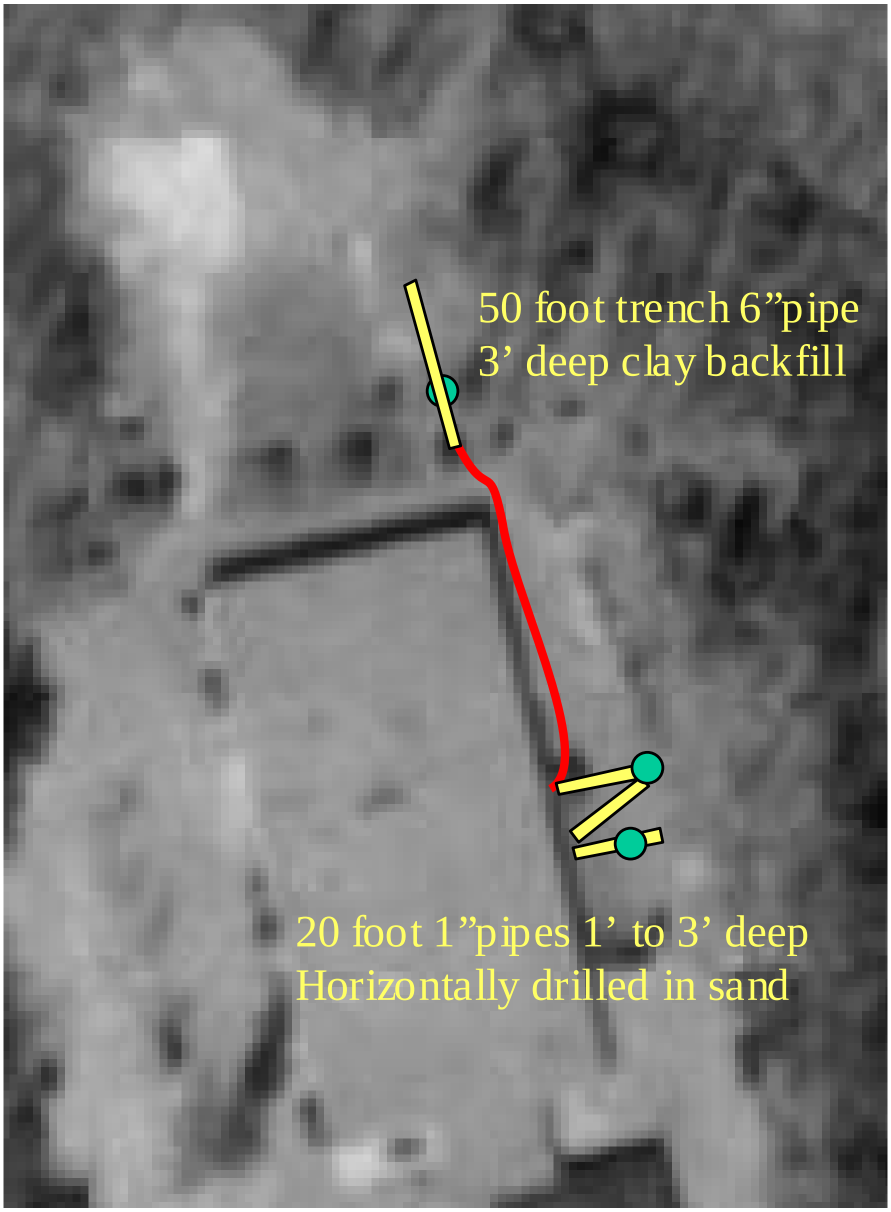


Figure 22 Leak Test pit layout

Then one end of a pipe was hooked to an air compressor and which forced air in at one cubic foot per minute. This is admittedly much higher than the 10 CFH that is more typical of a real gas leak, however, a gauge that went any lower than 1CFM could not be found.

It was then quickly learned that dried air was required, since the compressed air would expand and actually *increase* the soil moisture as it expanded out of the end of the pipe. An industrial drier was used and then an evaporator to get the humidity of the air going in to about 20%.

3 RESULTS

A development project like this does not divide cleanly between experimental procedures and results. In fact many of the "results" of development have already been presented, in the significant improvements and innovations that have been made in the areas of auto target recognition, hardware design and user interface design. However, for the purposes of this report we will simply define the results as: does the tool locate pipe and can it find leaks.

3.1 TARGET LOCATION RESULTS

3.2 LEAK SIMULATION RESULTS

Throughout all of the tests local changes in conductivity were sought by mapping the Max Depth in 3D … to no avail. After hours and even weeks, any change in soil conductivity using this method (Figure 23) could not be detected.

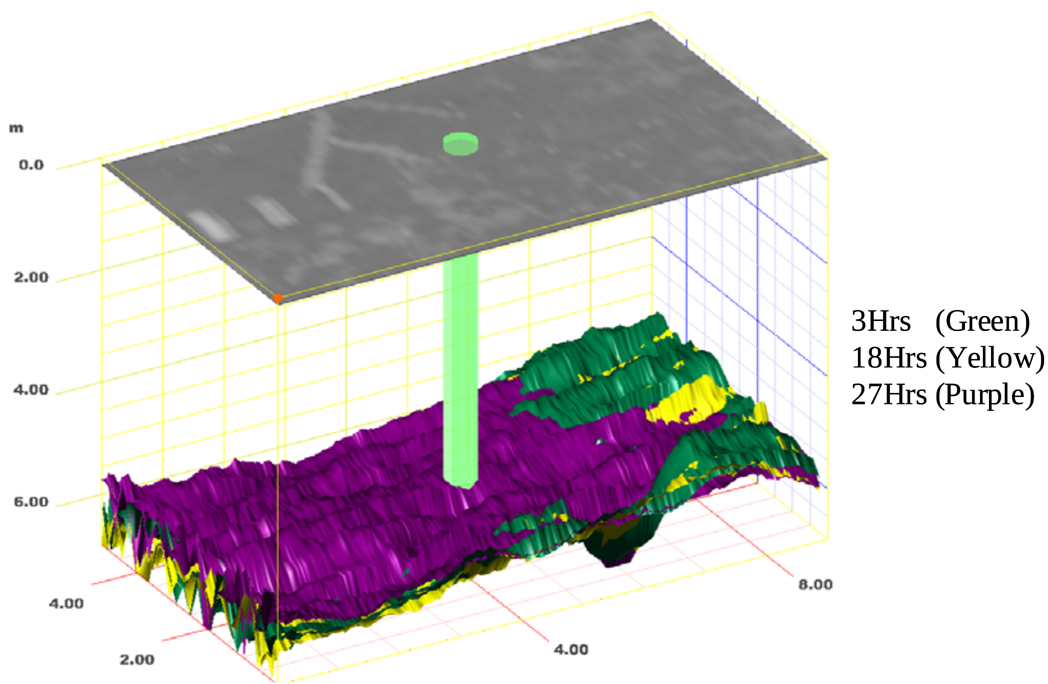


Figure 23: Leak Test results show no max depth improvement after 27 hours. This was carried on for several weeks with no change.

It was thought, based on the PECO report[1], that the sandy soils might be too porous to actually hold the dry gas pocket long enough to measure. So then a 18m long 1m deep trench was dug with a back hoe. 17m of 10cm diam. pipe was buried under 1m of dense clay. The open end of

[1] Graf F.L., "Using ground-penetrating radar to pinpoint pipeline leaks", Materials Performance, 1990, Vol. 29, No. 4, p. 27-29.

an air hose was buried just on top of the pipe to simulate a leak. After tamping it down and measuring over several weeks, no change in the radar signature was observed.

Next a Mr. Fred Graf (retired) was located who originally did the study for Philadelphia Electric Co. back in 1985. His assurance was not only that the results he saw twenty years ago were robust and repeatable[2], but also that the current methods could not work since the air would never be as dry as the natural gas in a pipeline. He suggested either pumping propane (infeasible for safety reasons) or actually surveying real leaks sites in the field. The results from this are presented next.

3.3 FIELD TESTS

Two gas companies very graciously allowed the Util-Lite to be tested in the real world. In these tests we surveyed about seven different gas lines looking for leaks and seeing how good the tool was at locating and following pipes. All of the pipes that were tracked were metal 10cm (4”) gas lines whose depths ranged from 0 to 3m deep.

3.3.1 Columbia Gas: Waynesburg, PA

In Waynesburg, PA, representatives from the Columbia Gas Company presented four leak sites to test the equipment. One, near a county jail, had a steeply sloped section with high grass right in the critical region which made leak detection nearly impossible. The antenna could not swing along the ground and so the amplitude and depth measures that were needed for leak detection could not be done. However, as a pipe locator, Util-Lite worked very well.

Figure 24: The first location was not conducive to making a good leak measurement.

[2] (http://www.geo-graf.com/leaks-ch.htm)

As opposed to the conventional GPR, Util-Lite could handle the high grass and steep slopes while still being able to follow the path of the pipe. The 10 cm (4”) gas line was tracked for several hundred yards to the next building. Since the penetration depth was set to 3m, a section of pipe was missed that went to 3.75m (about 10 feet) as measured by the induction device. 4m is the operating range of the induction device.

(For the specifications of the pipe locator see: www.metrotech.com/pdt.asp?productselect=61)

Util-Lite’s locating accuracy was between 0 to 30 cm compared to the Metrotech. Sometimes it was right on; but sometimes the return sweeping erased the red dot, making it hard to guess the correct location of the pipe. This accounted for the 30cm errors, something easily fixed in software. Otherwise the Util-Lite was quite accurate as compared to the inductive locator.

As for repeatability results, that depended on the soil types and depths that were encountered. In good soil, the pipe would be recognized on nearly every sweep (>90%). In poor conditions, even a hit rate of 25% meant that the pipe could be tracked. One of the advantages of the system if that, when the trail is lost, the user can keep sweeping over the same area until the trail is picked up again. So even a poor result still gets the job done.

The system worked so well that it was even correctly locating the sacrificial anodes that are placed a few feet to one side of the pipe to fight corrosion. Every 5 meters or so a short line would branch off from the pipe. This surprise was good confirmation that the unit was responding correctly and robustly to complex scenarios.

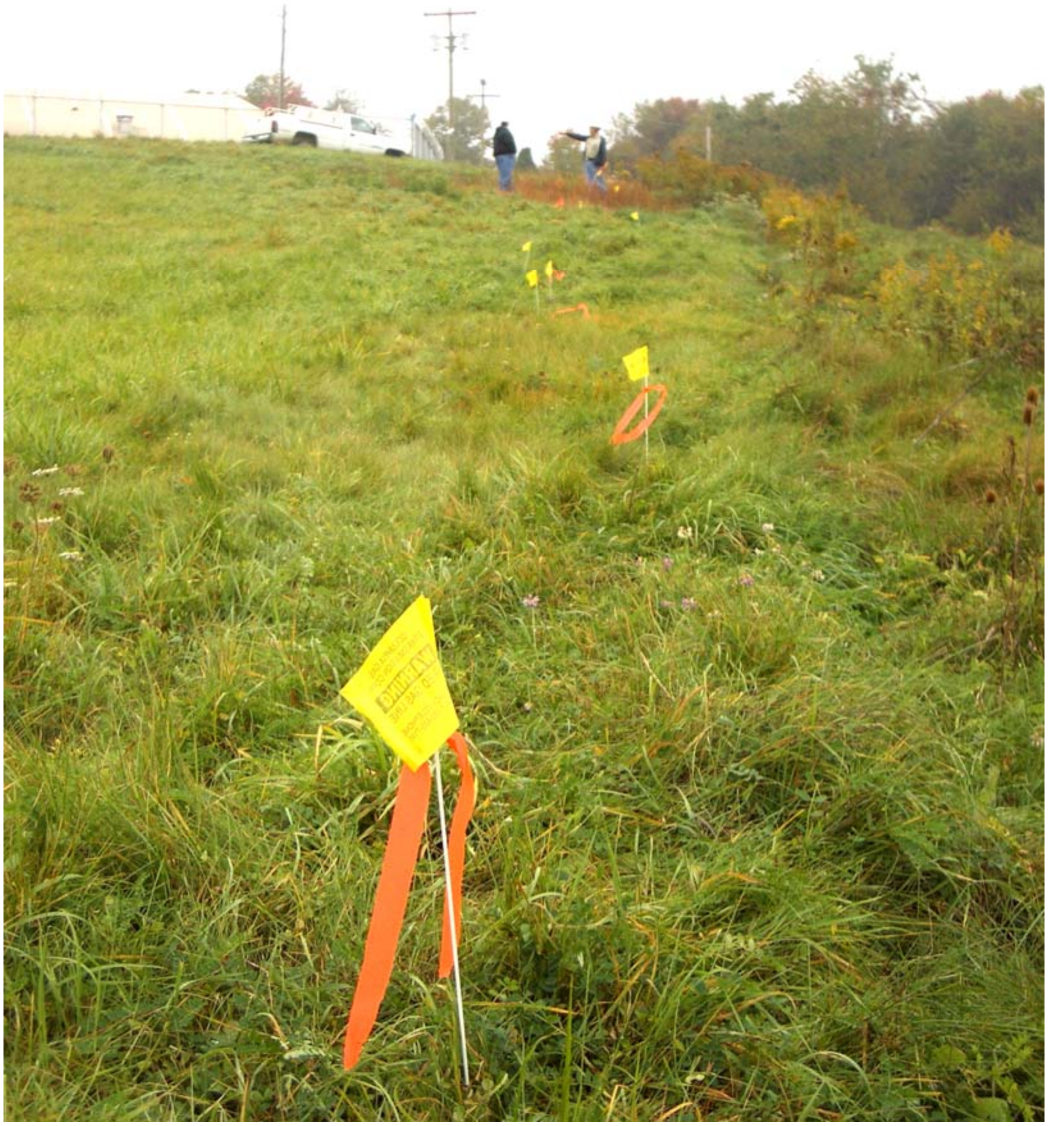


Figure 25: Yellow flags indicate Util-Lite location points. The orange blazes indicate confirmation by an induction locator.

The second site was in a pasture, where there were clearly two leaks. The target location worked very well again, although occasionally Util-Lite's position was off by about 30cm. This probably had more to do with the inability to reposition the cursor in software than any recognition errors.

Figure 26: A production line. Util-Lite could locate the line. At times its reported position was off by about 30cm.

The third site took place across a cow pasture. The leak results at this location are intriguing. The soil clearly showed the general location of a gas leak. The Util-lite was deployed to follow the dipping pipe. There is a pull up in the data at the likely spot. This

pull-up in four targets can be seen in

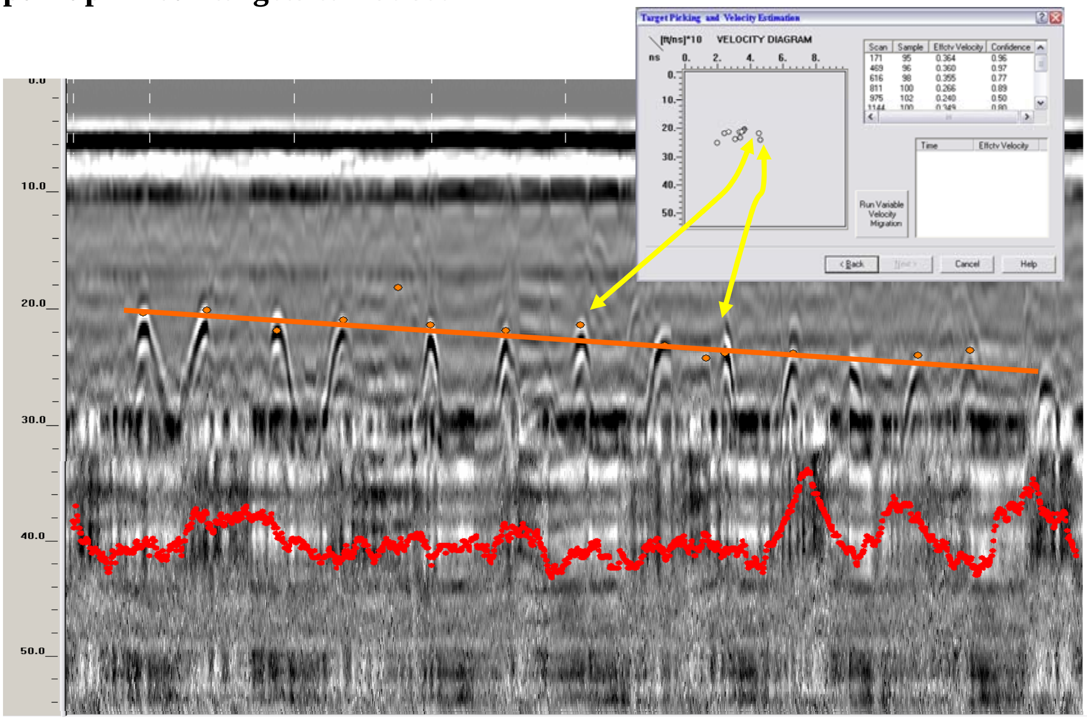


Figure 27. It is also true that there is the expected velocity increase on two of the four target hyperbolas

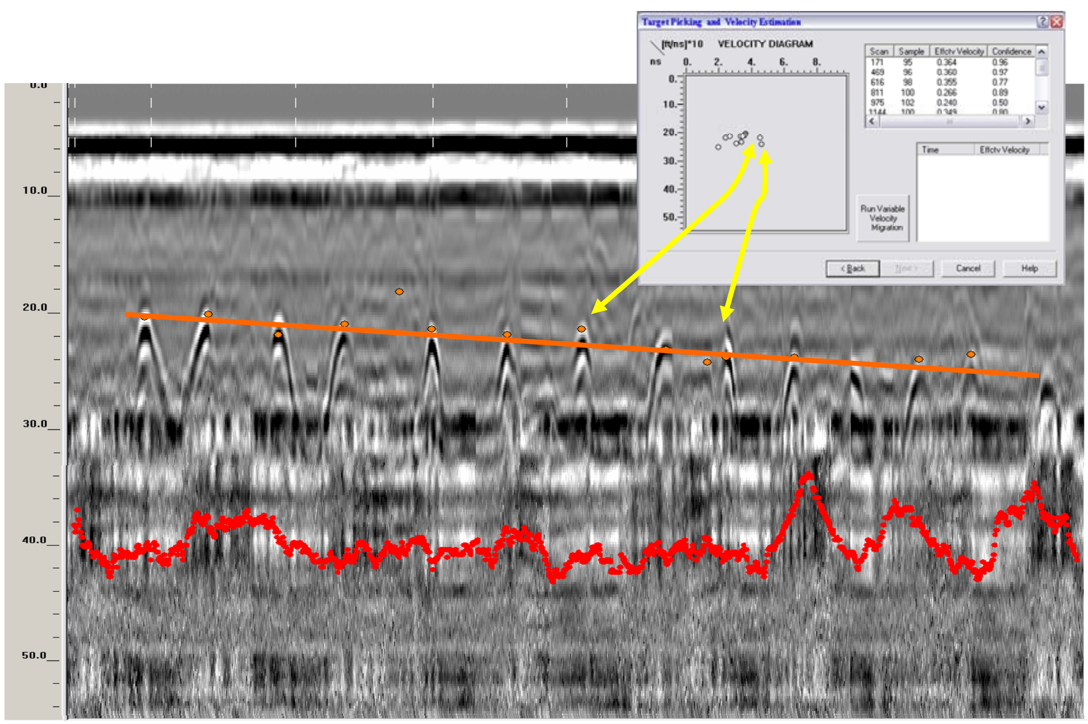


Figure 27: Possible leak area along a dipping pipe. Note the velocity increase in the central target. However, also note no drop in the Max Depth shown in red.

However, one should also see an amplitude and velocity increase as well as an increase in the Max Depth. These did not all seem to happen together. Figure 28 shows the velocities and reflection amplitudes as circles around each target.

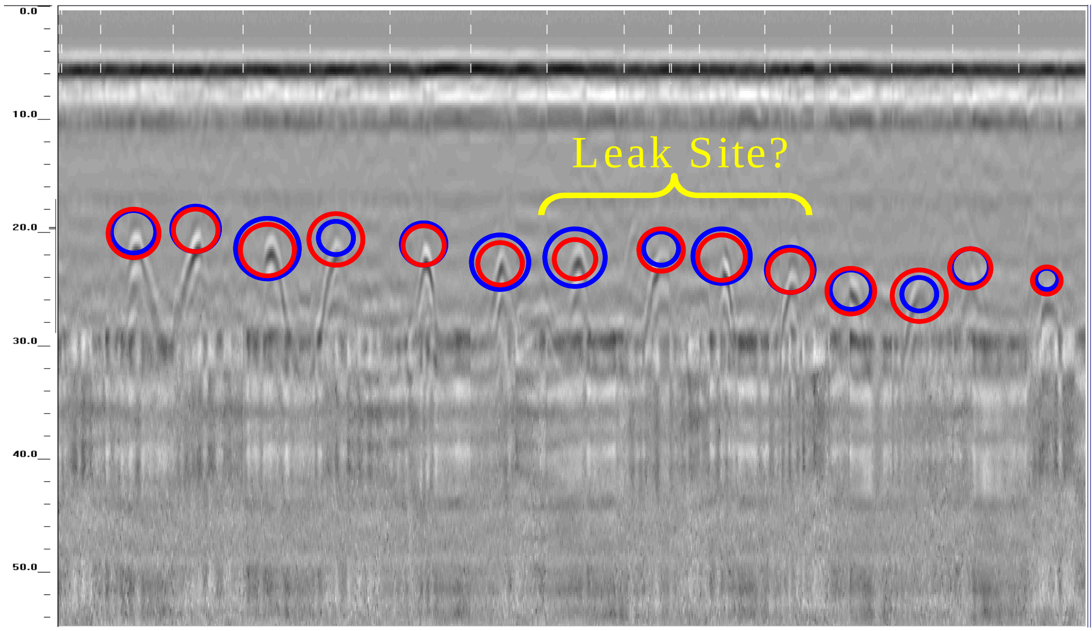


Figure 28: Plots of the change in Velocity (Red) and Amplitude (Blue). The graphs show that for the four points in question, there is little to distinguish our suspected location with the rest of the region.

While there are interesting results in the data, the results from the area of interest could not be used to separate the leak location from the rest. Therefore, successful location of a leak cannot be established.

The last location was pretty much a complete bust, since the 4m pipe depth was deeper than what the radar could penetrate in the riverine clay soil.

3.3.1.1.1 BAY STATE GAS: METHUEN/ LAWRENCE

3.3.1.1.1.1 Delmont St.

The next site, thanks to Bay State Gas was a gas line along Delmont St. in Methuen, MA. Since this was road data, it was a much more controllable environment. The survey was performed with both the Utility Scanner and the Util-Lite, yielding some excellent data comparisons.

The first result (Figure 29) was that one can see the nearly exact correlation between both the Utility Scan system and the Util-Lite, even though the data acquisition schemes are perpendicular. They both could follow the pipe along its course down the road. The target recognition was perhaps 90%: plenty for locating and following the pipe in real time. Many other targets: sewer lines, drainage culverts and laterals where also clearly evident in both data sets.

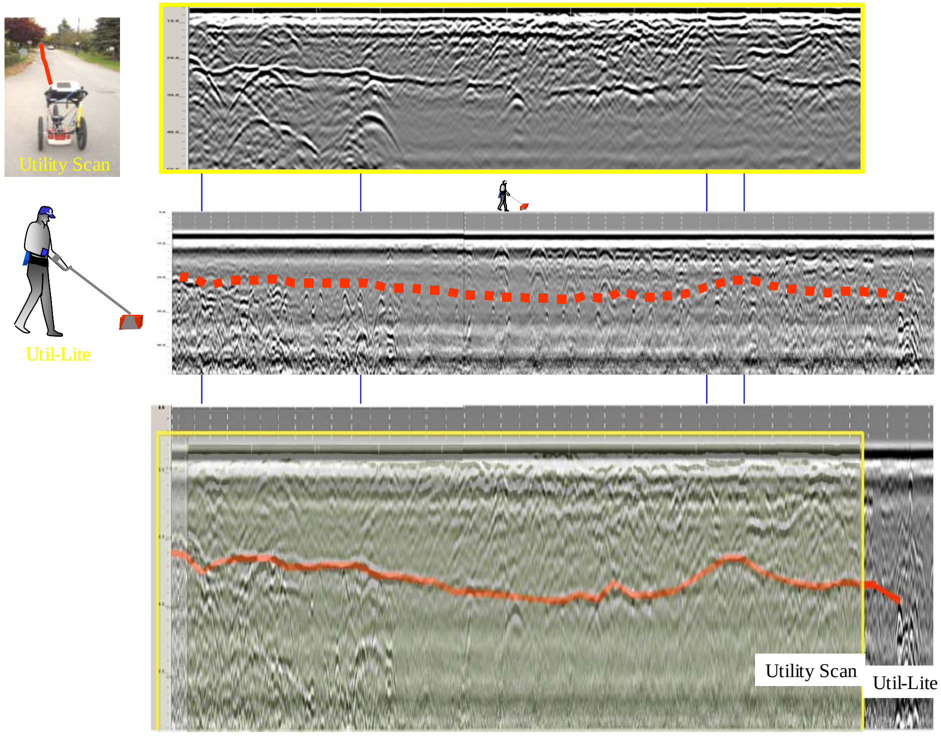


Figure 29: Pipe locating and looking for leaks.

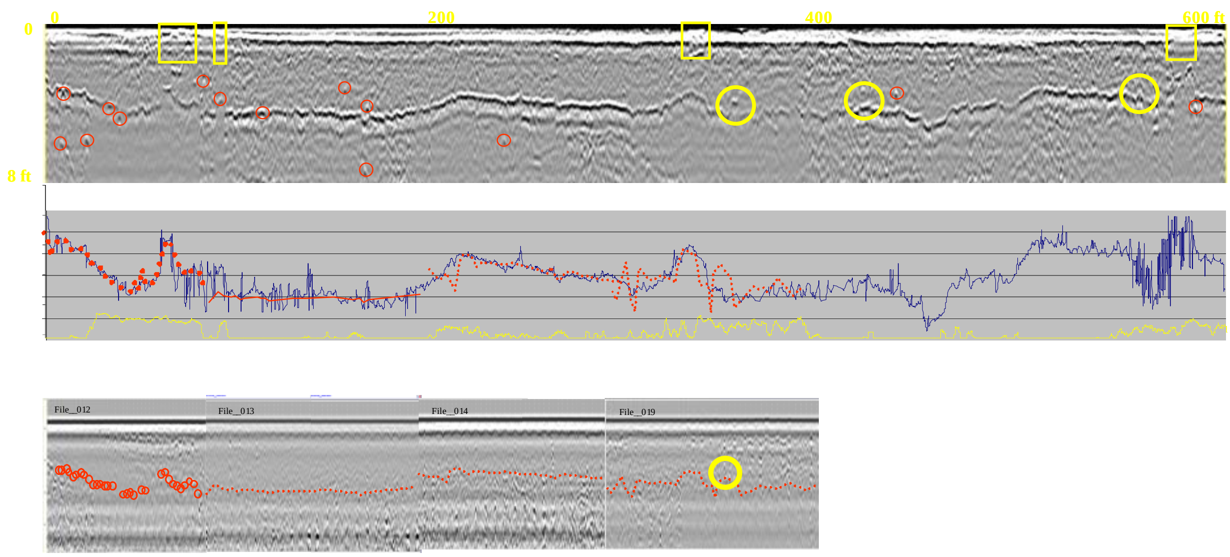


Figure 30: Three possible leak sites are circled in yellow

As far as leaks go, three places are suspected (indicated by yellow circles Figure 30) where the pipe depth was clearly and unnaturally higher than it should be. Two of these happen to coincide with gas odor.

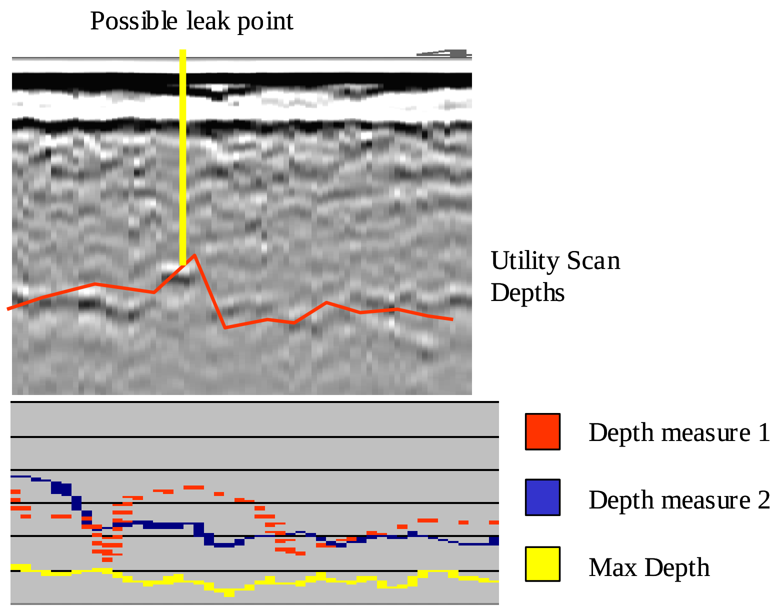


Figure 31: Utility Scan close up view of the suspected leak zone. Note the sudden pull up in the pipe depth.

One location, Figure 31 and Figure 32 show that that max depth and amplitude variations, though too faint to make a positive diagnosis, at least trend in the proper direction to support this theory.

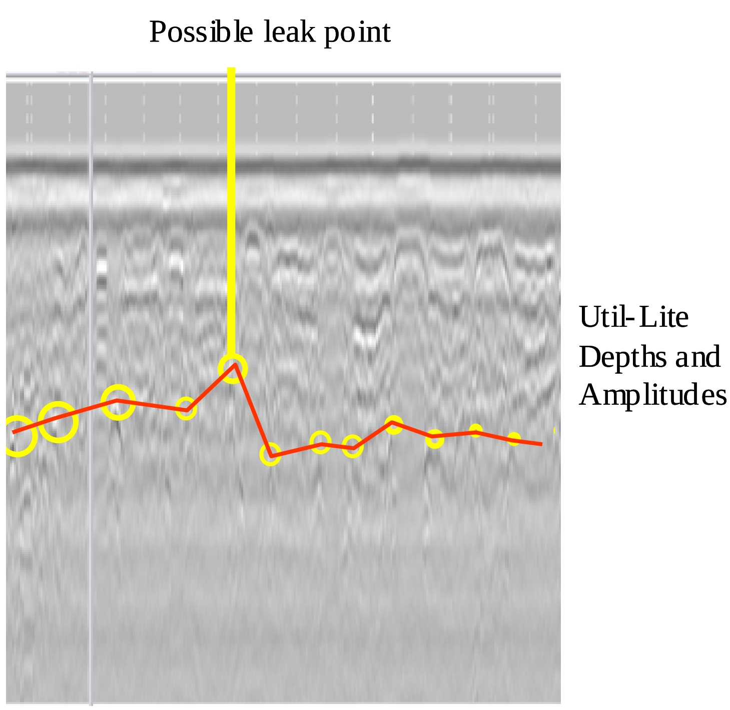


Figure 32: Util-Lite locates the pipe crossing depths, the amplitude variations as well as the velocity changes at each location.

One trench was dug and a leak was found and repaired directly under the patch indicated as a yellow square on the far right side of Figure 30.

Since results await confirmation by digging, nothing concrete can be said about the tool's abilities as a leak detector.

3.3.1.1.1.2 Sheridan Rd., Andover, MA

The last site was in a quiet residential street with an erratically dipping gas line.

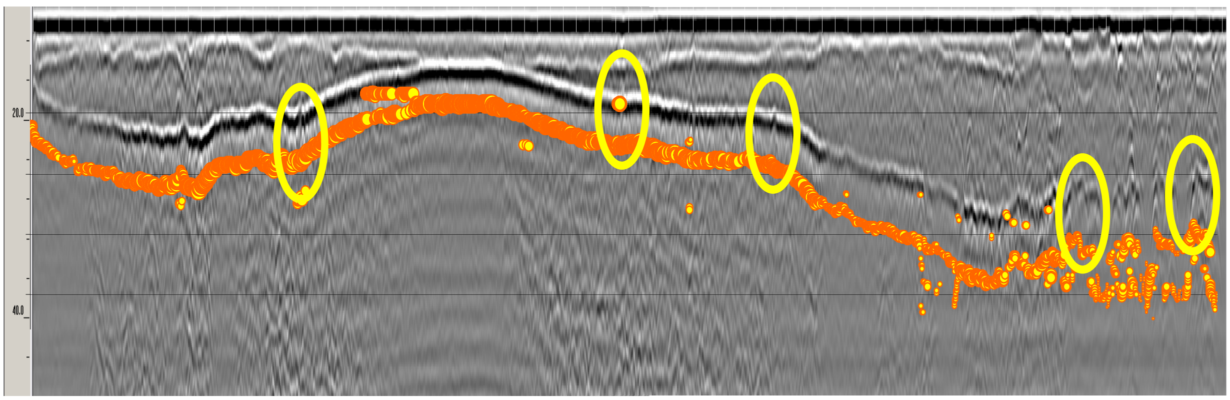


Figure 33: Possible leak locations along the pipe using the Utility Scan

In this soil the Util-Lite located the pipe in somewhat spectacular fashion. Each sweep produced a high confidence return until the very end, when the signal started to fade. The pipe depths and the soil changes at the bottom of the hill (on the right side of Figure 33) started to obscure the pipe. This was also the location of repeated patching, making the disturbed soils difficult to interpret.

Five locations have been indicated as possible regions where the soil has dried out above the gas pipe. This bears little comment until the locations of the leaks can be positively identified.

4 CONCLUSIONS

Through the support of the DOE, GSSI has developed a prototype of a new kind of GPR system that is light and portable and simple to use. It uses innovative pattern recognition techniques to automatically locate and track pipes and other underground targets in real-time as one walks along. It is designed to locate pipes of almost any material type: metal, PVC plastic, concrete etc.

The concept required a completely new lightweight antenna with a built in gyro to sense the angular position of the head. The many benefits of such portability include the ability to negotiate otherwise "hostile" terrain: high grass, tree roots, parking meters, many trees and narrow passages.

The system is designed to pinpoint the location of a target as the unit is swept back and forth in front of the slowly walking user. Dots appear on the screen that correspond to the target position along the sweep. These dots appear at the proper depth. The dot size corresponds to recognition confidence: small means low confidence, large means high confidence. The lower part of the screen displays the GPS position and track as the user walks around. The highly confident target dots appear on this screen as well so that the user can start to sweep out a general layout map of the utilities and their orientations.

In general the location accuracy was between 50% and 90%, where each sweep might produce a target recognition with varying degrees of confidence. In “good” soils with a shallow pipe, a high confidence recognition with each sweep was virtually assured (90%). Poorer soils and deeper pipes returned recognitions with weaker confidence. At the point where the recognition return was about 25%, then a pipe could no longer be tracked using this device.

It is also designed to collect the data needed to locate leaks in gas lines. Although the results are still very much inconclusive, the data and past research in the 1980s suggest that leaks can be found using this device.

5 REFERNCES

Only a small handful of papers has been written, reporting results of GPR's effectiveness as a tool for detecting leaks in utility pipes. Over the last 20 years, several important tests have been conducted mapping controlled releases of fluids in test pits using GPR. (DNAPL and LNAPL releases for example (Sneddon, 2000)). These confirm GPR's sensitivity to subtle changes in soil moisture. Many other experiments have been reported under more realistic conditions where a pipe is actually leaking and the leak in need of detection. (Hunaidi, 1998.) Some have noted the difficulty of GPR in detecting these changes in wet/clay soils. Some of the following references might be helpful.

The only known prior study for detecting gas leaks with GPR was performed by GSSI in collaboration with PECO in the mid eighties by Mr. Fred Graf. His correspondence has been very helpful in the development of this project.

Graf F.L., "Using ground-penetrating radar to pinpoint pipeline leaks", Materials Performance, 1990, Vol. 29, No. 4, p. 27-29.

Carlson B. N., "Selection and use of pipeline leak detection methods for liability management into the 21 st century", Pipeline Infrastructure II, Proceedings of the International Conference, ASCE, 1993

Farmer E., Kohlrust R., Myers G., Verduzco G., "Leak detection tool undergoes field tests", Oil and Gas Journal,December 1988

Hunaidi, O, Giamou, P., GPR for Detection of Leaks in Buried Plastic Water Distribution Pipes, Seventh International Conference on Ground-Penetrating Radar, Lawrence Kansas, USA, 27-30 May 1998.

Sneddon, K. W., Olhoeft, G. R., and Powers, M. H., 2000, Determining and mapping DNAPL saturation values from noninvasive GPR measurements: in Proc.of SAGEEP 2000, 21-25 February 2000, Arlington, VA, M.H. Powers, A-B. Ibrahim, and L. Cramer, eds., EEGS, Wheat Ridge, CO, p. 293-302. (http://www.g-p-r.com/sageep00.PDF)

Links on leak detection:

www.geo-graf.com/leaks-ch.htm
http://www.epri.com/newsletter.asp?issueid=5353&marketnid=8
http://www.geog.leeds.ac.uk/people/e.obrien/research.html
http://www.kcl.ac.uk/kis/schools/hums/geog/phdcharl.htm
www.geophysik.uni-kiel.de/itrinks/ABSTRACT/Abstract.html
www.st-and.ac.uk/~www_sgg/personal/crblink/web/GPRpipe.pdf
http://www.marrserv.com/detsol/water.htm

http://www.nrc.ca/irc/leak/leakdetect.html
http://www.awwa.org/journal/j200es2.htm
http://www.awwarf.com/exsums/90770.htm

http://www.nrc.ca/irc/fulltext/nrcc42068.pdf
http://bigisland.ttclients.com/frtr/pdf/13_wurtsmi.PDF
http://www.cssip.uq.edu.au/gpr2000/abstracts/king01.html

6 APPENDIX A: PRIOR ART

6.1 ELECTRONIC PIPE DETECTION METHODS

There is a limited arsenal of tools available for pipe detection. However, the diversity of techniques shows that each has advantages and shortcomings. For example, only GPR can claim to reliably detect non-metallic pipes, but may fail to detect pipes in some soils. The main categories of pipe detection tools in common use are summarized below.

6.1.1 Pulsed Induction

Pulsed Induction methods detect pipes by generating a displacement current at the surface and trying to detect eddy currents induced in a metal object underneath. This is the technique used in most standard metal detectors[3]. Pulsed Induction equipment is used generally four different ways depending on the application: as an inductive locator, an inductive tracer, a conductive tracer, or as a passive receiver. [4]

6.1.1.1 Inductive Line Location

One positions the Transmitter Box in front, the Receiver Box behind. By walking a grid pattern, one can discover the location of buried metallic objects, with a signal tone indicating their locations. Marking the pavement with chalk reveals a pattern that shows the location of the underground objects.

6.1.1.2 Inductive Line Tracer

When one point of an underground linear conductor (such as a pipe or cable) is known, the transmitter box can be placed over it while the user swings the receiver box around in either direction, listening for the audio signal tone. As one walks away from the transmitter box tracing farther down the line, the transmitter signal will become faint. The transmitter box can then be moved closer so that tracing can continue to the end of the line, or two operators can walk together.

6.1.1.3 Conductive Line Tracer

This is the preferred method of tracing. If one can make electrical contact with a conductive pipe, a signal can be transmitted along it. One can then walk along the ground, following the pipe. This would typically involve following a line from the basement of a house. Plastic pipe is now usually laid with an embedded metal tape or a tracer wire alongside it to allow tracer detection. Otherwise a plumber's snake can be used.

6.1.1.4 Passive Line Tracer

This mode relies on a power line to supply the transmission signal. For example, with the receiver tuned to receive 60Hz, the antennas will be sensitive to signals given off by buried power lines.

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[3] a simple tutorial is provided at http://www.protovale.co.uk/abtpi.html
[4] http://www.fisherlab.com/1_Utility/HTML_Pages/tw8800.asp

High-end units measure depth using two coils separated some distance, so that the signal return from the pipe can be compared. The accuracy is reportedly quite good (<10%) under ideal conditions. However, depth estimates are thrown off by several factors: poor induction by the transmitter, poor signal strength at the receiver, adjacent utilities or Ts or elbows, and soil that is too dry or overly saturated.[5] [6] Another shortcoming of these systems has to do with detecting large diameter pipes ($\geq$ 24"), since the signal gets diffused away. Following pipes that are close together is also difficult, as well as tracing pipes that have gasketed joints that interrupt signal conduction. Power line interference can also interfere with the signal.

6.1.2 Magnetic Locators

These devices take several forms, all of which rely on measuring changes in an induced magnetic field to detect the presence of a ferromagnetic object. They locate buried ferrous objects while rejecting non-magnetic objects such as aluminum cans and bottle caps.

But they are especially useful in detecting valves and junction boxes associated with metal lines, since these are generally undetectable with the pulsed induction pipe locators.

Cast-iron or steel pipe laid end to end will produce a strong signal to the magnetic locators at each joint — even if the pipes are welded together – since these devices are most sensitive at the ends of magnetic objects.[7]

6.1.3 EM Locators

Basically the same as magnetic locators, EM locators use more sophisticated processing. They typically have the transmit and receive magnetic coils separated by distances of up to several meters, whereas the magnetic locators have them co-located. The larger separation means that deeper objects may be detected, although at a loss of spatial resolution. The EM locators may use pulses, for a transient time domain solution, or they may use a sinusoidal wave. This can be either a fixed frequency, or multiple variable frequencies such as GSSI's GEM-300.[8]

6.1.4 Resistivity Methods

Resistivity locators have been used for pipe location, but the method is generally cumbersome and time consuming, often requiring several probes drilled into the ground.[9]

6.1.5 GPR Pipe Detection

GPR can accurately pinpoint buried pipeline leaks without digging. The leaking substances can be 'seen' at the source by the radar via the changes in the surrounding soil's electrical parameters. A handful of papers has recently been written, reporting results of GPR's

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[5] http://www.fisherlab.com/Operation_Man/TW-8800.pdf
[6] http://www.radiodetection.com/theorybook/html/theory2_10.html
[7] http://www.sslocators.com/
[8] http://www.geophysical.com/ or http://www.geonics.com/em31.html
[9] see for example: http://www.agiusa.com/brochure_sewer_pipe.shtml
http://home.intekom.com/SpectralGeophysics/Pipe.html

effectiveness as a tool for detecting leaks in utility pipes.[10] Over the last 20 years, several important tests have been conducted mapping controlled releases of fluids in test pits using GPR.[11] These confirm GPR's sensitivity to subtle changes in soil moisture. Many other experiments have been reported under more realistic conditions where a pipe is actually leaking and the leak in need of detection. Some have noted the difficulty of GPR in detecting these changes in wet, clay soils.

GPR has a long and sometimes checkered history of pipe detection. Although it is perhaps the best general pipe locator available, it is often mistakenly assumed to be a silver bullet. In fact, GPR has difficulty in highly conductive clay and silty soils. Sometimes clutter from other objects can obscure pipes. And most commonly, subtleties in processing and interpretation mean that less skilled surveyors may fail to detect pipes that would otherwise be clearly resolved.

This means that GPR can never be 100% successful at locating pipes. However, expanding GPRs capabilities into full 3D images has made detection much more robust, and interpretation much simpler. This means that GPR is really now entering into a new phase of capability, making it far more versatile than ever before.

There are two classes of GPR that are in general use. The most widely used is impulse, where a single cycle (or several) is transmitted, and the resulting echo is sampled down to audio frequencies for processing. This radar corresponds to a Time Domain Reflectometer instrument. The second class or GPRs is Stepped CW. In this, a single frequency is output and the receiver is allowed to come to equilibrium. This can take from 50 microseconds to milliseconds. The cycle is then repeated for many different frequencies, and the results converted to an equivalent time display via an inverse FFT. The stepped CW system has a narrower beam then impulse, and so does not show the typical hyperbolas for pipe targets. This may make it harder to discriminate many targets nearby, and also makes it almost impossible to obtain direct depth verification. Depth accuracy can only depend on how well the soil dielectric constant is known. With impulse, the shape of the hyperbola contains information on the average dielectric constant and the accurate depth.

Although several companies compete to produce ever-simplified tools for general use in locating underground utilities, This current proposal really has no good GPR prior art analog with which to compare it. Perhaps it should most fairly be compared to multi-element prototype systems that

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[10] Hunaidi, O, Giamou, P., GPR for Detection of Leaks in Buried Plastic Water Distribution Pipes, Seventh International Conference on Ground-Penetrating Radar, Lawrence Kansas, USA, 27-30 May 1998.
(http://www.nrc.ca/irc/fulltext/nrcc42068.pdf)
www.geo-graf.com/leaks-ch.htm
www.st-and.ac.uk/~www_sgg/personal/crblink/web/GPRpipe.pdf
http://www.kcl.ac.uk/kis/schools/hums/geog/phdcharl.htm
http://www.geog.leeds.ac.uk/people/e.obrien/research.html
www.geophysik.uni-kiel.de/itrinks/ABSTRACT/Abstract.html

[11] Sneddon, K. W., Olhoeft, G. R., and Powers, M. H., 2000, Determining and mapping DNAPL saturation values from noninvasive GPR measurements: in Proc.of SAGEEP 2000, 21-25 February 2000, Arlington, VA, M.H. Powers, A-B. Ibrahim, and L. Cramer, eds., EEGS, Wheat Ridge, CO, p. 293-302. (http://www.g-p-r.com/sageep00.PDF)

have recently been produced. An example would be GSSI's Terravision system that produces a 3D picture after one swath of data has been acquired**.** The Swedish company, Mala Geoscience AB, has also built a radar array in the CART Imaging System for WTI.

TABLE 1 - COMPARISON OF KEY ATTRIBUTES OF PIPE DETECTION METHODS

Method	**Max Depth 10" Metal Pipe**	**Depth Estimation Accuracy**	**Pipe Diameter Estimation**	**False alarm rate**	**Detection Problems**	**Survey Speed**	**Cost (capital + operating)**
Pulsed_Induction							
Inductive Locator	10'	GOOD	NO	MEDIUM	Large Pipes; Plastic	SLOW	LOW
Inductive Tracer	10'	GOOD	NO	MEDIUM	Large Pipes; Plastic	MEDIUM	LOW
Conductive Tracer	15'	GOOD	NO	MEDIUM	Large Pipes; Plastic	FAST	LOW
Mag	6'	NA	NO	MEDIUM	Non-Mag	FAST	MEDIUM
EM	10'	POOR	NO	HIGH	Non-Metal	FAST	MEDIUM
Resistivity	10'	POOR	NO	LOW	Non-Metal	V. SLOW	LOW
GPR	20'	GOOD	NO	LOW	Deep Clay Soils	MEDIUM	HIGH

6.2 GENERAL LEAK DETECTION OVERVIEW[12]

The current best practice for leak detection takes several forms depending on the situation. Much has been written on the subject and there are several good sites[13] and references[14] available

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[12] Much of the leak detection overview information is derived from an article by Dr Jun Zhang of REL Instrumentation Limited, Manchester, UK., entitled *Designing a Cost Effective and Reliable Pipeline Leak Detection System*.

[13] http://www.epri.com/newsletter.asp?issueid=5353&marketnid=8
http://www.nrc.ca/irc/leak/leakdetect.html
http://www.awwa.org/journal/j200es2.htm
http://www.awwarf.com/exsums/90770.htm

[14] This list, taken from Dr Jun Zhang's article mentioned above, is included here as a useful reference guide.

[1] Bose J. R., Olson M. K., "TAPS's leak detection seeks greater precision", Oil and Gas Journal, April 5, 1993, p43.
[2] Carlson B. N., "Selection and use of pipeline leak detection methods for liability management into the 21 st century", Pipeline Infrastructure II, Proceedings of the International Conference, ASCE, 1993
[3] Farmer E., Kohlrust R., Myers G., Verduzco G., "Leak detection tool undergoes field tests", Oil and Gas Journal, December 1988
[4] Graf F.L., "Using ground-penetrating radar to pinpoint pipeline leaks", Materials Performance, 1990, Vol. 29, No. 4, p. 27-29.
[5] Griebenow G., Mears M., "Leak detection implementation: modelling and tuning methods", American Society of Mechanical Engineers, Petroleum Division, 1988, Vol.19, p9-18
[6] Hamande A., Cie S. et, Sambre J. sur, "New system pinpoints leaks in ethylene pipeline", Pipeline & Gas Journal, April 1995, Vol. 222, No. 4, p38-41
[7] Hennigar G. W., "Leak detection: new technology that works", Gas Industries, January 1993, Vol. 37, p16-18
[8] Hough J.E., "Leak testing of pipelines uses pressure and acoustic velocity", Oil and Gas Journal, Vol. 86, No. 47, 1988, p35-41.
[9] Klein W. R., "Acoustic leak detection", American Society of Mechanical Engineers, Petroleum Division, 1993, Vol.55, p57-61

6.2.1 **Biological:**

Experienced personnel will walk along a pipeline, looking for unusual patterns nearby, smelling substances that could be released from the pipeline or listening to noises generated by product escaping from a pipeline hole. Trained dogs are also used to smell substances released from a leak.

6.2.2 **Temperature change**:

Some leaks can be detected by temperature changes in the soil. Temperature sensors such as an optical time domain reflectometer, are used to detect changes of temperature in the immediate surroundings of a leak.[15]

6.2.3 **Acoustic devices**:

Noise is generated as the gas escapes from the pipeline. An acoustic pipe tracer locates buried plastic gas lines by introducing an identifiable acoustic signal into the pipe. The receiver detects the sound waves that radiate from the pipe into the surrounding soil. The system operates through a variety of surface materials and is safe for use by suitably trained gas industry personnel. Due to the limitation of the detection range, it is usually necessary to install many acoustic sensors along the line.[16]

6.2.4 **Sampling devices**:

If the product inside a pipeline is highly volatile, a vapor monitoring system can be used to detect the level of hydrocarbon vapor in the pipeline surroundings. This is usually done through gas sampling. The sampling can be done by carrying the device along a pipeline or using a sensor tube buried in parallel to the pipeline. The response time of the detection system is usually from several hours to days.

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[10] Kurmer J. P., Kingsley S. A., Laudo J. S., Krak S. J., "Applicability of a novel distributed fibre optic acoustic sensor for leak detection", Proceedings SPIE Vol. 1797, 1993, p63-71

[11] Liou C. P., "Pipeline leak detection based on mass balance", Pipeline Infrastructure II, Proceedings of the International Conference, ASCE, 1993

[12] Liou J. C. P., Tian J., "Leak detection: a transient flow simulation approach", American Society of Mechanical Engineers, Petroleum Division, 1994, Vol.60, p51-58

[13] Mears M. N., "Real world applications of pipeline leak detection", Pipeline Infrastructure II, Proceedings of the International Conference, ASCE, 1993

[14] Parry B., Mactaggart R., Toerper C., "Compensated volume balance leak detection on a batched LPG pipeline", Proceedings of Offshore Mechanics & Arctic Engineering conference (OMAE), 1992

[15] Sperl J. L., "System pinpoints leaks on Point Arguello offshore line", Oil & Gas Journal, Sept 9, 1991, p47-52

[16] Turner N. C., "Hardware and software techniques for pipeline integrity and leak detection monitoring", Proceedings of Offshore Europe 91, Aberdeen, Scotland, 1991

[17] Weil G.J., "Non contact, remote sensing of buried water pipeline leaks using infrared thermography", Water Resources Planning and Management and Urban Water Resources, 1993, p404-407

[18] Zhang X. J., "Statistical leak detection in gas and liquid pipelines", Pipes & Pipelines International, July -August 1993, p26-29

15 http://www.predictive-maintenance.com/pipe.html

16 http://www.marrserv.com/detsol/water.htm

6.2.5 **Negative pressure**:
When a leak occurs, a rarefaction wave is produced in the pipeline contents, which propagates both upstream and downstream. Pressure transducers can be used to measure pressure gradient with respect to time. Usually two sensors are used for each pipeline segment.

6.2.6 **Flow or pressure change**:
If the flow or pressure rate of change at the inlet or outlet is higher than a predefined figure within a specific time period, then a leak alarm is generated.

6.2.7 **Mass or volume balance**:
If the difference between an upstream and down stream flow measurement changes by more than an established tolerance, a leak alarm will be generated. This method allows the detection of a leak that does not necessarily generate a high rate of change in pressure or flow.

6.2.8 **Dynamic model based system**:
This technique attempts to mathematically model the fluid flow within a pipeline. The method requires flow, pressure, temperature measurements at the inlet and outlet of a pipeline, ideally also pressure/temperature measurements at several points along the pipeline.

6.2.9 **Pressure Point Analysis (PPA)**:
Based on the assumption that the pressure in the line drops due to a leak. An appropriate decrease in the mean value of a pressure measurement generates a leak alarm.

TABLE 2 - COMPARISON OF KEY ATTRIBUTES OF DIFFERENT LEAK DETECTION METHODS

Method	Leak sensitivity	Location estimate available	Work through operational changes	24 hour availability	False alarm rate	Maintenance requirement (expertise)	Cost (capital + operating)
Biological	YES	YES	YES	NO	LOW	MEDIUM	HIGH
Temperature change	YES	YES	YES	NO	MEDIUM	MEDIUM	HIGH
GPR	YES	YES	YES	NO	MEDIUM	MEDIUM	HIGH
Acoustic	YES	YES	NO	YES	HIGH	MEDIUM	MEDIUM
Sampling	YES	YES	YES	NO	LOW	MEDIUM	HIGH
Negative pressure	YES	YES	NO	YES	HIGH	MEDIUM	MEDIUM
Flow change	NO	NO	NO	YES	HIGH	LOW	LOW
Mass balance	NO	NO	NO	YES	HIGH	LOW	LOW
Dynamic model	YES	YES	YES	YES	HIGH	HIGH	HIGH
PPA	YES	NO	NO	YES	HIGH	MEDIUM	MEDIUM

Note that the above attributes are common features of the leak detection methods. In practice, the performance of each method varies considerably depending on the vendors, pipeline operating conditions and quality of the hardware/instrumentation system available. Examination of **Table 1** shows that there is no method that is rated "good" for all the attributes. In particular, **false alarm** appears to be a common problem for all the techniques except the biological and sampling methods, which cannot monitor a pipeline continuously.

http://bigisland.ttclients.com/frtr/pdf/13_wurtsmi.PDF
http://www.cssip.uq.edu.au/gpr2000/abstracts/king01.html
http://www.seg.org/publications/geoarchive/1997/may-jun/zeng.pdf

7 Appendix B: User Interface

The user interface has several screens used to control both the basic and the more advanced features. All features are described briefly below.

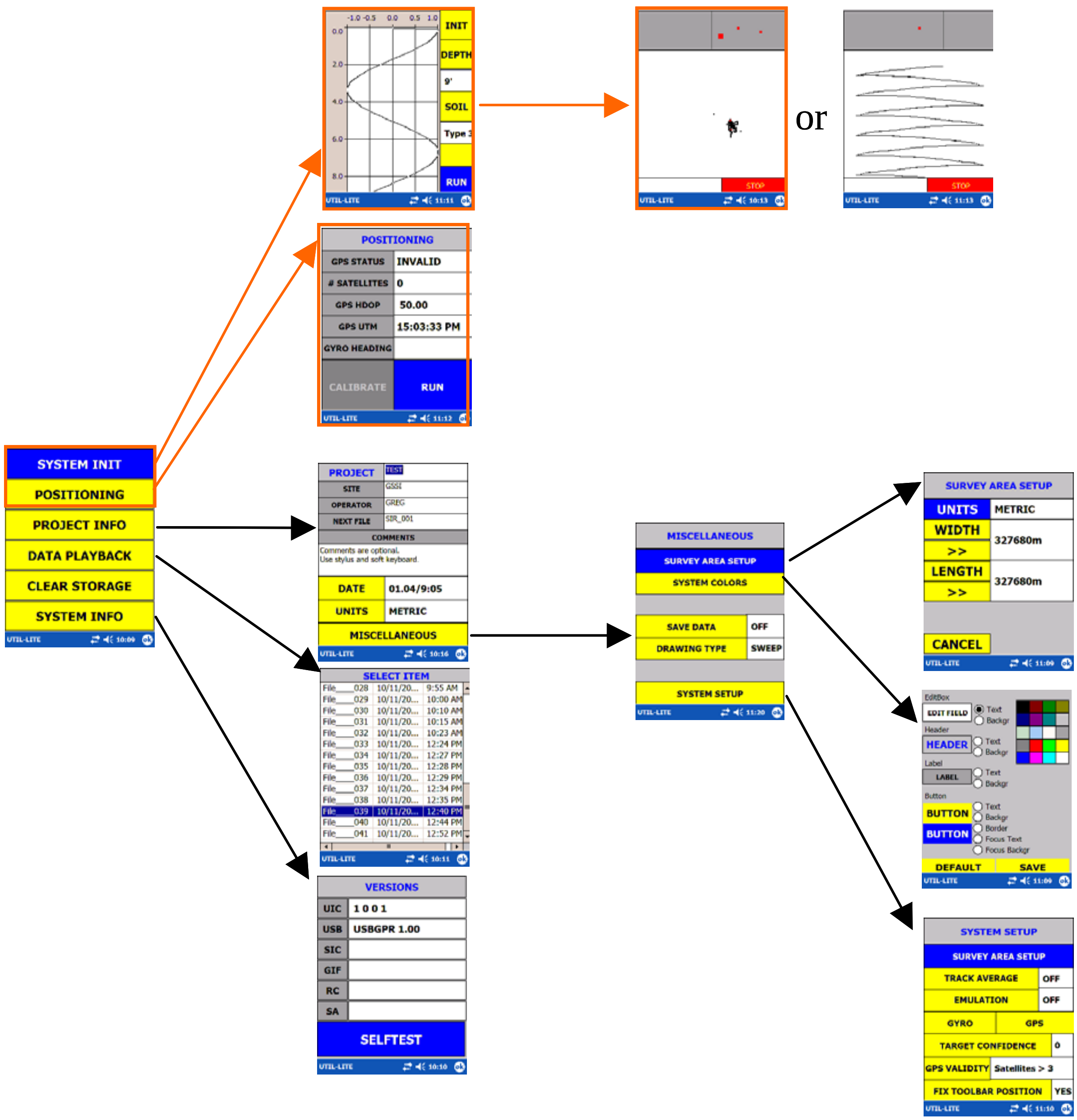

Figure 34: Flow diagram of the user interface srceens.

7.1.1 Positioning

The first thing to do is hit positioning to calibrate the gyro. Place the antenna directly in front of the user and rest it on the ground. Hit calibrate and wait several seconds while an average of the baseline voltage is calculated for the gyro. This helps prevent drift during operation. Once the system beeps and shows numbers (like –0.13 degrees) in the GYROHEADING slot one is now ready to locate pipes. If one also uses the GPS, hitting RUN collects GPS information and shows to whether there are enough satellites visible to get good positioning. Once the GPS STATUS is VALID one can track GPS data. For a “cold start” the longest delay for getting a valid position is about a minute. Hitting **ok** returns to the main menu.

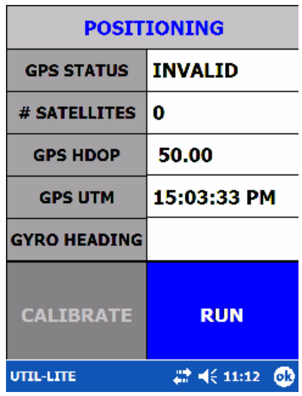

Figure 35: Positioning screen

7.1.2 System Init

Now hit System init. One should see data appear in the data pane.
Set the desired depth and the anticipated soil type. The depth options are 3,6,9,12,18 feet. There are four soil types. Soil 1 corresponds to a dielectric of 5 which is good for dry sands. Soil 2 is dielectric 5 for wet sands and granite. Soil Type 3 is dielectric 9, appropriate for loose, and Soil Type 4 is dielectric 11 which could be used for clay.

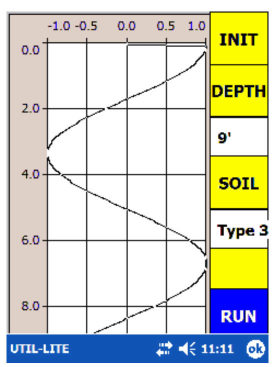

Figure 36: The initialization screen shows both that the antenna is working and the quality and depth penetration of the data.

After each change, look at the bottom of the trace for signs of signal instability. Notice that the deeper one goes, or the higher the soil type, the noisier the bottom of the trace looks. This will give a rough idea of whether one can penetrate as deeply as one would like.

7.1.2.1 RUN

Once the depth/dielectric parameters are, hitting RUN presents the main data screen. Depending on how the parameters are set (see below) one of two screens will appear.
The normal screen displays a cookie trail using the GPS information, but one can set it instead to display the path in an idealized fashion, as the system is swept back and forth: sort of a moving strip chart.

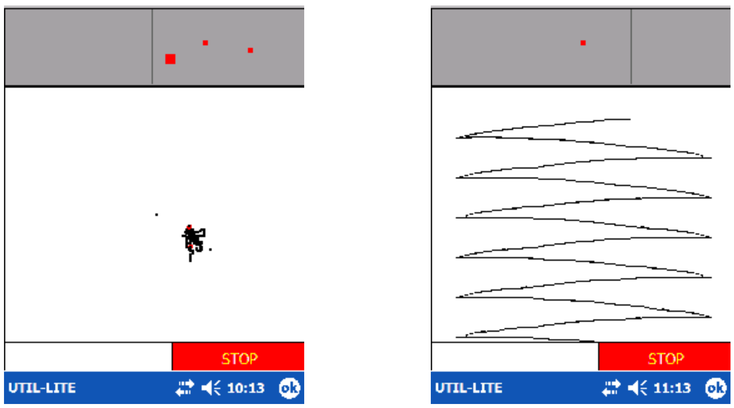

Figure 37: The two data collection options.

7.1.3 Project Info

Here one can define the names within the project and write in comments. Here the date stamp can be set and the units defined. Hitting Miscellaneous gets to the part where most of the preset values are controlled. Hitting **ok** returns to the main menu.

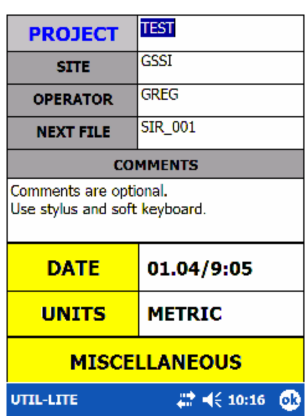

Figure 38: The project Information page for storing site notes.

7.1.4 Miscellaneous

Most of the more complex options are buried in the “miscellaneous” menu.
Here is where one can set the RUN display mode mentioned above to SWEEP or GPS depending on which display is preferred. One can also choose to save the data to the standard DZT file type opening viewing the actual data in RADAN is desire.

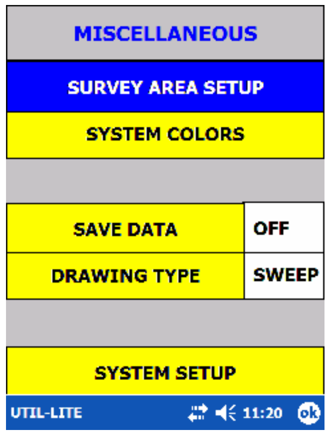

Figure 39: This miscellany menu s is where a lot of the advanced controls are kept.

7.1.4.1 Survey Area Setup

Accessed from the miscellaneous menu, System Area Setup lets one set the area of the initial GPS field. As the user wanders out of this area, the screen is zoomed out to fit all the data on the page.

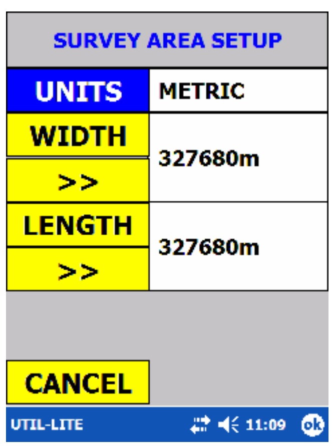

Figure 40: This page sets up the initial zoom factor for the GPS window.

7.1.4.2 System Colors

Accessed from the miscellaneous menu, The System Colors page lets one change various colors in the user interface.

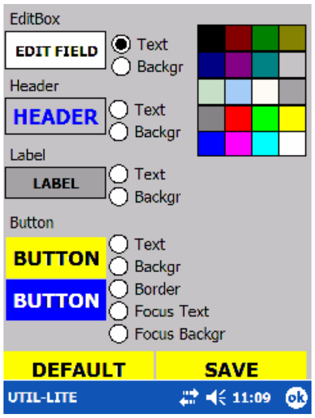

Figure 41: Color menu

7.1.4.3 System Setup

Accessed from the miscellaneous menu, The System Setup screen allows for control and test of different parts of the system,

- One can turn Track Average ON if not going in a straight line, but wandering all around. It tries to keep the GYRO sweeps in the center of the screen. Turning it off assumes progress roughly straight ahead based on the initial calibration.
- Emulation mode ON is used for testing the PDA without being hooked up to the antenna. It simply produces a fake sinewave signal and fake targets.
- GYRO and GPS buttons are used to test each separately.
- Target Confidence sets the threshold at which targets found in the top screen get painted in the GPS window.
- GPS Validity lets one decide which threshold to use to determine whether the GPS signal is valid.
- Fix Toolbar Position is basically a Pocket PC bug fix and should be left to YES.

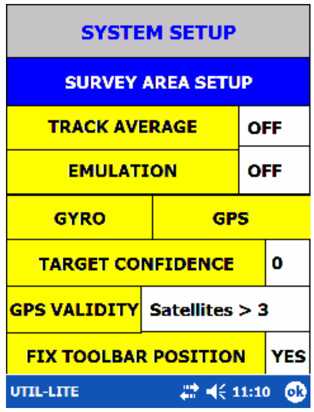

Figure 42: System Setup screen.

To get back to the Main Menu hit **ok** several times.

7.1.5 Data Playback

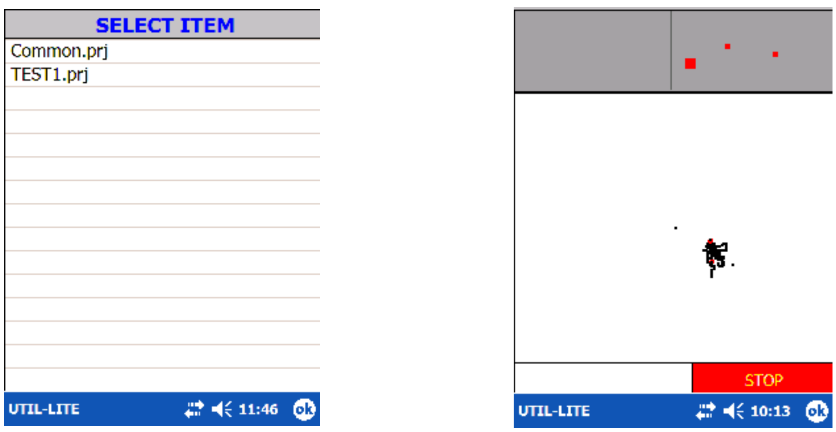

Figure 43: The Data Playback menus.

This function is accessed back at the Main Menu. The user selects the project in which he has stored the data. Then he clicks the central button below the screen to go inside that folder. Then, after selecting the file to play back, he hits that center button again to play back the file. The user then sees the data reappear in exactly the way in which it was collected. Hitting **ok** returns to the main menu.

7.1.6 Clear Storage

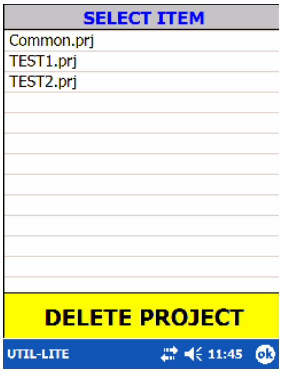

Figure 44: Clear Storage

This function is accessed back at the Main Menu. The screen allows the user to get rid of obsolete projects by selecting and hitting DELETE PROJECT. Hitting **ok** returns to the main menu.

7.1.7 System Info

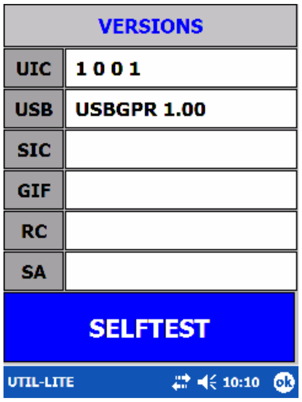

Figure 45: Screen Info provides software and firmware information.

Again accessed from the main menu, this screen simply gives the version information for the software. Hitting SELFTEST cycles through each component to check its version information. Hitting **ok** returns to the main menu.