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An Ultra-Precise System for Electrical Resistivity Tomography Measurements

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Original Objectives:

The objective of Phase II research is to determine the feasibility of building and operating an ERT system that will allow measurement precision that is an order of magnitude better than existing systems on the market today and in particular if this can be done without significantly greater manufacturing or operating costs than existing commercial systems.

In order to meet this objective, we defined the following tasks:

1. Short-term and laboratory studies of electrode impedance and electrode decay effects,
2. Long-term survival of subsurface electrodes: field studies,
3. Improvements in receiver and transmitter electronics,
4. Characterization of cables and development of strategies to reduce cable cross-talk,
5. Data acquisition strategies,
6. Full system tests, and
7. Technical publications.

The integration of the results of these efforts will result in an operational monitoring system which is ready for commercialization in Phase III.

Accomplishments

We successfully completed all proposed tasks and developed a prototype ERT system which includes:

- A monitoring system with improved receiver and transmitter electronics;
- Improved operating software; and
- Prototype compound (non-polarizing) electrodes.

Project Activities

A summary of the original project tasks, approaches used to accomplish these tasks, and results:

Task #1: To perform short-term and laboratory studies of electrode impedance and electrode decay effects.

Under this task, we propose expanding the study of both short-term aging effects and electrode impedance curves. These studies will included performing tests over time frames of about a year, expanding the number of metals and expanding the number of solutions in which the electrodes are embedded. We also need to study scale effects in electrode impedance particularly in reference to the relation between impedance measured using relatively high current and the effective impedance observed at the receivers. This will involve measurements at field scales using electrodes at active, accessible sites and installation of surface electrodes or electrodes in shallow boreholes.

Accomplishments under Task #1:

Under Task #1 we performed an empirical estimation of measurement errors in galvanic resistivity data that arise as a consequence of the type of electrode material used to make the measurements. Measurement errors for both magnitude and induced polarization (IP) were estimated using the reciprocity of data from an array of electrodes as might be used for electrical resistance tomography.

Ten identical electrodes were placed in a plastic tank of water or water-saturated sand and arranged in a circular array as shown in Figure 1. Both the sand and water tanks were 69 cm square and filled to a depth of 25 cm. Four electrode measurements were made using all combinations of dipole transmitters and dipole receivers where all dipoles were adjacent electrodes. All of the reciprocal pairs were included. This measurement scheme on ten electrodes produces 35 reciprocal measurement pairs for a total of 70 measurements and this protocol is repeated ten times so that 700 measurements of impedance (700 resistance and 700 chargeability measurements) are available for each frequency on each electrode material. These 700 measurements were acquired at each of three frequencies, 0.2 Hz, 1 Hz and 5 Hz, and in each measurement 3 cycles were stacked. The source dipole drive voltage was kept at 20 volts.

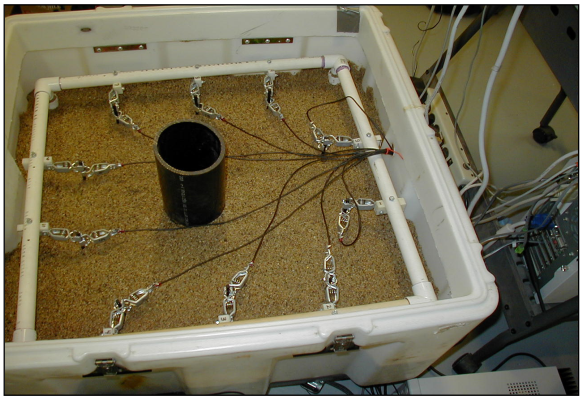

Figure 1. Water saturated sand tank, showing the 10 electrode configuration.

From these data, our primary measure of error is the percent difference between the reciprocal resistance values. With the electrodes in the water tank we have a second measure of error, the value of induced polarization (chargeability). The water should have a negligible reactive component at 5 Hz and below, therefore, there should be no chargeability so that any non-zero measurement is an error.

Fourteen different materials were used as electrodes and in the sand tank copper-copper sulfate electrodes were also tested.[1] It was necessary to limit the materials to a manageable number, but we attempted to include those that are commonly used in geophysics. Most electrode types were 0.635 cm (¼ inch) diameter rod inserted 4 cm into the water (or sand) presenting an 8 cm^2 surface area.

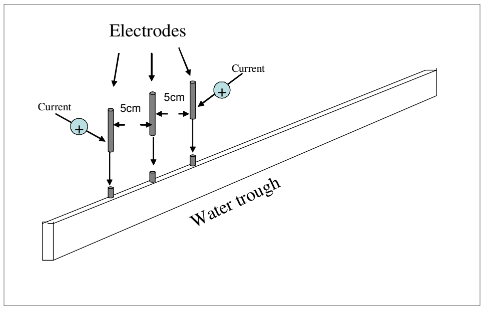

Figure 2. Schematic of water trough used for contact impedance measurements and electrode conditioning.

A second study performed was measurement of the contact resistance of the electrode material which can be an important control on noise level. Contact resistance of an electrode is the resistance to current flow even if the earth is perfectly conducting. It is present as a result of the fact that all metallic electrodes develop a boundary or layer (called the Helmholtz layer) at their surface that allows electronic current to flow in the metal, and ionic current to flow in the ground (Madden, 1967). The impedance of this layer was estimated by measuring the two-point resistance between two electrodes at various separations and then extrapolating these data to the resistance when the separation is zero. If current flow between the electrodes is linear (imposed in our measurement by a plastic, water-filled trough the width of the electrodes, Figure 2), the extrapolation is linear.

In a third study, the contact resistance was again measured in the same plastic trough but this time it was filled with various electrolytes at different concentrations, as opposed to pure water used in the previous study. Electrolyte compounds used included

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[1] Copper-copper sulfate electrodes were not used in the water tank because the copper sulfate could slowly leak from the porous element and change the water conductivity during the test.

copper sulfate ($CuSO_4$), magnesium sulfate ($MgSO_4$), ferric chloride ($FeCl_3$), ferrous sulfate ($FeSO_4$), and saturated salt water.

As a result of our tests of various electrodes mentioned above, it became apparent that to achieve very low noise/high precision measurements we will likely need to use compound electrodes. In compound electrodes the electrical double layer is controlled by embedding the metal in an electrolyte which is specific to the metal. The most common of these currently in use are copper-copper sulfate in which a pure copper rod is embedded in a concentrated copper sulfate solution. The solution is held in a container with a porous ceramic base. We tested organic acids as electrolytes in our contact resistance study, as they are readily available, reasonably inexpensive as well as non-toxic, and are easily shipped and handled.

We tested a variety of materials for durability and ease of installation, hoping to improve upon the plastic sheath and porous ceramic tips typically used in these electrodes (i.e. copper-copper sulfate half cell). There are two issues within this research: 1) to find a chemical formulation that is non-toxic and has similar or lower noise levels than compare to copper-copper sulfate electrodes and 2) to find an encapsulation method that is both cheaper and more durable than the porous ceramic based electrodes commonly in use. To test the chemistry, we placed potential electrolytes and electrodes in shells of standard, ceramic tipped compound electrodes (Tinker and Rasor Half Cell reference electrode).

The new encapsulation method depends on using polymer gels to contain the electrolyte within the porous plastic. Both the interior of the cell and the plastic casing itself are infused with gel containing the electrolyte. Therefore the second stage of the test was to determine the effects of these polymers on the chemistry by adding them into the casings of the ceramic based compound electrodes. The final stage was to place the electrodes and electrolyte/polymer mixture in the porous plastic casings.

Results

Electrode Aging

Figure 3 compares systematic errors for electrodes in sand and water for thirteen different metals and graphite with those for non-polarizing electrodes. The plot also shows the reciprocal errors for a resistor network used to indicate the level of errors originating from the measurement system.

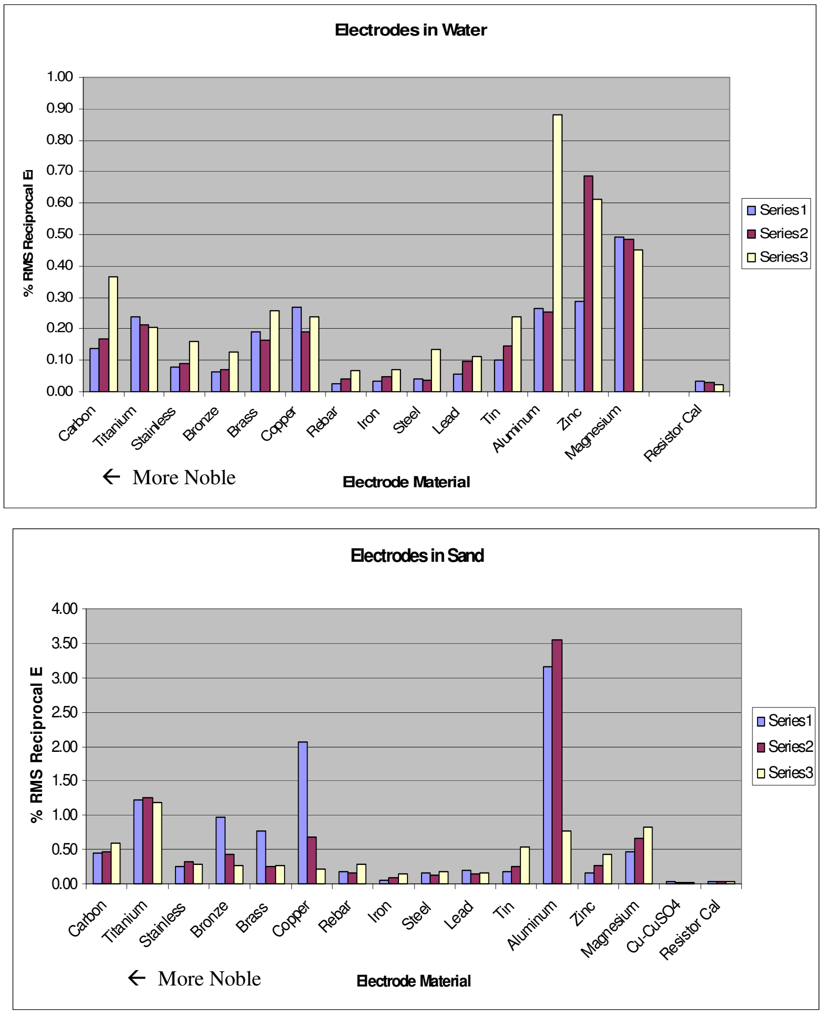

Figure 3. Change in reciprocal errors during repeated measurements for the selected electrodes in water and in water-saturated sand.

To gain a better understanding of the error levels and to be able to predict the effectiveness of a given electrode/metal type, we calculated current density versus impedance curves for metal-water and metal-electrolyte combinations. These curves are similar to the Tafel curves used in electrochemistry but differ in that an alternative electrical current flow is used. With the exception of copper, these curves provide a fairly effective method of predicting electrode types that will perform well. Those electrodes which show little change in impedance with current density generally have lower noise levels. A number of such curves are shown in Figure 4. In interpreting these results, it is important to note that when a metal electrode is used as a transmitter, typically the current density is of the order of amperes per square meter which is near the maximum level in our tests and thus the lowest impedance (Figure 4) whereas the receivers operate at very low current densities, lower than the lowest current levels tested.

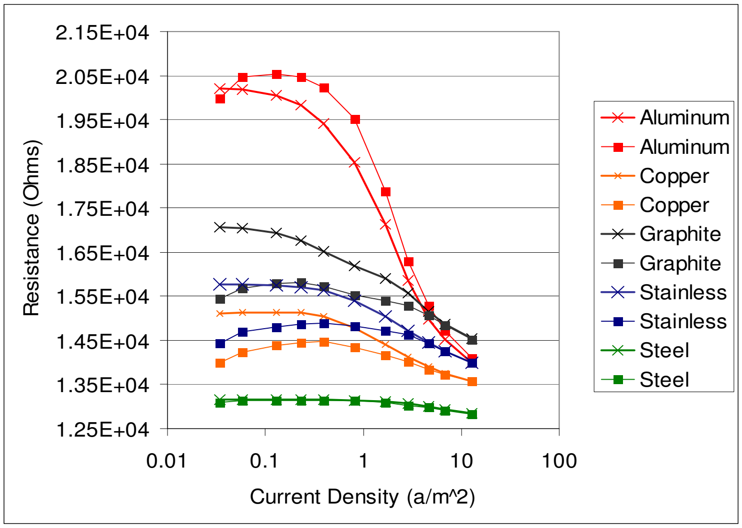

Figure 4. Contact impedance measurements for selected materials. Measurements were taken in tap water.

For metals such as aluminum (Figure 4) there are large changes. This impacts the noise levels in two ways: 1) the impedance is higher than anticipated for the receivers and 2) the impedance varies from measurement to measurement creating inconsistencies.

Our best candidates use steel, tin or heavy tin plated steel as the electrode surrounded by a non-toxic electrolyte. Two candidates for electrolytes are ferrous sulfate (the ingredient that gives Cheetos their orange color) and sodium chloride. Figure 5 compares tin and iron electrodes in ferrous sulfate. The tin/ferrous sulfate electrode has a fairly low impedance that is stable over a broad range of frequencies and current densities.

We conducted preliminary tests of our compound electrodes in a laboratory sand tank, using the same test method as for individual electrode materials (see pages 2-3). The electrode uses a chemical formulation consisting of a tin metal electrode in an electrolyte of a chloride salt and an organic polymer. The electrodes were used as both transmitters and receivers. Figure 6 shows the RMS differences in millivolts per volt between forward and reciprocal measurements at 5 Hz for the new electrodes and commercially available copper-copper sulfate electrodes. In the test, noise levels for the new electrodes were somewhat lower than those for the standard copper-copper sulfate electrodes, probably due to the lower contact impedance of the new electrodes.

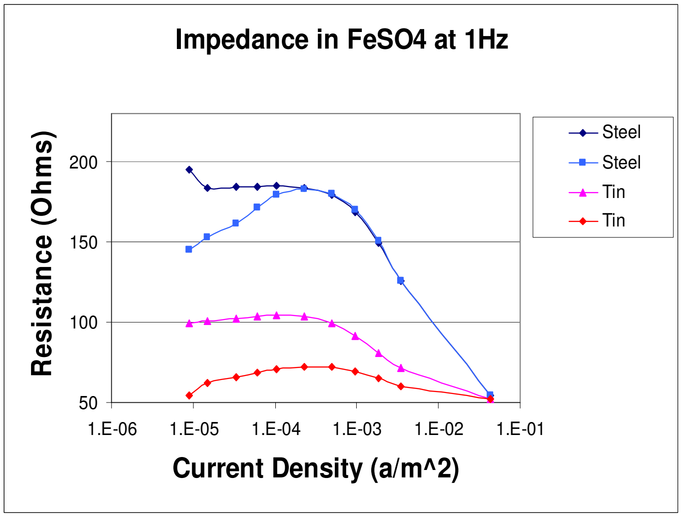

Figure 5. Contact impedance of tin and mild steel electrodes taken in ferrous sulfate.

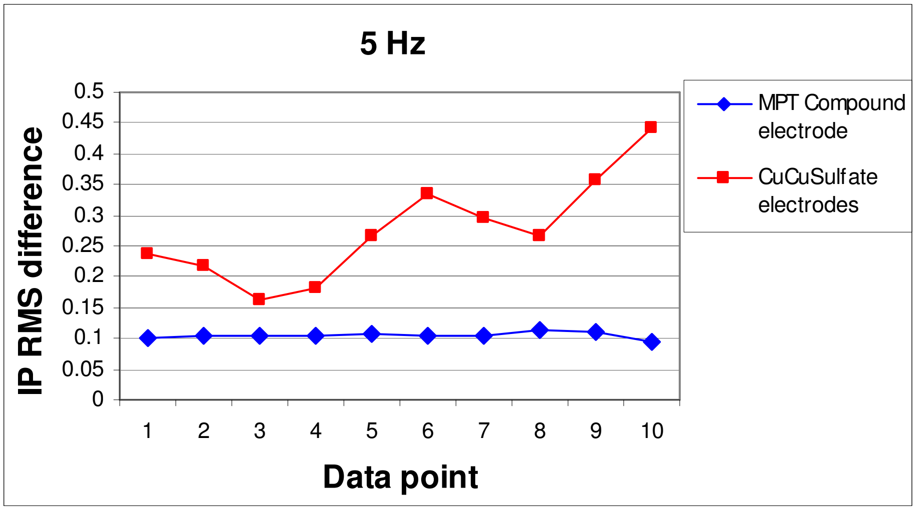

Figure 6. Results for IP measurements for the NPE-SE compared to standard copper/copper sulfate half-cell electrodes. Measurements were taken at 5 Hz.

Task #2: Long-term survival of subsurface electrodes: field studies

We propose to either acquire data from active on-going sites, or return to existing sites to compare contact resistance values with historical values and/or determine the percentage of electrodes that have failed entirely. Under this task, MPT personnel will travel to between 5 and 10 existing installations which have had electrodes in place anywhere from 3 to 15 years.

We will also identify additional sites during the course of the project. Impedance estimates will be collected using both standard high current techniques and the input loading method thus allowing better comparison of the relation between contact impedance measured with standard techniques and the effective contact impedance of receiver electrodes.

An additional benefit will be to measure electrode decay curves for a subset of these aged electrodes to improve our understanding of stacking algorithms and the effect of electrode aging.

Accomplishments under Task #2:

Rather than travel to specific field sites to collect repeat data sets, we instead used archival data from two long-term ERT surveys: the Drift Scale Test at Yucca Mountain, Nevada which was sponsored by the U. S. Department of Energy as part of the civilian radioactive waste management program, and a water infiltration test at a site adjacent to the New Mexico Institute of Mines and Technology in Socorro, New Mexico and sponsored by the Sandia/Tech vadose program. Results of the study are presented below.

In many applications, electrodes must perform over periods of years or even decades. The most practical approach to examine the long-term survivability of electrodes is to evaluate existing data from long-term projects and/or revisit older ERT sites. One of the most complete of such data sequences is the ERT monitoring performed during the Drift-Scale Heater Test at Yucca Mountain, Nevada. The data were generously provided to us by the Department of Energy, Office of Civilian Radioactive Waste Management. More than eight years of archival data made available from the project are currently being processed. The Drift-Scale Heater Test was conducted to study the potential host site of the geologic repository for civilian nuclear waste in the United States. The proposed repository lies within the unsaturated zone in the welded volcanic ash of the Tonopah Springs Tuff, about 1,000 feet beneath the surface of the mountain and about 1,000 feet above the water table. Electric heaters, simulating the radiological heat source, were distributed along a drift in the repository and heated the rock mass for a little more than four years.

The ERT electrodes are a fine mesh or screen of type 304 stainless steel, each about 20 cm x 20 cm, which were wrapped around a PVC pipe. Stainless steel electrodes of similar design have been used in mining, engineering, and environmental geophysics (e.g., Daily et al., 2005). At the drift test, an assembled electrode array (PVC pipe, electrodes, and wire from each to the surface) was inserted into an open hole and then grouted in place. Twelve of these arrays, a total of 200 electrodes, were placed around the heated drift for the purpose of mapping the electrical resistivity distribution and thereby the moisture distribution during the test. Over the period of 97 months, 496 sets of data monitored the drying and then, once the heaters were turned off, the rehydration of the rock mass in the vicinity of the heated drift. All the Drift-Scale Heater Test ERT data were of the 4-electrode type and included all the reciprocal pairs. Each full data set provided 7260 separate measurements for imaging along eight different planes. The source frequency was a 4 Hz switched DC square wave and transmitted current varied widely between several microamperes (when the rockmass was very dry) and a few hundred milliamperes.

Results

Long-Term Electrode Studies

Figures 7 and 8 show the errors estimated from comparing reciprocal data values for three representative data points. Also shown on the figures are the average transfer resistance (i.e. the data value collected by the resistivity instrument) and the average transmitter (TX) dipole resistance. The TX resistance shown on the plots is the resistance of the transmitting dipole estimated from dividing the transmitter voltage, 75 volts, by the transmitted current which varies from reading to reading. The TX resistance is a function of the electrochemical surface impedances of the two transmitting electrodes, the geometry of the electrodes, the resistance of wires, cables and multiplexer switches used to connect the electrodes to the transmitter, and the three-dimensional resistivity structure around the electrodes. Thus, the TX resistance is strongly correlated but not identical to the electrochemical surface impedances of the two transmitting electrodes.

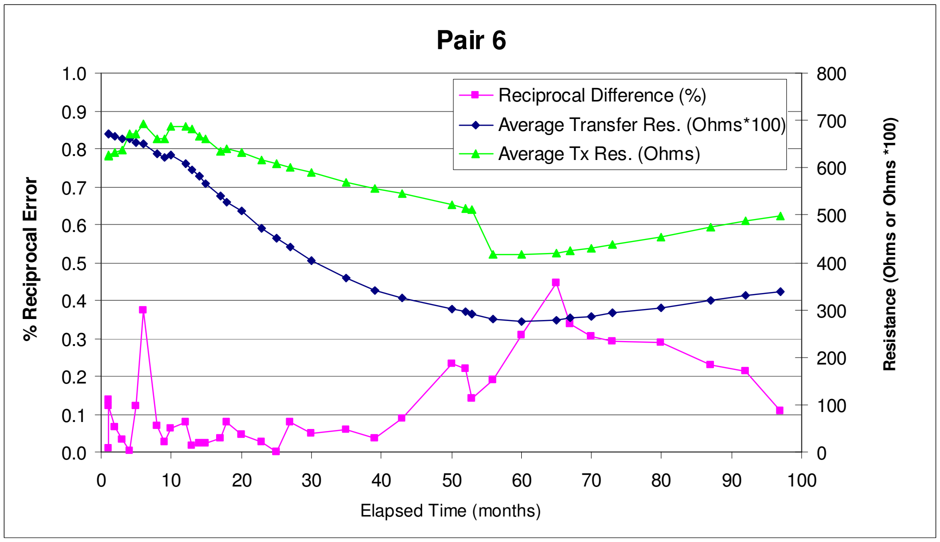

Figure 7. Long-term changes for closely spaced electrode dipoles placed as far from the heated drift as possible.

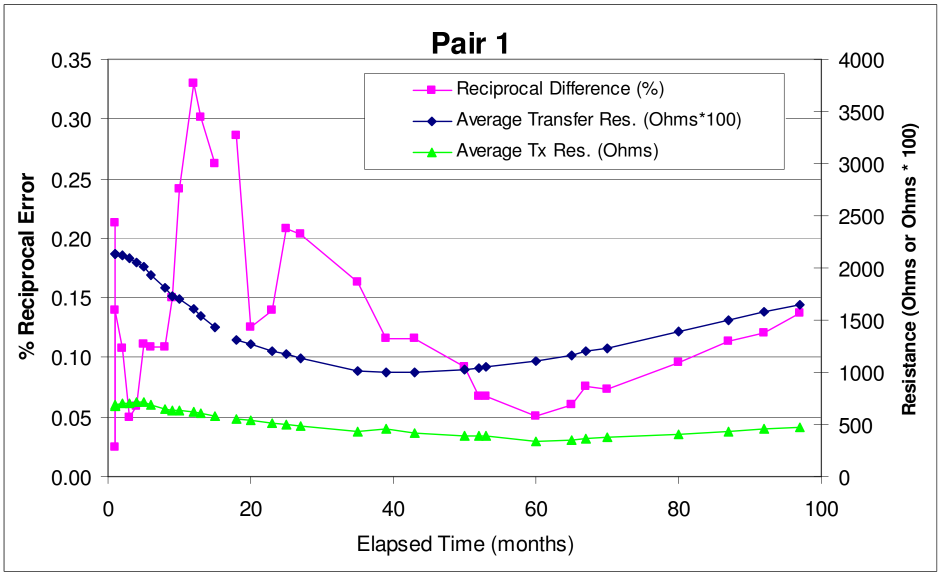

Figure 8. Long-term changes for closely spaced electrode dipoles placed as far from the heated drift as possible.

The two examples (Pairs 1 and 6 in Figures 7 and 8) used closely spaced dipoles located near the ends of the arrays and as far from the heater as possible. As our goal here is to observe long-term changes in the electrodes and not the rock, using electrodes far from the drift minimized the changes of temperature and moisture content in the rock due to the tests. This strategy was not perfect; both arrays show about a 2-to-1 decrease in transfer resistance (dark blue lines with diamonds, Figures 7 and 8) over the period of tests indicating a comparable change in background resistivity values. The decrease is likely caused both by the increase in temperature near the drift and the movement of water away from the drift and into the region of these particular electrode arrays. Choosing closely spaced electrodes also results in large received voltages; about 2.1 volts for the example in Figure 7 and 0.6 volts for the example in Figure 8 (not shown). With such large voltages one would expect relatively good signal-to-noise ratios and we see that the reciprocal errors tend to be a small percentage of the transfer resistances, much less than 1% for both examples. Although there is a sudden jump in both received voltages (not shown) and transmitter (TX) resistances around month 50 (Figure 8), it is not clear whether these changes are caused by changes in the arrays or by changes in the measurement system or procedures.

Task #3: Improvements in receiver and transmitter electronics

We propose improving the calibration stability of the receiver circuits. The goal is to reduce the short-term drift to below 0.1%. This will largely require implementation of a better calibration scheme and possibly improvements of the programmable gain amplifiers. The system should also be optimized for measurements at lower frequencies including increasing the number of receiver channels. Finally the input impedance of the receiver will be increased. This will require removing the attenuator and restricting the range of input voltages which in turn will require modifications of the transmitter to allow full control over the output voltage to prevent exceeding the input range of the receiver. The stability of the current measurement reference must also be improved. Finally, the calibration system developed in Phase I will be incorporated directly into the system hardware to allow automated, full system calibrations without dedicating a substantial portion of the external multiplexer.

Accomplishments under Task #3:

During this project we constructed an initial prototype receiver system, made modifications and revised the receiver design. A prototype of the revised design has been completed. The prototype uses a new 24 bit analog to digital converter from Linear Technologies with amplifier chips from Texas Instruments. The input impedance of the system will be increased from 10^7 Ohms to approximately 10^{10} Ohms. The input noise level of the system has been decreased to approximately 10 Nanovolts and system resolution to about 1 Nanovolt at the highest gain range of 125 to 1. The receiver also uses very high precision and high temperature stability components. The goal is to improve the accuracy to better than 0.1%. The system has more receiver channels, eight, to allow efficient data collection at lower base frequencies. We are also implementing a frequency-domain acquisition mode in addition to the time-domain acquisition mode used in the earlier systems.

The design of the prototype system including the transmitter and receivers has been completed. Initial field tests were started in the fall of 2008.

Task #4: Characterization of cables and development of strategies to reduce cable cross-talk

During the Phase I project we found the leakage from inexpensive, PVC multiconductor cables commonly used for cabling of ERT surveys has a limited effective isolation impedance potentially falling below 10^8 ohm-meters. Furthermore, that impedance has large frequency dependency and large phase / chargeability effects. These effects can be reduced but not eliminated by using higher quality cables. The goal of this project is to substantially improve the precision and accuracy of the measurements without substantially increasing the costs. Critical to the success of the project is to more carefully characterize readily available types of cables in order to understand these effects and find cost-effective methods to mitigate them. It is likely that any such mitigation will either increase costs or decrease the flexibility of the surveys. For example, we found that using cables with twisted pairs, especially shielded twisted pairs, reduces the cross-talk. However, this would require either a dramatically different hardware strategy or restrict the array types used in surveys to pre-determined electrode pairs. For some surveys it may be possible to determine operation bounds on the use of the cables in terms of waveform frequency, cable lengths, contact impedance, etc. To do this we must improve our understanding at the leakage characteristics of these cables under the types of conditions found in geophysical field surveys.

Accomplishments under Task #4:

We conducted tests on a number of types of cable commonly used for resistivity surveys. Using the configurations in Figure 9, a series of different tests were designed to determine if the couplings were primarily resistive, capacitive, or inductive in nature and to ascertain that the response was due to the cable cross-talk and did not depend on the receiver electronics. The results show that the problem appears to be primarily capacitive in nature and does not appear to be due to problems in the receiver electronics. Cables that use inexpensive PVC insulation had very large leakage responses and should never be used for high precision resistivity surveys. To date, the best methods for mitigating these problems appear to be 1) use cables with polyethylene or Teflon insulation, 2) use longer time delays or lower base frequencies to collect the data, and 3) reduce the contact impedance of the electrodes. The last of these methods, reducing the contact impedance of the electrodes, is more complex than anticipated as the contact impedance is highly nonlinear, decreasing with increased current flow. It is also time and frequency dependent, as well as dependent on the electrode construction. Thus a great deal of emphasis has been placed on finding stable electrodes that have low contact impedance at the very low current flows observed at the receiver.

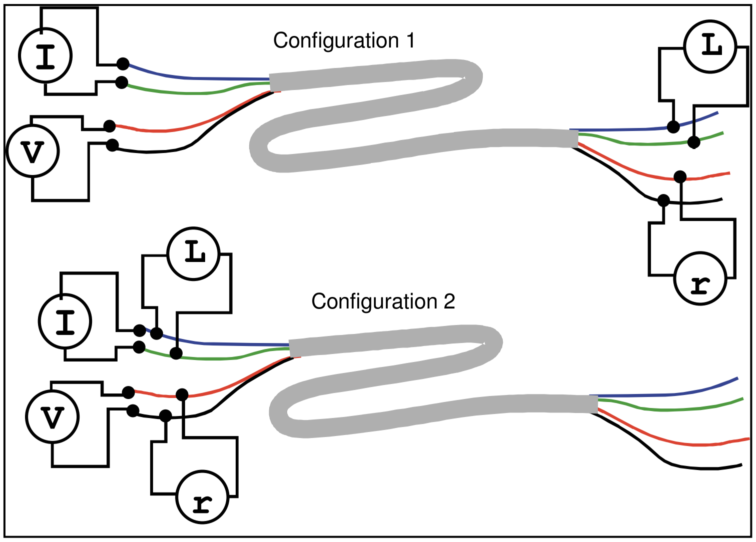

Figure 9. Configurations used for tests of cable cross-talk. I is the ERT system transmitter, V is the ERT system receiver, L is a 220 Ohm resistive load, and r is either a 10kOhm or 1MOhm precision resistor.

Results

During the previous project period we tested a number of types of cables used at ERT sites including inexpensive, polyvinylchloride (PVC) insulated cables and custom made, polyethylene (PE) cables. The results included in Figure 10 showed very large effects for PVC cable and particularly for high impedances.

Note that the different cables have very similar, though not identical, time-domain decay curves. This is somewhat counter intuitive as the lower-quality cables with higher capacitance and high "contact" (note that a resistor from cable to cable simulates contact impedances) impedance should have much slower decay rates. Although the better quality cables do have somewhat faster decay rates, the results do not follow a simple resistor-capacitor filter circuit model which would have an exponential decay whose fall off was inversely proportional to the product of the cable capacitance multiplied by the resistance. Because of the unusual form of the decay, it was important to make certain that this was not an instrumentation effect. We performed a number of tests changing both the transmitter load and input impedance One possibility that we considered was that the early time transmitter turn-off was saturating the input amplifiers on the receiver cards. One method of testing this was to collect data at a broad range of gain settings. The existing instrument includes a very broad range of gain range settings. One method of accomplishing this is to incorporate a 100 to 1 attenuator used for the highest (1000V and 100V) range settings. Thus, the input signal path is very different for these settings. Figure 11 compares plots for a single type of cable, Carol 4073 with a 1 mOhm resistor. Note that the 1000V range is very noisy. However, all of the other gain ranges give nearly identical results. To date, we have found no indication that large decay waveforms resulted from any instrumentation effect.

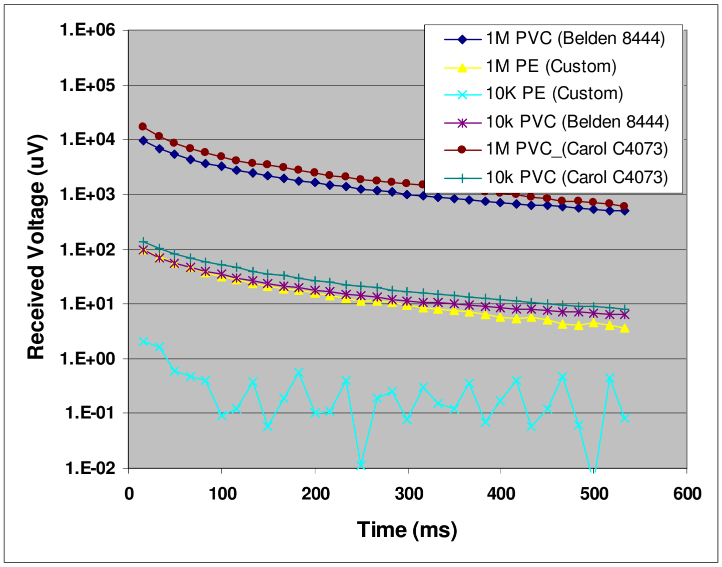

Figure 10. Voltage decay waveform due to leakage of current from the transmitter to receiver circuits for 30m lengths of common cables.

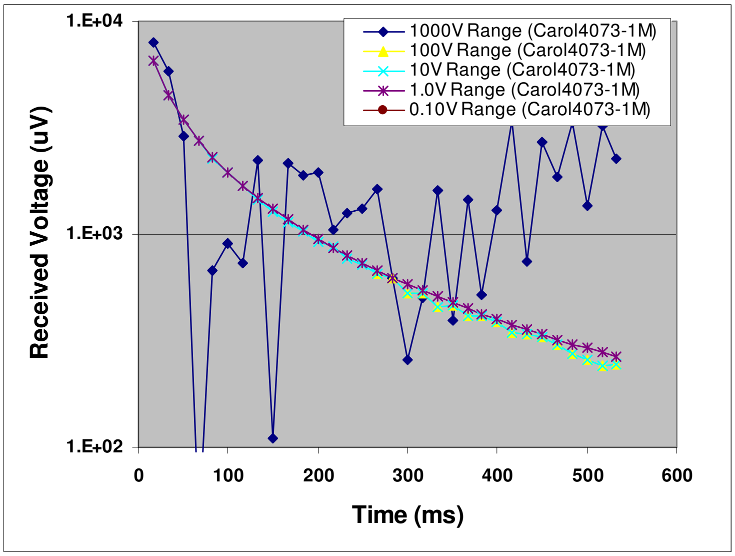

Figure 11. Voltage decay waveforms using a broad range of gain settings for a single type of cable (Carol 4073).

Task 5: Data acquisition strategies

In the past the design of a site survey has predominately been a matter of choosing the number and location of boreholes or surface lines, the spacing of electrodes along those lines, and finally the choice of an appropriate array or combination of arrays. Understanding the importance of systematic errors requires the consideration of a number of other important variables. Often, avoiding noise effects from high contact impedance will the base frequency/window timing and electrode construction of electrodes. In turn the base frequency/window timing for measurements and the type of electrodes in turn influence the choice of stacking algorithms, the transmit-receive interval for electrodes.

Accomplishments under Task #5:

When an electrode is used as a transmitter, a large, slowly decaying voltage is created on the electrode which can affect the electrode impedance. One of the issues in survey design and data collection has been determining how long one must wait before using the same electrode as a transmitter and as a receiver. A series of tests was completed in the laboratory sand tank (see Task 1) where four-electrode measurements were made using the same dipole transmitters and dipole receivers (the dipoles used adjacent electrodes). For each data series, a single set of normal measurements were collected with no reciprocals and electrodes were never reused as a receiver after being used as a transmitter. After waiting a specified length of time, the reciprocal measurements were collected using a schedule of measurements. The order of this second schedule was rearranged such that if this second set of measurements were performed without first using the normal schedule, no electrode would be used as a receiver after being used as a transmitter.

Another issue in ERT data collection is the potential for the transmitter as well as the receiver end of an ERT system to create problems with reciprocity readings. Existing ERT systems typically use a constant voltage source. For the transmitter dipole, a constant voltage source has low output impedance, whereas a constant current source has high output impedance. Therefore, we devised an experiment to determine if a constant current source transmitter might produce smaller errors than a constant voltage source. In the experiment, measurements were taken using a constant voltage source of 17 V. We chose a 17 V constant voltage source because it produced the same average current flow as the constant current source used in our previous experiment. Shortly after completing the first series of measurements, a series of measurements were taken using a constant current source with an output of 13.7 milliamps. Following this, a third set of measurements were made using the 17 V constant voltage source. This third set of measurements can be compared with the first set to determine if there is a long-term drift in the measurements unrelated to power source. All measurements were taken at 5 Hz.

Results

The results for the data collected within the sand tank at a frequency of 5 Hz are shown in Figure 12. For these preliminary results, there was not apparent improvement in the results with increased wait times. One issue with this type of experiment is that it is very difficult to discriminate between reciprocal errors and long-term drift inside the sand tank. Thus, for this study, we cannot conclude that increasing the wait time increased or decreased the reciprocal errors, only that there was not a dramatic change in results with different wait times. Because of the small scale of the sand tank, and since the electrodes had to be completely removed and reinserted for each test, the transfer

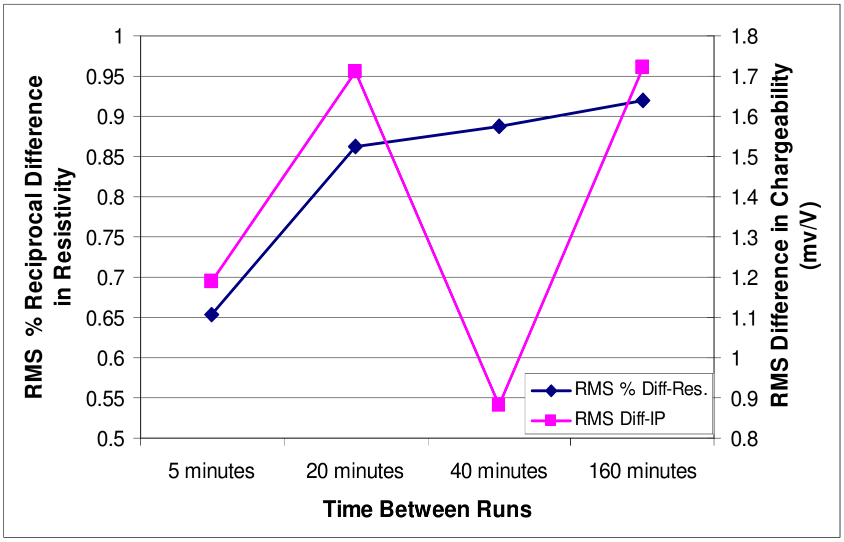

Figure 12. Results from time-delayed readings of normal and reciprocal measurements of stainless steel electrodes at 5 Hz.

resistance (i.e. the primary data value for resistivity) changed by as much as 10% from one experiment to the next creating a random component to the tests. Another issue with this experiment is that electrodes were sanded for each experiment and not allowed time enough to fully equilibrate before starting the experiment. Thus the results are noisier than other tests where the electrodes are left in place for long periods of time. Thus, we are in the process of revising the experiments to provide a more realistic comparison.

These preliminary results suggest there is little or no difference in either resistivity or chargeability reciprocal errors using a constant voltage or constant current dipole drive source. Figure 13 (below) shows there is < .02 percent variation in resistivity reciprocal errors regardless of power source and only slightly higher for chargeability (IP). The measurements were taken at two minute intervals, except the last data point in the series, which was taken after a much longer delay (> 1 hour). The constant current transmitter does not appear to improve the data quality.

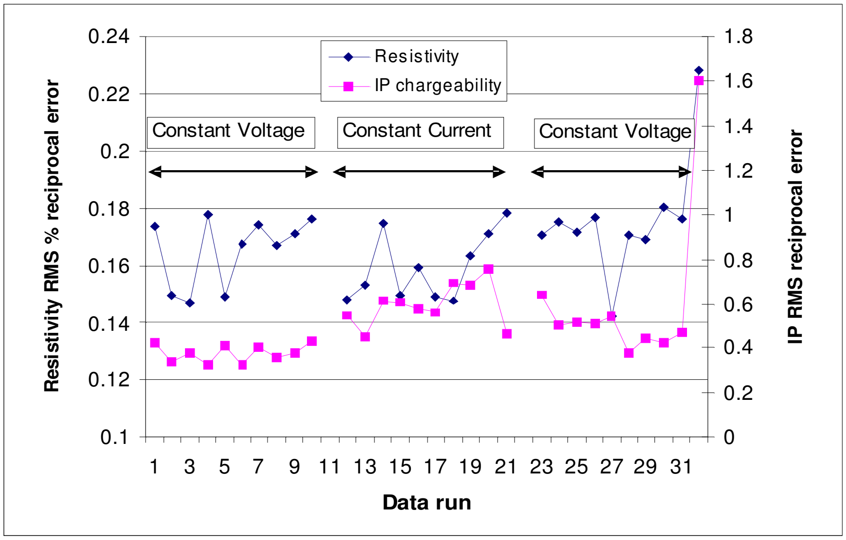

Figure 13. Resistivity and chargeability reciprocal errors on stainless steel using a constant voltage versus constant current dipole drive source.

Task 6: Full system tests

Full system tests were started in the fall of 2008.

Publications

A paper titled: “Assessment of measurement errors for galvanic-resistivity electrodes of different composition” by Douglas LaBrecque and William Daily, was published in Geophysics, 73 (2), F55-F64, 2008.

A paper titled “Long-term performance of galvanic resistivity electrodes” by Douglas LaBrecque and William Daily is in progress.

Conference Proceedings

A paper titled: “Strategies for accurate automated ERT data acquisition” by Douglas LaBrecque, Paula Adkins and William Daily was published in the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP) conference proceedings, Philadelphia, April 6-10, 2008.

A poster titled “Building better electrodes for electrical resistivity and induced polarization data” by Paula Adkins and Douglas LaBrecque was presented at the American Geophysical Union (AGU) fall meeting in San Francisco, December, 2007.

A paper titled “Systematic errors in resistivity measurement systems” by Douglas La Brecque, William Daily and Paula Adkins was published in the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP) conference proceedings, Denver, April 1-5, 2007.

A presentation titled “Systematic errors in resistivity and IP data acquisition: Are we interpreting the earth or the instrument” was given by Douglas La Brecque at the American Geophysical Union (AGU) fall meeting in San Francisco, December, 2006.

A poster titled “Ultra-high precision resistivity tomography” by Douglas La Brecque was presented at the Environmental Remediation Science Program (ERSP) meeting in Warrenton, VA, March, 2006.