DIFFERENTIAL SOIL IMPEDANCE OBSTACLE DETECTION

QUARTERLY REPORT

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ABSTRACT

This project develops a new and unique obstacle detection sensor for horizontal directional drilling (HDD) equipment. The development of this new technology will greatly improve the reliability and safety of natural gas HDD construction practices. This sensor utilizes a differential soil impedance measurement technique that will be sensitive to the presence of plastic and ceramic, as well as metallic obstacles.

The use of HDD equipment has risen significantly in the gas industry because HDD provides a much more cost-effective and less disruptive method for gas pipe installation than older, trenching methods. However, there have been isolated strikes of underground utilities by HDD equipment, which may have been avoided if methods were available to detect other underground obstacles when using HDD systems. GTI advisors from the gas industry have ranked the value of solving the obstacle detection problem as the most important research and development project for GTI to pursue using Federal Energy Regulatory Commission (FERC) funds available through its industry partner, GRI.

GTI proposes to develop a prototype down-hole sensor system that is simple and compact. The sensor utilizes an impedance measurement technique that is sensitive to the presence of metallic or non-metallic objects in the proximity of the HDD head. The system will use a simple sensor incorporated into the drill head. The impedance of the soil will be measured with a low frequency signal injected through the drill head itself. A pair of bridge type impedance sensors, mounted orthogonal to one another, is coupled to the soil. Inclusions in the soil will cause changes to the sensor balance distinguishable from homogeneous soil.

The sensor will provide range and direction data for obstacles near the HDD head. The goal is to provide a simple, robust system that provides the information required to avoid obstacles. This must be done within the size and ruggedness constraints of the HDD equipment. Imaging obstacles is not within the scope of this work, as it would require a more elaborate sensor than is practical within the HDD head.

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EXECUTIVE SUMMARY

The North American gas industry is increasing its usage of guided directional drilling for the installation of gas services and mains. This increased usage is limited by an increased awareness of the hazards associated with drill head collision with buried utility lines such as gas, electric power, water, telephone and sewer. Users of guided drilling equipment, the customers they serve, and the owners of buried utility lines would all benefit from the development of sensing technology that could help avoid unintentional contact with buried obstacles.

GTI has kept abreast of recent developments in proximity sensing and ranging. GTI also maintains a dialogue with the natural gas industry through various advisory groups. This feedback has provided a set of criteria for an obstacle detection system. These define the constraints on the cost and complexity of any system to be deployed in an underground construction environment.

The obstacle detection system being developed in this project utilizes an impedance sensing technique. This technique can resolve small changes in the impedance of the surrounding environment caused by objects of varying resistive and dielectric properties. Plastic pipe and ceramic conduits represent discontinuities in the soil that should be easily discernable. The sensor would simply be an array of electrodes around the drill head; no additional sensors are required above ground. The body of the drill itself is used to launch the sensing signal into the soil, eliminating any blind spot ahead of the drill. The sensing signal is in the frequency range below 500kHz, avoiding the attenuation issues associated with Ground Penetrating Radar operating in the range above 100MHz.

Simple signal processing and multiplexing will be used to determine the direction and range of an obstacle. The goal is to detect and avoid the obstacle, not to image it, eliminating the need for high frequency time-of-flight signal processing. The normal rotation of the drill head will be utilized to scan the vicinity of the head for obstacles. The array could also be used to passively sense the 60 Hz signatures radiated from buried power lines.

INTRODUCTION

This project will focus on the development of technology to improve the reliability and safety of gas distribution systems and construction methods. The objective is to further develop an obstacle detection system for directional drilling rigs by testing a sensor concept in a variety of simulated field conditions

GTI has been involved in developing new technologies for guided directional drilling since 1984. GTI supported the conception and commercialization of new products that made horizontal directional drilling (HDD) an increasingly growing practice in the gas distribution industry. In the 1980s, several manufacturers developed new hardware and methods for guided horizontal drilling for service installation applications: gas line services, electrical and cable installations, water and sewer lines, and telephone systems. Consequently, today there are many manufacturers and users of horizontal directional drilling equipment worldwide. In North America, GTI-patented technology is present on about 70% of all newly manufactured HDD equipment (Figure 1).

Figure 1. Typical HDD Rig For Gas Applications

With the success in reducing installation costs and the subsequent increased use of HDD, crowded utility easements have become more common and the potential for underground contact with other utilities or obstacles has risen dramatically. Over the past few years, there have been a few extreme incidents of damage resulting from drill collisions with buried facilities.

In addition to dramatic incidents, there are thousands of other utility strikes on gas, electric, telecommunications, water, and sewer lines that occur on a yearly basis. Taken together, these examples illustrate the problems for guided drilling equipment and the need for obstacle detection. For the gas

industry, one of the most serious situations occur when a guided drilling head or back reamer penetrates a residential sewer line, and a plastic gas pipe is then inadvertently installed through the sewer line. Later, when the sewer becomes clogged, a sewer-cleaning device can cut through the live gas line, releasing natural gas into the sewer and potentially releasing a flammable gas mixture in adjacent buildings (Figure 2). Several gas companies have experienced this type of incident.

Figure 2. Damage To Lead Sewer Pipe From HDD tool

EXPERIMENTAL

Significant advancements have been made with the sensor in this, the last quarter of the project. Recall at the end of the previous quarter that tests were being done with steel shim-stock sense elements on the outside of the sensor, but with poor results. Namely, there was a significant contact potential issue contributing to the difficulties in achieving a balanced state in a homogeneous soil condition. There was also poor repeatability of measurements between tests.

In this quarter, a new hybrid prototype (Figures 3 and 4) was made which keeps the second drive configuration, but incorporates a capacitive pickup used in the first prototype. The capacitive pickup configuration was abandoned previously because it was also incorporated with a drive configuration which would very likely yield poor results when the long length of steel drill stem was added aft of the sensor during an HDD installation. There were also other issues with sensitivity which prompted a change in both the drive and sense configurations. The change in the drive configuration and conditioning circuitry resolved some of the issues. The contact issues with the sense configuration, though, prompted the desire to change the pickup back to a capacitive setup.

Figure 3. Newest Prototype September 2004

Figure 4. Close-up Of Newest Prototype

A few differences should be noticed between the sensor in Figures 3 and 4 compared to earlier versions. Mechanically, the overall sensor is larger in diameter (2.75" compared to 2"). This is mainly to fit the tolerances of the outer lexan, inner white polyethylene tube, and steel portion. It also allows more space for inclusion of circuitry within the pod. The resulting sensor is not only much cleaner than the previous version (Figure 15), but it is also easier to assemble/disassemble for quick changes to different portions of the pod. Each portion of the sensor is self-contained so it can be removed without significantly changing the rest of the pod.

The sensor was also designed with the intention of it eventually having to be a field-ready prototype. The previous version had too many threaded pieces that could be loosened with enough vibration to the pod. This could eventually cause the sense elements to get misaligned from the tool tip. The new version has set screws throughout the different portions of the sensor, so turning the steel portion will rotate all portions equally and keep the sense elements aligned. There are also setscrews going from the lexan to metal portions for this same purpose, as well as a threaded rod going to the tip. The threaded rod remained to more easily allow changes to the overall sensor length. Setscrews through the lexan portion are adequate for lab testing, but some of the load is being transferred to the lexan during rotation. In the final version, the threaded portion will be replaced with a piece welded to the tip for added durability, and the sensor made such that the load will transfer through the internal metal portion of the pod.

The sensor was also designed to eliminate the air gap between the sense elements and outer lexan skin. The earlier version with capacitive pickup had a small air gap between elements and lexan. There were concerns that having two dielectric layers, air and lexan, between the sense element plate and virtual plate of the soil could be contributing to some of the

sensitivity issues. Now the sense elements are applied to the outer portion of the white polyethylene tube that is friction fit into the outer lexan. The only significant dielectric between the sense plate and the soil is the wall of the lexan tube.

A very significant change was the addition of the copper tube, a portion of which can be seen just after of the white polyethylene tube portion in Figure 4. This copper tube is inserted through the length of the white plastic tube and provides additional shielding for the sense elements. Shielding around the threaded rod portion had already been used to prevent the excitation signal from bleeding directly to the sense elements. The addition of the copper tube provides shielding to prevent “cross-talk” between the sense elements. Having a friction fit between this shielding and the polyethylene carrying the sense plates normalizes the impedance seen by the sense plates. The chance of spurious signals coupling to the non-soil side of the sense elements is greatly reduced.

Initial tests with the new sensor still had the first stage on the bench top breadboard connected by long lengths of mini-coax cable. Results were not good, so it was decided to place the first stage amplifier as close as possible to the sense elements. This is the small board in Figure 4 within the lexan tube. It was also decided to switch the first two stages. The previous version of the schematic had the AD621 differential amplifier as the first stage, followed by the LF412 amplifier stage, and finally the AD630 stage. It was decided to put the LF412 stage first to provide buffering for each of the sense element legs. This also allows for manipulation of the feedback circuit of the LF412 to insure the maximum gain covers an adequate frequency range. The current circuit is shown in Figure 5. The circuit is the same for the asymmetric axis.

Figure 5. Schematic Of Symmetric Axis

C_{pe} is a representation of the capacitance between the sense element (plate) and the soil (earth). It is difficult to measure the exact value of this capacitance while the sensor is in the soil, so an approximation was made based on the element size. Each of the elements is 1" x 4.5". The dielectric constant of polycarbonate (lexan) is about 3. Using the equation

$$C=0.224*(KA/d)*(n-1)$$

where K =dielectric=3, A =area in inches= $4.5in^2$, d =distance between plates (wall thickness of lexan=0.1279in), n =number of plates (2)

yields **$C=23.64\text{ pF}$** . The aim is for reasonable gain over the frequency range of 100-300 kHz. Earlier tests were performed at 50 kHz, so the R -value would be

$$R=1/(2\pi fC_{pe})=1/(2*\pi*50kHz*23.64pF)=\mathbf{134.6k\Omega}$$

For a gain of 10, the desired feedback resistor, R_f , is 10 times the series impedance of the input capacitance plus the input resistance.

$$R_f=10(R+(1/(2*\pi*f*C_{pe})))=\mathbf{2.693M\Omega}$$

The closest and most convenient resistors were 120k and 2.7M. There is a difficulty with obtaining a feedback capacitor to attenuate the frequencies above 300kHz. The value of C_f is given by the following equation.

$$C_f=1/(2*\pi*300kHz*2.7M\Omega)$$

This yields a C of 0.19pF. Anything available commercially is too large, so the feedback capacitor wasn't included. It was concluded, and later demonstrated, that the gain bandwidth (GBW) product of the amplifier would provide a high frequency roll-off.

The first tests with the board inside the pod showed 1.5MHz noise. De-coupling capacitors between power and ground were added to match those on the bench breadboard.

Initial tests with the resistors above did not yield maximum gain for the desired frequency range of 100-300 kHz. The gain was only good up to a frequency of about 30kHz with no apparent low range. The first thought was that the C_{pe} value was different than the calculated estimate. Adjusting the resistor values to 12k/270k did allow the gain to work for the desired frequency range, but tests on the signal showed a sloping issue with the AD621. After more testing, it was decided that the best results occurred at 25kHz and going back to resistors of 120k

and 2.7M. Data and results explaining the situation further are given in the “Results and Discussion” Section.

With the addition of the copper guard tube, the first stage inside the sensor, and the adjustment of resistor values, test results have been much better. When tested on a bench top (background medium is air), an obstacle placed near each sense element of the symmetric axis causes an equal and opposite imbalance depending on the sense element compromised. In comparing an equally sized plastic and copper obstacle, the copper causes more of an imbalance. Again, since the background medium is air, this is expected. It is expected with a background medium of soil, the opposite would be true. Data is shown in the Results and Discussion section.

The sensor was then tested in the loam test bed. The first test was done with the permanent 4” PE pipe. The permanent pipe is about 3.5’ deep. The sensor was placed so the tip was about 1’ foot above and about 1-2’ away from the pipe. Again, an equal and opposite imbalance was seen depending on the sense element orientation.

Testing was then performed with a smaller section of 4” PE pipe as an obstacle and with the sensor rotated 360 degrees to determine the field of view of the sense elements. When one of the elements was pointing directly at the pipe, the sensor bridge showed its maximum imbalance, as expected. When a given pair of elements was oriented parallel to the pipe the imbalance was minimized, again, as expected. The elements had a sensing range of approximately +/- 45 degrees, or one quadrant each.

The loam tests were not perfect, however. There do appear to be some contact issues while the pod is being rotated. The contact issues weren’t nearly as pronounced as with the setup using the shim stock on the outside of the sensor tube, but enough to keep notice. More details and data are given in “Results and Discussion”.

Sensor Configuration

Certain aspects of the sensor design remain consistent regardless of the method used to inject the signal into the soil. The basic shape and construction of the drill head dictate constraints to the design. In all cases the drill blade, or tip is used to inject an electrical signal into the soil ahead of the drill. This strategy was adopted to eliminate any blind spot dead ahead. In all cases the rotation of the drill head is used to scan the surrounding volume for obstacles. Some discussion of the original, capacitive, sensor concept is provided to illustrate both the common issues and the reasons for changing the approach.

The initial proposed configuration for a capacitive tomography sensor consisted of a series of electrodes distributed circumferentially about the drill head just aft of the blade. Figure 6 shows the typical structure geometry for a directional drill head. The blade itself is used to inject the signal into the soil ahead of the drill. The anticipated embodiment is four equally spaced electrodes. Each diametrically opposed pair of electrodes being the differential sense elements of one sensing bridge.

Figure 6. A Typical HDD Drill Head

Figure 7 shows the arrangement of the sense electrodes on the original capacitive prototype. The opposed pairs of electrodes provide two orthogonal axes over which the soil impedance can be measured. The angle of the drill blade will cause an asymmetry in the distribution of signal current. The leading edge, or tip, of the prototype is simply an angled cylinder. A blade could also be bolted on to the elliptical face of the tip to simulate varieties of drill heads used in the field.

This arrangement of two orthogonal bridge sensors yields two channels of obstacle detection data. The symmetric channel will be most sensitive to objects that are off center with respect to the drill path. The asymmetric channel will be most sensitive to objects directly in the

drill path. The exploitation of the tool tip and its asymmetry to prevent a blind spot dead ahead of the sensor is a unique feature of this technology. With other sensor technologies, such as GPR, the metallic mass of the tool tip is a substantial obstacle to forward sensing.

The data fusion of these two channels can be used to sense extended objects such as pipes in the drill path. In order to use the normal drill rotation to scan the vicinity of the drill head a third channel of orientation data is necessary. A tilt sensor will be required on the drill head to provide the instantaneous angle between sensing electrodes and the “down” direction.

Figure 7. Capacitive Sensor Breadboard With Electrodes In Place

Figure 8 shows the disassembled capacitive prototype prior to applying the electrodes. The sensing electrodes are capacitively coupled to the soil in this earlier version of the sensor. The outermost lexan tube prevents the sense electrodes from shorting directly to the soil and generally protects the internal electronics. The inner lexan tube carries the sense electrodes on its outer surface, in proximity with but not touching the soil. A third tube slides directly over the threaded rod, within the one carrying the sense electrodes. This innermost is the electrode labeled “drive” in Figure 9.

Figure 8. Sensor Breadboard Disassembled

The return path for the sensing current is capacitive, passing through both the sensing electrodes and a “drive” electrode located behind them. The anticipated current paths are shown in Figure 10.

The circuitry to support this low number of channels and modest frequency requirements will be straightforward and inexpensive. Since the sensing signal is injected by direct contact the device can operate at multiple frequencies. This is in contrast to GPR, where each frequency of operation requires a tuned antenna. This broadband sensitivity also allows the sense elements to detect 60 Hz or other active signatures that may radiate from buried infrastructure.

Figure 9. Equivalent Circuit Of Capacitive Differential Electrode Pair

In relation to the equivalent circuit of Figure 9, the drill tip corresponds the “tool blade”. The drill tip is one terminal of the signal generator providing the bridge excitation signal. The intimate contact between the drill tip and the soil ensures a reasonable amount of excitation current is injected into the soil. The “drive” electrode is the silver cylinder at the center of the other lexan tubes in Figure 7. The drive electrode consists of a lexan tube that is covered with aluminum tape and wiring brought out. The copper strips in the foreground are the sense electrodes, mounted on an intermediate lexan tube between the drive electrode and the outside world.

There are four sense electrodes equally spaced about the circumference. Diametrically opposite pairs are wired together to form the impedance bridge. This arrangement forms a three-layer capacitor where the third plate is the soil outside of the largest lexan tube. The soil is in resistive contact with the tool tip as noted above. With reference to the equivalent circuit, this three-layer capacitor is identical to two capacitors in series, which make up each leg of the bridge circuit.

Figure 10. Anticipated Current Flow Of Capacitive Configuration

Figure 10 shows the anticipated current flow of the capacitive configuration as described in the original proposal. Keep in mind there is a layer of air and a sleeve of lexan between the sense elements and the soil. The pod with capacitive sense elements is about 18" in length. If you then add several hundred feet of metal pipe behind the pod, the current flow will likely be from the drill pipe as well as the tip. This was cause for concern of the effectiveness of the design, resulting in a change of configuration.

The next sensor configuration was based on resistive rather than capacitive tomography. With this setup, the signal current is intentionally injected at the tool blade and collected by the drill pipe. Instead of having the sense elements separated from the soil with a section of air and the lexan sleeve to create a capacitor with the soil, the sense elements protruded through the lexan sleeve to make resistive contact with the soil. These contacts are depicted as the rounded protrusions on the sides of the drill body in Figure 11. They are located on an insulating sleeve that separates the drill tip from the drill pipe.

Figure 11. Block Diagram Of New Sensor Configuration, Asymmetric Axis

The prototype resistive contact elements are 4 screws placed equidistant around the circumference of the lexan. These contacts would probably be made flush with the drill body as prototyping progresses. The concern is that any projection will be subject to wear in the normal environment of a horizontal directional drill. The actual area and construction of the contact points will require additional investigation. The contacts must also be sensitive to 60Hz currents and other known infrastructure signatures.

Figure 11 shows the two elements measuring across the asymmetric axis of the tool blade. There are another two screws used to measure across the symmetric axis. The signal current passing from the drill tip to the drill pipe generates voltage potentials along its path. The contacts directly sense these potentials. The signal is detected by taking the voltage difference between opposed pairs of these contact points. The signal is then amplified and filtered to get a signal that can be measured.

In a perfectly homogenous soil, the amplitude of the signal after the filtering will have a reasonably steady value. Notice in Figure 11 that the one equipotential line does not pass directly through the sense contacts at the same point. Along the asymmetric axis, the upper current path is slightly shorter. It is anticipated that there should be a small differential voltage across the drill body in this plane, caused by the asymmetry. As a result, the equipotential is slightly askew. This is why when comparing values for the two axes, the values for the asymmetric axis should be slightly unbalanced when compared to the symmetric axis in a homogenous soil. For comparison, view how the symmetric axis would most likely look in Figure 12. Contacts on opposite sides of this symmetric axis should see very little differential voltage in homogenous soil.

Figure 12. Equipotential Lines For Symmetric Axis

Any inclusions in the soil change the potential distribution, therefore changing the differential voltage. Figure 13 shows the distribution when an obstacle is introduced. Take note of the equipotential line going through the sense elements. When an obstacle is introduced, the current path on that side now becomes longer and slightly distorted. This affects the equipotential line, causing an imbalance to be detected by the signal conditioning electronics.

Figure 13. Equipotential Lines Of Symmetric Axis With Obstacle Introduced

The version of the prototype based on resistive tomography is shown in Figure 14. The tool blade tip and the length of the first section of lexan remain the same. The screws that act as the sensing elements can be seen protruding from the lexan just before the first section of PVC pipe. The section of PVC connects the lexan portion to the steel pipe portion representing the drill pipe. Another PVC section connects the end of the steel pipe to another portion of lexan to provide an exit point for the cabling. Finally, the metal end cap of the sensor attaches to the end of the small portion of lexan, keeping the metal cap, threaded rod, and drill tip electrically isolated from the drill pipe. The PVC coupling pieces needed to be added because the lexan pipe does not have the same ID and wall thickness as standard PVC or steel pipe.

Figure 14a and 14b. Second Prototype

The source excitation signal is applied between the steel pipe and the tool blade tip. The tool tip is connected to the threaded rod, creating a coaxial feed for the excitation signal. Because of this, there is no need for the added buffering layers of the drive tube used with the capacitive configuration. The threaded rod connects the tool blade tip to the end cap. The black miniature coaxial cable is the cabling for the sensing elements. The entire sensor pod is now 41.5” in total length.

Tests with the version based on resistive tomography had some issues. Most notably, the initial screws used as the sense elements were made of zinc-plated steel. Since this is a different material than the tool blade tip, a potential was created which affected the readings. Another

version was made using steel screws and shown in Figure 15. In addition to changing the setscrews, the lexan portion was replaced with PVC to make it easier to assemble/disassemble the device. Shielding around the threaded rod portion was also added to keep the signal from bleeding directly to the sense elements.

Figure 15. Third Prototype

The version with carbon steel setscrews had pickup issues. It was initially thought that these issues were due to the small surface area of the sense elements. A modification was made to add steel shim stock to the setscrews, thus increasing the surface area of the sense elements. The result is shown in Figure 16

Figure 16. Close-up Of Prototype With Steel Shim Sense Elements

Adding the shim stock did not improve results. It was apparent there was still a contact issue using the version based on resistive tomography. It was then decided to go with a hybrid version of prototype. A new custom built prototype, shown in Figures 3 and 4, was made which made it easier to assemble/disassemble the unit, made it a more waterproof, and included lexan as the outer tube. The new version has the latest drive configuration with current flow from tool tip to drill stem. The pickup went back to a capacitive version, but this time the sense elements were closer to the lexan wall, thus virtually eliminating the added dielectric of air caused by the gap in the previous capacitive pickup version. A copper tube was added to provide additional shielding between sense elements. There were also issues with the version using threaded components, where the portion with sense elements could get misaligned from the drill tip with enough rotation/vibration. The new version used setscrews throughout the sensor to keep the various pieces in line.

RESULTS AND DISCUSSION

The recent changes to the configuration, including switching the first stage to the LF412, modifying the resistor values, placing the first stage close to the sense elements, and most importantly including the copper tube as shielding between sense elements, have significantly improved results.

The first test with the new configuration was performed on a bench top. This test was without the initial balanced state set (i.e. for balance the mean level output of the AD630 should be zero). Keep in mind on a bench top with no target obstacle present, it is difficult to assume there is balance; the sensor could be picking up any large obstacle nearby (such as another work bench or metal cabinet). Initially, adjusting the phase of the excitation signal relative to the reference signal can produce the balanced state. This test was to confirm that regardless of the initial state, an obstacle affected each sensor of the symmetric axis equally. After the obstacle tests, the reading should return to its initial value.

Data is shown in Table 1. The test was performed with a 25 kHz, 20Vpp excitation signal. A 2.75" OD lexan tube was introduced as the obstacle to determine if it equally affected both sides of the symmetric axis.

STATE	AD630 OUTPUT PK-PK
Balanced/Initial State	9.6 V
Lexan by S- Symmetric Axis	10.4 V
Lexan by S+ Symmetric Axis	9.4 V
Balanced/Initial State	9.8 V

S+

S-

TABLE 1. DATA FROM LEXAN BENCHTOP TEST

As seen by the results, the variance wasn't exactly the same for each element, but the relative change (above or below the initial state) occurred with each test. The return close to initial state is better than was seen by any previous configuration.

The oscilloscope screen captures for the data is shown below in Figure 17. The signal for the data is the pink/rectified signal, or the bottom trace. The top trace is the output of the function generator. The middle trace is the output directly from the S+ sense element before any amplification. An item to note is the pk-pk value of the S+ element does not change when the obstacle is placed by the S- element; only the AD 630 output changes. This verifies that the copper tube in the middle of sense elements is doing a good job at shielding the elements from one another.

One thing noticed during the bench top tests is that the phase of the excitation signal has to be changed each time the function generator is powered up if a balanced condition is desired. The device used for testing is a dual output arbitrary waveform function generator. One output is used as the excitation signal whose amplitude is altered throughout tests. The other output is the reference signal having the same frequency as the excitation signal, but whose amplitude doesn't change. The reference signal is fed directly to the AD630 and compared with the signal from the sense elements after they go through the pre-amp and the differential amplifier.

The function generator has a master power button, and also individual power buttons to allow each output to be activated/deactivated separately. If the sensor is in a balanced state (no obstacle present) and the phase of the excitation signal altered to properly exhibit the balanced state (zero mean output from the AD630), the phase characteristics will remain the same if just the individual output power buttons are toggled. However, if the master power button is switched off and on, and the same phase numbers manually entered, the output of the AD630 isn't always in the same balanced state. Stated another way, although the sine and square outputs of the generator have the same frequency, the phase between the two is arbitrary each time the generator is powered up.

This issue is simply noted as contributing to past repeatability problems. Other than manually setting the balanced condition for each test, the issue won't be addressed in further testing with the function generator since the function generator will not be present in the final prototype. The issue will be addressed when the signal generator components are placed in the pod, to insure there is some type of phase calibration before each HDD installation.

The next of the bench top tests were performed with the phase of the excitation signal adjusted to a balanced condition. This time, equally sized pipes (2.5" diameter) of copper and plastic were introduced as obstacles to verify the sensor behaved as expected. Since the background medium is air, it is expected that the copper pipe would cause more of an imbalance. If the background medium is dirt, plastic is expected to provide a stronger response. In general, the sensor detects discontinuities in the electrical properties of its immediate environment. The copper pipe is a conductor in non-conductive air. The plastic pipe is an insulator and is easy to detect embedded in conductive soil. The dielectric properties of plastic are sufficiently different enough from air that it was detectable.

As expected, the copper pipe did cause more of an imbalance. The tests were performed with a 50kHz/20Vpp excitation signal, with the objects about 3" away from the sense elements. Care was taken to make sure the obstacles were placed in the same position on each side of the sensor. The data is shown in Table 2.

	Copper Mean Out	Plastic Mean Out
Balanced/No Obstacle	40.3 mV	35.1 mV
S- Imbalance	6.53 V	2.74 V
S+ Imbalance	-5.32V	2.82V

TABLE 2. DATA FOR TESTS COMPARING COPPER AND PLASTIC IN AIR

Further tests showed that, in air, the sensor could pickup the obstacle up to 12” away. It is expected that this range should increase in soil. Specific range tests in soil were not performed in this quarter.

The addition of the copper guard tube has significantly improved results. Figure 18 shows a comparison of the signals when the copper tube is connected to ground compared to when it is not. The first picture in the figure shows the balanced state with the guard connected to ground. The second picture shows what happens when the guard is disconnected from ground.

Figure 18. Comparison With/Without Copper Guard Tube Connected

Equations in the experimental section showed the values initially selected for the input and feedback resistors of the LF412 stage. Ideally, the output should show a gain of 10 in the frequency range of 100-300 kHz, but the gain did not properly correspond. The output of the LF412 was highest in the range of 10-60kHz, with the peak output around 20-30kHz.

At first it was thought that the plate-to-earth capacitance was different than calculated. To double check, the tests were repeated on a protoboard with a 23pF cap representing the plate-to-earth capacitance and the function generator feeding directly to this capacitor. The figure below shows the output of the LF412 for two cases: Case 1 is with an input resistance of 120k and feedback resistance of 2.7M. Case 2 is with the input resistance of 12k and feedback resistance of 120k.

Figure 19. Graph of Output vs. Frequency Data from Table 3

Table 3 shows the data corresponding to the values in Figure 19. Looking at the output values of the LF412 for case 1, the best results occur in the 20-30kHz ranges, or 10-60kHz if you include values as low as 5.5V. Outside of this, the values start dropping substantially. This was not what was predicted by the ideal equations and amplifier specification. The bolded text is where the relatively flat responses of the gain occurred.

Freq (kHz)	Output Case 1	Output Case 2
1	820mV	N/A
2	1.6V	N/A
3	2.24V	N/A
4	2.88V	N/A
5	3.68V	N/A
10	5.52V	960 mV
15	6.32V	N/A
20	6.56V	N/A
25	6.72V	N/A
30	6.64V	2.40 V
40	6.40V	3.04V
50	5.92V	3.64V
60	5.60V	4.20V
70	5.20V	N/A
90	N/A	5.52V
100	4.32V	5.76V
110	N/A	6.08V
120	N/A	6.32V
130	N/A	6.48V
140	N/A	6.64V
150	3.20V	N/A
175	N/A	6.80V
200	2.56V	6.80V
225	N/A	6.72V
250	N/A	6.48V
275	N/A	6.32V
300	1.92V	6.00V
350	N/A	5.60V
375	N/A	5.36V

TABLE 3. GAIN CHARACTERISTICS. $R_{IN}=120K$, $R_F=2.7M$ (CASE 1) $R_{IN}=12K$, $R_F=120K$ (CASE 2)

Since the frequency range was off by a factor of 10, it was decided to try tests with the resistor values also dropped by a factor of 10. This case is the third column of Table 3 using resistor values of 12k and 270k.

In this case, the highest output occurs in the range of 150-225kHz, or 110-300kHz if including 6.0V. The 23pF capacitor was taken out and the board hooked up to the sense elements. Very similar results were found; the maximum output occurred in the range of 90-300kHz. The conclusion is that the higher resistance values caused the circuit to be overly

sensitive to parasitic capacitance in the circuit board and cabling. The lower resistance values provide a flat gain characteristic in the frequency range of interest.

At first it was thought the optimal resistors were found. But when looking at the rest of the circuit there appeared to be a slope overload issue with the AD621 (differential amp stage after the LF412). At 200kHz the waveform started to triangulate, rather than tracking the sine wave fed to the input. Also the phase and bias levels of the AD621 output signal were affected with a change in amplitude of the excitation signal. All of these are indicators that the signal is changing more rapidly than the amplifier can track. This is at odds with the published specification for the AD621.

For reference look at the screen captures shown in Figure 20. The frequency is kept at 200kHz, but the excitation signal amplitude is increased. For the first three screen-captures, the pink trace is the output of the 621. The bottom trace is the output of the function generator used for the excitation signal. The third trace is the other output of the function generator, which is used as the reference signal, but remains unchanged.

For the next three captures, the pink trace is still the output of the 621. The top two traces are the excite signal and the output of the LF412 for one of the elements. The bottom trace is the output the AD630. The only important trace to compare in all signals is the pink output trace of the AD621.

It's difficult to see the values in the captures, but the waveform for 200kHz starts to triangulate at 3.36V pk-pk. When comparing with a frequency of 25kHz, but with resistors of 120k and 2.7M, the sloping effect does not come into play. With a frequency of 25kHz, the pk-pk can get up to 11.6V and still not triangulate. Based on these observations the in-soil testing was performed at 25kHz.

Figure 20. Distortion at 200kHz vs. 25kHz

The sensor was then tested in the loam test bed. In the first test with the permanent pipe as the obstacle (the sensor placed just above and to the side of the pipe), the symmetric axis was parallel to the pipe to achieve balance. The phase of the excitation signal was adjusted so the mean filtered output of the AD630 was -212mV . With the S+ element facing the pipe, the mean

output jumped to -4.81V . With the S- element towards the pipe, the mean output changed to 4.94V .

Initially these results look very good, but when the sensor is rotated just slightly either way, the S- output can quickly jump negative. This is either because the field of view for the sense elements is too small or there is a contact issue with the soil, especially where the tip interacts with the ground. The latter is more likely true since the readings can also be affected by pressing the sensor against the soil wall.

One of the theories of the contact issue is in the process of rotating the sensor, the drill tip digs out a slight air pocket in the soil. The sensor is designed to use the shape of the drill tip to its advantage, especially when comparing the symmetric and asymmetric axes. When an air pocket is created around the tip, the electrical contact with the soil is compromised. This is an artifact of the way the experiment is performed; in a real HDD the drill rotates and moves forward simultaneously. The forward motion will maintain contact between the soil and drill tip.

To test the contact issue, water was poured into the hole around the sensor. Since the loam soil has a slight mixture of clay, it generally filters water a little slower than sand so water remains in the hole longer.

The water didn't help with keeping the readings steady, although there was a visible change seen in the signal if the sensor was rocked slightly back and forth while the water was settling (i.e. where the water level was settling around the drill stem). This suggests that there must indeed be a contact issue.

The next test was with a smaller section of 4" PE pipe. Whereas the permanent pipe tests were done with the sensor slightly above and to the side of the pipe (similar to the orientation in an HDD installation), the tests with the smaller pipe were done with the pipe at the same level as the sense elements. This is a similar orientation of the obstacle when the bench top tests were performed. This time, though, the sensor is being rotated to determine the field of view of the sense elements.

The pipe was placed about 2.5-3' deep into the loam soil with the sensor 4" away from the pipe. As the sensor was rotated, the sensor was lifted up slightly and placed back down before the reading to optimize the tip to soil contact and limit any air pocket created. The orientation of the sensor is shown in Figure 21 with data shown in Table 4.

Figure 21. Orientation Of Rotation Test

Degrees	Output
0	874 mV
45	-4.68 V
90 (S+ towards pipe)	-4.28 V
135	-4.40 V
180	325 mV
225	4.34 V
270 (S- towards pipe)	5.06 V
315	2.99 V
360	-632 mV

TABLE 4. RESULTS FROM ROTATION TEST

From the data it can be seen that the sensor has about a quadrant per sense element field of view. However, at times during the test, slight movement of the sensor did cause the values to jump similar to what was seen with the permanent pipe tests. When this occurred, the sensor was lifted and reset, giving a good reading.

Even though there is still an apparent contact issue with the newest hybrid design of the sensor, it is much better than other configurations. In addition, the strength of the signal seen by the sense elements is more stable, with no bias drifts.

This is the last quarter of project, so no other work will be done on this project. If time allowed in this quarter, the next step would have been to examine the contact issue more closely. For one, the angled tip would have been temporarily replaced with one that is symmetrical, such as a hemisphere or cone. This would verify if the air pocket dug out by the tip is creating the contact problems. After that, more tests would have been done to determine range in the soil. Tests on the bench top showed the ability to detect obstacle up to 12" away. The first test with

permanent pipe showed a range of about 2', but this was not tested further to see how far away the pipe could be detected. Several tests would then be performed with different obstacle materials (ceramic, metal, plastic) to determine if repeatability could be achieved at a given range.

After these tests were satisfactory, steps would be taken to make a new prototype that could include all the electronics within the pod, including an inclination sensor and transmitting coil.

CONCLUSIONS

- Adding the copper tube for additional guard shielding greatly improved signal quality by eliminating any crosstalk between the sense elements.
- Moving the first stage amplifier to the interior of sensor pod, immediately adjacent to the sensor plates, also improved the signal quality by eliminating the cable capacitance in parallel with the sensor elements.
- The first two changes enabled the use of capacitive coupling between the soil and sense elements that eliminated many of the contact potential issues that plagued the previous version of the prototype.
- In background medium of air, a metal obstacle caused more of an imbalance than plastic, just as expected.
- In a background medium of soil, plastic pipe was readily detectable, as predicted.
- Tests in loam soil showed approximately one quadrant per element viewing area as the sensor was rotated.
- There are still some apparent contact issues at the drill tip, but greatly improved over other configurations. This may not be a problem in the case where the drill is moving forward continuously.
- The change in the mechanical configuration of the sensor allowed for ease of changing various components as well as keeping the sense elements properly aligned with the drill tip.

Work Performed in the Tenth Quarter

Task 1: Research Management Plan

The ninth quarterly report was prepared and submitted.

Task 2: Evaluate Sensor Concept

Sub task 2.1, “Evaluate Impedance Bridge Based Sensors” is in progress. Tests with the newest hybrid sensor were performed on the bench top and the in the large indoor soil test bed. Tests on the bench showed a range up to 12”, with copper causing more of an imbalance (as expected). Tests in soil were successful with a range of 2’, but the maximum was not tested. The field of view is approximately one quadrant per sense element.

Task 3: Demonstrate Obstacle Detection in Ground

Initial tests were performed in the ground, but only with the sensor vertically placed in the soils and rotated to sense a permanent obstacle. There was not time to get all the components into the pod and test the device with a horizontal directional drill.

Technical Problems Encountered

There is still a slight contact issue with the hybrid configuration, but greatly improved over previous designs. The contact between the drill tip and the soil can degrade as the drill is rotated in place. In real operation the drill would also be moving forward while rotating. It is felt that the tip contact issue may be an experimental artifact.

Project Management Problems Encountered

No project management problems were encountered this quarter.

Action Requested of Doe NETL Project Manager

A no cost time extension was formally requested from DOE National Energy Technology Lab and granted through September 30th of 2004. This report serves as the last quarterly report of the project. A final report is due December 31st of 2004.

WORK PLAN

Work Planned For The Next Quarter

A final report will be created and submitted, due December 31, 2004. A presentation of the project will be made at the International Gas Research Conference in Vancouver, BC, Canada, in November. This effort will be billed to the other co-fund on this project.

REFERENCES

In a patent entitled “Driven Shielding Capacitive Proximity Sensor”, patent number 5,166,679, dated November 24, 1992, inventors John M. Vranish and Robert L. McConnell have presented an invention for a capacitive proximity sensor that will detect the intrusion of a foreign object into the working space of an electrically grounded robotic arm. The capacitive proximity-sensing element is backed by a reflector that is driven by an electrical signal of the same amplitude and phase as that signal which is detected by the sensor. It is claimed that by driving the reflector plate with the same signal that is on the sense element significant increases in the sensor's range and sensitivity are accomplished.

In a patent entitled “Steering Capaciflector Sensor”, patent number 5,363,051, dated November 8, 1994, inventors Del T. Jenstrom and Robert L. McConnell, present an invention that will allow for the steering of the electric field lines produced by a capacitive type proximity sensor. The inventors assert the claim that by steering or focusing the electric field will allow an increased ability to discriminate and determine the range of an object in the area of observation over that of previous capacitive sensors. Differential voltages applied to shielding plates spatially arranged around the sensor plate accomplish steering of the electric field lines.

In a patent entitled “Buried Pipe Locator Utilizing A Change In Ground Capacitance”, patent number 5,617,031 dated April 1, 1997 inventor John E. B. Tuttle has invented a portable buried pipe detection device that utilizes changes in the electrical properties of the soils surrounding underground pipes. The detection method consists of the injection of a low frequency sinusoidal wave into the ground via an array of injector/sensor plates. Subsequent modification of the injected signal by variations in ground impedance brought about by the existence of buried piping structures will result. The modified signals will be detected by the spatially separated sensor elements located on the device. The injector/sensor elements are constructed in such a manner as to comprise a capacitive bridge circuit when viewed in conjunction with the ground. As the detection array is moved along the ground any occurrence of underground piping structures will imbalance the capacitive bridge and give rise to a detectable electrical signal.

The website entitled “Underground Radio by Le Magicien” was used to help design and explain the new sensor configuration. The website is located at http://www.geocities.com/lemagicien_2000/elecpage/ugr/undr.html.

LIST OF ACRONYMS ABBREVIATIONS

CT - Capacitive Tomography

COR – Contracting Officer’s Technical Representative

DOE - Department of Energy

FERC – Federal Energy Regulatory Commission

GPR – Ground Penetrating Radar

GRI – Gas Research Institute

GTI - Gas Technology Institute

IGT – Institute of Gas Technology

IRNG –Infrastructure Reliability of Natural Gas

APPENDIX A
Differential Soil Impedance Obstacle Detection
Detailed Work Plan

A. OBJECTIVES

The objective of this project is to design, fabricate, and test a prototype sensor system for detecting obstacles in front of or around the head of a horizontal directional drilling (HDD) rig. The sensor system shall be sensitive to metallic, plastic, or ceramic obstacles embedded in the soil. The detection live power lines with the same sensor will also be investigated.

B. SCOPE OF WORK

In order to reach the goal of designing, fabricating, and testing, a viable prototype of an obstacle detection system for guided directional drilling, GTI shall perform the following tasks.

1. Program Management
2. Evaluate Sensor Concepts
3. Demonstrate Obstacle Detection in Ground

The completion of these Tasks in an orderly fashion will result in the fabrication and testing of a sensor that can be mounted on the drilling head of a horizontal directional drill. The sensor will be tested with a mixture of target obstacles in soil. This testing will be performed using a sensor probe driven vertically into the soil rather than horizontally bored in the interest of saving time and costs.

C. DELIVERABLES AND SCHEDULE

1.0 Program Management

1a Detailed Work Plan – 6/02

1b State of the Art Assessment – 7/02

1c Quarterly Technical and Financial Reports - 8/02, 11/02, 2/03, 5/03

1d Final Technical Report – 8/03, 10/03

1e Topical Reports and presentations as required

2.0 Evaluate Sensor Concepts

2a Evaluation of Impedance Bridge Sensors –11/02

2b Evaluation of Soil Properties – 2/03

2c Detailed Plan for In Ground Tests – 4/03

3.0 Demonstrate Obstacle Detection in Ground

3a Test Passive Sensing of Live Power Mains – 5/03

3b Test Active Sensing of Obstacles – 6/03

3c Demonstrate Sensor with Multiple Obstacles – 7/03

D. TASK WORK DETAILS

1.0 Program Management

This task will subsume all the necessary reporting, meeting, presentation, and demonstration requirements for DOE. The FERC provided cofunding will cover any additional program management requirements incurred by the gas industry sponsors.

1.1 Research Management Plan

GTI shall develop a work breakdown structure and supporting narrative that concisely addresses the overall project as set forth in the agreement. GTI shall provide a concise summary of the technical objectives and technical approach for each Task and, where appropriate, for each subtask. GTI shall provide detailed schedules and planned expenditures for each Task including any necessary charts or tables, and all major milestones and decision points. This statement of project objectives shall form the basis for the deliverable Research Management Plan

1.2 Technology Assessment

GTI shall prepare and submit a report describing the current state-of-the-art of the technology being developed. The report should describe existing technologies and positive and negative aspects of using this technology. The report shall not exceed five typewritten pages in length. The report is not to contain any proprietary or confidential data as the report will be posted on the NETL website for public viewing. The report is to be submitted within 60 days of award. The DOE Contracting Officer's Technical Representative (COR) shall have 20 calendar days from receipt of report to review and provide comments to the contractor. Within 15 calendar days after receipt of DOE's comments, the contractor shall submit a final Report to the DOE COR for review and approval.

2.0 Evaluate Sensor Concept

In this task GTI will do a more detailed evaluation of specific technologies relating to obstacle detection. Some of these technologies may be identified in the state of the art evaluation. Bench experiments will be carried out in this task preparatory to performing tests in soil.

2.1 Evaluate impedance bridge based sensors

GTI shall survey existing methods of remote obstacle detection with a focus on those methods employing impedance bridge based sensors. Capacitively coupled impedance bridges have been evaluated for the location of sub-surface plastic objects such as plastic pipes and landmines. There is also a large body of work dealing with capacitive sensors for soil moisture measurement.

Simple experiments shall also be carried out in this task. A small-scale model consisting of a steel rod with an angled tip and an electrode array shall be constructed. This shall be tested in an electrolyte tank with submerged samples of various obstacle materials. Custom electronics are not necessary for these experiments. They shall be carried out using laboratory instrumentation.

2.2 Evaluate Soil Properties

Given the critical interaction between the soil and the sensing method, current data on soil properties shall be examined. The conductivity and dielectric properties of typical obstacles shall also be examined at this time. Soil survey data shall be obtained to estimate the distribution of soil types over North America. Part of this sub-task is to identify any “problem” soil types and extents. Any deficiencies in soil dielectric and conductivity data shall be identified at this time. Using the previously constructed probe and laboratory instruments, tests shall be carried out on single obstacles in representative soils.

2.3 Design of Task 3 Demonstration

Once the sensor and soil data are available, design of experiments shall be carried out. Tests for the detection of electric power mains in both the energized and off states by passive methods shall be designed. Tests for detecting and ranging inclusions in the soil by change of impedance shall be designed. Examples of obstacles with impedance lower than the soil are cast iron or metal pipes and metallic debris. Examples of obstacles with impedance higher than the soil are plastic pipes, clay tiles, and masonry rubble.

3.0 Demonstrate Obstacle Detection in Ground

Using the results of Task 2, GTI will demonstrate the detection of obstacles using differential impedance measurements in soil.

3.1 Passive Sensing Tests

In passive sensing tests the sensor probe will be used to detect the electromagnetic radiation signature emitting by live power lines. The probe will not emit signals in the frequency range characteristic of power lines. Electric mains may be buried directly in soil or buried in metal, concrete, or plastic conduits in the soil. Electric mains may be carrying three-phase or single-phase power at various voltage and current levels. These power lines shall have known voltages, currents, and phasing. In order to test the passive EM sensing mode of the array in soil, the test probe array shall be inserted vertically into the ground in the proximity of AC mains. Current and voltage monitors on the power mains will provide reference data for the evaluations of the array's sensitivity to this category of sources

3.2 Active Sensing Tests

In active sensing tests the sensor probe will be injecting an electrical signal of known characteristics into the soil. GTI shall develop a simplified field test site. Input shall be solicited from industry advisors during the construction of this facility to insure that relevant features are not overlooked. The number of representative soil types shall be determined. Appropriate numbers and sizes of obstacles shall be buried. Test sites that provide interference between obstacle types shall be included.

3.3 Perform Obstacle Detection Tests

After the simplified field environment has been completed, tests to determine the range, accuracy, and resolution of the sensor array shall be carried out. The effects of soil type, obstacle type, and obstacle size on array performance shall be observed. These experiments shall be performed with vertically driven probe arrays in the interests of keeping costs within bounds. These probes shall be driven incrementally closer to buried obstacles while simultaneously rotating the probe. A simple user interface and display shall be constructed to facilitate these tests.

APPENDIX B

**Presentation for International Gas Research Conference, Vancouver, BC, Canada;
November 2, 2004.**

Differential Soil Impedance Obstacle Detection (DIOD) Sensor for HDD

Max Kieba
Chris Ziolkowski

IGRC
November, 2004
Vancouver, BC, Canada

Objective

- > To design a prototype sensor system for detecting obstacles in the vicinity of a Horizontal Directional Drilling (HDD) head during pre-bore
- > Should be sensitive to metallic, plastic or ceramic obstacles embedded in the soil

Sponsors/Technical Support Staff

> Sponsors

- DOE/NETL (proof of concept)
- FERC (proof of concept)
- AWWARF (co-fund of demonstration/commercialization phase)

> GTI Technical Staff

- Principal Investigator: Max Kieba B.Sc.E.E
- Project Manager: Chris Ziolkowski B.Sc.E.E

Max Kieba (GTI since 1999) Chris Ziolkowski (since 82)

- > GTI has experience with No-Dig/HDD technologies, including patents
- > Kieba/Ziolkowski worked on Tow Tension Monitor for HDD (patent pending)
- > Contacts with industry and academic experts in the field
- > Ziolkowski; PM of Capacitive Tomography for location of buried plastic pipe

What Is Horizontal Directional Drilling (HDD)?

- > Trenchless Method to Install Pipe
- > Reduces Costs of Installation
- > Two Small Holes vs. One Long Trench
- > Drill Rig Pre-bores Hole Underground
- > Pipe is Attached and Pulled Back

DIOD for HDD

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What Is HDD?

DIOD for HDD

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Other Relevant Projects

- > Tow Tension Monitor (patent pending)

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Other Relevant Projects

- > Capacitive Tomography Sensor for Locating Plastic Pipe

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Why Do We Need the DIOD?

- > With reduced installation costs and increased use of HDD comes crowded utility easements
- > In the last few years, there have been a few extreme incidents of damage resulting from drill collisions with buried facilities
- > Thousands of other utility strikes on gas, electric, telecommunications, water and sewer lines occur annually

Why Do We Need the DIOD?

- > Example
 - Gas HDD installation penetrates and accidentally installs pipe through sewer line
 - Sometime later, sewer becomes clogged
 - Sewer-cleaning device accidentally cuts through gas line, releasing natural gas into sewer and potentially releasing a flammable gas mixture into adjacent buildings
 - Several companies have experienced this

Why Do We Need the DIOD?

Damage to lead sewer pipe from HDD tool

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Initial Technical Approach

> Initial Proposal Concept

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Initial Technical Approach

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DI-OD Technical Advantages

- > **The use of drill head to carry signal minimizes modifications to drill**
- > **The use of drill head also eliminates any blind spot dead ahead**
- > **The low frequency of operation gives better penetration than GPR**
- > **The system is self-contained, requiring no sensors on the surface**

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Initial Prototype – Version 1.0

- > Inner silver tube is drive; copper tape pieces are the sense elements

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Results Of Version 1.0

- > Sensitivity lower than expected
- > Concerns with effects of adding several hundred feet of drill pipe aft of the sensor
 - Current flow also likely be from drill pipe
 - Wish to force the sensing current ahead of drill through the tip

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New Technical Approach

- > Use the metallic body of the drill to inject a low frequency signal into the soil
- > Current flow from tip to drill pipe

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DI-OD Technical Approach

- > Obstacles in the soil cause changes in the soil impedance

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Prototype – Version 2.0

- > Used screws as sense elements
- > Long steel portion to simulate drill stem

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Prototype – Version 2.1

- > Used steel shim stock pieces to increase sense element size
- > Shielding added around threaded rod portion to ensure excitation signal wasn't "bleeding" directly to sensor elements

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Results of Version 2.0/2.1

- > Difficulty in balancing symmetric axis in homogenous soil condition
- > Contact issue even with larger sense elements
 - Readings significantly different when one element touching soil wall and other having slight air gap
 - Electrochemical contact potentials vary greatly even when all elements have good contact

Prototype – Version 3.0

- > Hybrid using the best of earlier versions
 - Resistive signal injection
 - Capacitive coupling of sense elements
 - No air gap between elements & skin

Version 3.1

- > Slightly better results, but still had balance issues
- > What do we do?
 - Increase lexan length to include first amplifier stage
 - Insert copper tube to limit element-to-element cross talk

Version 3.1

Version 3.1

Shielding

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Version 3.1 Results

- > Able to achieve balanced condition by adjusting excitation signal phase with respect to reference signal
- > In bench tests, medium is air
- > Equal sizes of copper and plastic tubes placed near symmetric axis elements
- > Copper caused larger imbalance, as expected in air

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3.1 Benchtop Comparison

- > 50 kHz/20 Vpp excite, obstacle~3" away from each element

	Copper Mean out	Plastic Mean out
Balanced/No Obstacle	40.3 mV	35.1 mV
S- Imbalance	6.53 V	2.74 V
S+ Imbalance	-5.32 V	-2.82 V

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Version 3.1 Tests With Copper

- > Green=ref signal; blue=instrumentation amp output; pink=lock-in out; yellow=filtered output

9/3/04 - "balanced" condition

9/3/04 - copper tube by S-

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Version 3.1 Copper (Cont'd)

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Version 3.1 With Plastic

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Version 3.1 With Guard Wire Disconnected

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Into The Pit!!

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Tests in Loam Soil

- > 25 kHz excitation, 4" PE pipe ~3' deep and 6" from sensor

Side View

Top View

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Results From Loam Test

Degrees	Output
0	873 mV
45	-4.68 V
90 (S+ toward pipe)	-4.28 V
135	-4.40 V
180	325 mV
225	4.34 V
270 (S- toward pipe)	5.06 V
315	2.99 V
360	-632 mV

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Loam Tests

- > Yellow/blue=signals after sense element pre-amps; pink=output of lock-in; green=filtered output

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So What's Wrong?

- > Still having some contact/repeatability issues between tests in soil
 - Believe contact issue may be a result of tip drilling out air pocket during rotation

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Next Tests

- > To verify contact issue, try replacing angle tip with symmetrical cone or hemisphere
- > Need to determine range capabilities
 - In air got up to 12"; soil should be better, but need over 9-10' range (length of drill stem to allow change in direction if obstacle found)
- > Determine optimal frequency (now 25 kHz)
- > Get entire electronics in pod, include inclination sensor
- > Compare different obstacle materials

GTI: Out Standing in Our Field

Thank You!!