DOE/ER/82159--T2

Inductive Resistivity Logging in Steel-Cased Boreholes

SBIR Phase II Progress Report
Project Number 40145-97-I

GRANT NO. DE-FG03-96ER82159

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Oil Field Inductive Resistivity Logging in Steel-Cased Boreholes

SBIR Phase II Progress report

Abstract

SBIR phase II project 40145-97-I calls for the design and construction of a prototype inductive logging device to measure formation resistivity from within a steel-cased borehole. The SCIL (Steel Casing Induction Logger) tool is intended for reservoir characterization and process monitoring in an oil field environment. This report summarizes findings from the initial project period.

In this phase, bench model measurements were made to test casing compensation schemes, numerical models were calculated to optimize the tool configuration and associated formation sensitivity and the preliminary design of the tool was completed.

The bench tests constitute fundamental research on determining the characteristics of steel well casing and on developing means of separating the effects of the casing and the formation. This technology is crucial to the success of the project and we have made significant progress towards our goal of recovering the formation resistivity from inside the casing.

Next, we have completed a series of sensitivity and tool configuration studies through our partner Dr David Alumbaugh at Sandia National Laboratories. These numerical results help us optimize the tool configuration and allow us to calculate the expected formation sensitivity. These models are preliminary to data interpretation software to be developed in the next project period.

We also completed the initial hardware design of the tool and began ordering parts for later manufacture and assembly. The tool, which is designed for maximum flexibility of deployment, will have a powerful transmitter, an array of three component sensors and sufficient dynamic range to operate in standard oil field steel-cased boreholes.

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Introduction

The Phase I research project entitled "Inductive Resistivity Logging in Steel-cased Boreholes" addressed the feasibility of designing an inductive logging device for operation in steel-cased wells. In phase II we use this knowledge to design and manufacture an in-hole logging device and test it in an oil field setting. The device, termed SCIL (Steel Casing Induction Logger), represents a major technological advancement in logging technology. The ability to collect induction resistivity logs within steel cased wells could be a significant factor in finding new reserves in many oil fields. For example these logs could help locate bypassed reserves and monitor the effects of water and steam flooding.

At this point we must underscore the difficulty of the tasks at hand. The steel well casing greatly attenuates and distorts electromagnetic fields created within the borehole by the transmitter. Induction logging data collected within the well casing will overwhelmingly reflect variations of the casing pipe rather than the formation resistivity or the local geological structure. These effects have to be precisely removed before formation logging can take place. In spite of these difficulties, recent advances in computer technology and engineering make the solution to this problem possible. In addition, the enormous potential benefit makes the effort worthwhile.

This report describes the progress made during the initial phase of the research. In this phase, we made bench model measurements to test casing compensation schemes, completed the preliminary design of the tool and used numerical models to calculate optimum tool configuration and associated sensitivity to formation structure. These tasks are preliminary to tool construction and testing, which begins in the next period.

Initially, we begin with a short discussion of the results of the phase I project. Next we discuss bench model and numerical model results that are used in the tool design. Finally, we discuss the preliminary tool design and provide a schedule for its construction and testing.

The project is in its eight month and is on time and on budget.

Summary of Phase I Research

The SBIR phase I research project entitled " Inductive Resistivity Logging In Steel-Cased Boreholes" constituted a feasibility study for the use of electromagnetic inductive methods to obtain formation resistivity through steel well casing. The work consisted of numerical modeling and some field

tests to determine what tool configurations are possible from within steel casing and what would be the resulting formation sensitivity and measurement errors. We also identified the remaining obstacles to developing such a device. The results of this research were used as a starting point for the phase II project. We summarize the significant phase I findings below.

The steel casing attenuates the electromagnetic (EM) signal severely, but in a predictable manner; the effect is analogous to a low pass filter. The signal attenuation and associated phase rotation caused by the casing is a function of the electrical conductivity, magnetic permeability and thickness of the steel pipe.

Numerical modeling shows that an induction tool must operate at lower frequencies and much larger source-receiver separations than conventional open hole devices. The studies show that these long offset measurements result in lower bed resolution than conventional devices but yield deeper penetration into the formation around the borehole.

Field tests, using a surface EM transmitter and vertically oriented borehole receivers, in steel and plastic cased boreholes showed attenuation and phase rotations consistent with theory. In addition, the field data clearly indicate the location of individual pipes within the steel-casing string and suggest that the attenuation caused by the casing is a local effect. That is, only that pipe that immediately surrounds the sensor is responsible for the observed attenuation.

The phase I report detailed a series of technical obstacles to be overcome before a successful tool could be developed (Wilt, 1997). The chief obstacle is the compensation for the casing effect, which comprises most of the total secondary field. For a homogeneous well casing this requirement is reasonable because it simply entails only a static correction to the collected data. For a more realistic segmented casing, where the casing affect may continually change with depth, the task is more challenging. Other obstacles included designing a new series of low frequency high-powered source and receiver antennas and associated electronics to operate in a steel-casing environment.

Part A: Bench Model Studies

Bench scale models are a very useful tool for predicting the behavior of full scale systems when numerical models are unsuitable. For example in our situation there does not exist a numerical model to calculate the the EM fields through segmented steel-casing. Such a measurement is straightforward on a

bench model. We have used our bench model in developing schemes for compensating for the effect of the steel well casing during logging. In addition the bench experiments provide a physical feel for the obstacles to overcome during full scale logging operations.

Previous research has shown that the casing effect is completely scaleable, (Wilt et al. 1996, Wu and Habashy, 1994; Lee and Wilt, 1997). That is measurements made with a small scale apparatus and a small thin pipe are equivalent to full scale measurements providing that the proper scaling function is used. We can therefore use the bench results with perfect generality to predict the logging measurements within full scale steel casings.

In particular there are several issues to be resolved with the bench device before we can proceed to design the full scale apparatus.

1. What is the casing effect if the source and receiver sensors are placed in different pipes? Numerical models allow us to predict the effect if both tools are situated within a single pipe but a full scale logging device will typically have source and receiver tool in different pipes, most likely of different electrical and magnetic properties.
2. Can a single set of measurements at a close source-receiver separation (where the formation effect is negligible) be used to predict the attenuation at logging separations? What is the nature of these measurements and how effectively can they account for the casing effect?
3. What is the effect of casing irregularities such as pipe joints and corroded or perforated zones?

Our strategy is to use the bench model to collect data under these various scenarios and use numerical models to interpret the data. Below we describe the bench model apparatus and give results for this task.

A.1 Bench Model Apparatus

A schematic drawing of the bench model system is provided in Figure 1. It consists of several custom built source and sensor coils¹ connected to laboratory instruments. The source antennas are connected to a standard signal generator and an inductive type current detector for measuring the source current. This voltage is then supplied to channel 1 of a Hewlett Packard model HP 9862 spectrum analyzer. The receiver coil is connected to a

¹ The source and receiver sensors are identical induction coils. They consist of several thousand turns of thin wire wrapped around 1/2" wide and 2 " long mu-metal cores. EMI uses coils of this type in horizontal sensor arrays for borehole induction receiver tools.

Figure 1 Schematic representation of the bench model apparatus.

battery powered pre-amplifier located adjacent to the sensor and this signal is fed to channel 2 of the spectrum analyzer. The spectrum analyzer measures the voltages of the source and sensor coils and calculates the amplitude and phase of the transfer function between the source and receiver coils.

The coils are placed on a rack where the coil separation may be adjusted and measured and then fixed for the experiment. Data are usually collected at a series of frequencies with the apparatus initially placed in the air and then at various positions within steel pipes. We can therefore measure the effects of the steel pipes by comparing the measurements in steel with those in air using the same configuration; this also simplifies the calibration procedure.

A.2 Bench Model Results

We have acquired several small pipes of various wall thickness and diameter and have machined the ends so they fit within each other to make good electrical contact. A listing of these pipes is provided in Table 1.

We have carefully measured the physical dimensions of the pipes and the electrical conductivity. The physical dimensions were measured with tapes and calipers. The electrical conductivity of the pipes was measured with a four electrode system using the same apparatus depicted in Figure 1. The pipes were found to be uniform in conductivity to within 10 percent. The magnetic permeability is more difficult to measure. This property is determined by fitting the measured spectral responses to numerical models (see section A.3)

Note that the pipes are typically 2-3 m in length and the source sensor separation in the modeling apparatus is 1 m or less. Recent studies have shown that, except for sensors very close to the edge, measurements in relatively short pipes are equivalent to data collected in an infinitely long pipe of the same electrical properties (Wu and Habashy, 1994). We can therefore use numerical models for infinite pipes to help interpret our results.

Table 1 Pipes Used in Bench Models

diameter	thickness	conductivity	estimated permeability
2 1/4 "	1.58 mm	2.75×10^6 S/m	105
2 3/8	3.18 mm	3.33×10^6 S/m	105
3.5 "	3.25 mm	2×10^6 S/m	120
3.5 "	3.25 mm	2×10^6 S/m	120

In Figure 2 we show amplitude spectral measurements our logging apparatus in air and in steel pipes 1 and 2. Here we plot the amplitude transfer function (observed voltage divided by source current) for a source receiver separation of 0.6m. Note that for an induction coil receiver the voltage response linearly increases with increasing frequency; this characteristic response is observed in Figure 2 when the apparatus was situated in air.

The plot illustrates two characteristics of measurements within the pipe. At frequencies below 10 Hz the fields within the pipes are larger than those measured in air. Above 10 Hz, however, the fields are smaller within the pipe and they get increasingly smaller at higher frequencies.

At low frequencies the fields within the pipes are larger due to the high magnetic permeability of the steel. This characteristic tends to concentrate or gather the fields near the pipe and can increase the dc or low frequency field by as much as a factor of two depending on the magnetic permeability and thickness of the pipe. This is the so-called "magnetic induction" effect. Note that this magnetic induction effect appears to be localized. Numerical models show that the effect diminishes with distance becoming 1 percent or less at source-receiver separations exceeding 20 meters.

Figure 2 Bench model amplitudes for 0.5 meter T-R separation in steel pipe

Above 10 Hz the source induces eddy currents to flow in the pipe and these currents, in turn, create a secondary magnetic field that opposes the primary (supplied) field. This is the so-called “electromagnetic induction” effect. The net effect is that the measured field becomes increasingly smaller with frequency. The magnitude of this effect is dependent on the electrical conductivity, magnetic permeability and thickness of the steel pipe.

In Figures 3a and 3b we plot the normalized amplitude and phase spectra of the fields within the first two pipes given in Table 1 for the apparatus shown in Figure 1. The amplitude data are “normalized” by dividing the observed data collected within the casing to data in the same configuration collected in a free space environment. The phase spectra represents the corresponding difference in phase. These normalized plots therefore give the magnetic field response to the casing for a unit source independent of the measurement apparatus.

The upper and lower curves correspond to cases where the apparatus was situated completely within the pipe. For the middle curve the source was placed in the thicker walled pipe while the receiver was situated within the thinner walled pipe at equal distances from the junction. The pipes were electrically connected with set screws.

Figure 3a Normalized amplitudes for the three cases considered.

Figure 3b Phase differences for the three cases considered

The plots in Figure 3a illustrate three distinct regions. At frequencies below 10 Hz there is an approximate 60 percent field enhancement due to the magnetic effects. Near 10 Hz the fields begin to decline and above 30 Hz they decay exponentially, falling to undetectable levels at frequencies above 500 Hz.

The phase data shown in Figure 3b form three sub parallel plots asymptotically approaching zero at low frequency. As with the amplitude data, the data where the coils straddle the pipe joints is intermediate between the measurements made in the individual pipes. It is interesting that the phase continues to change at low frequency whereas the amplitude data are relatively static. This suggests that the low frequency phase may be of use in determining the magnetic properties of the steel.

In Figure 4 we plot the phase response for pipe #2 (thicker wall in table 1) versus data from a numerical model. Numerical calculations were made using code FFT_CAS developed by Soong (1997). Using parameters obtained from physical measurements of the pipe radius, thickness and electrical conductivity the plot shows that the bench model data closely fit the numerical results. The magnetic permeability given in table 1 was determined by fitting the bench and numerical model data.

Figure 4 Fit of numerical and bench model results. Model parameters are given in table 1 using pipe # 2.

The above plots show that the bench amplitude and phase data are well behaved even when the sensors straddle a pipe joint. We now take this a step further to seek a means to consolidate these plots into one universal response.

In Figure 5 we plot the amplitude spectra on Figure 3a against a normalized frequency given by,

$$f_n = (f \sigma \mu) t^2 \quad (1)$$

where f is the measurement frequency, σ is the electrical conductivity of the pipe, μ is its magnetic permeability and t its thickness in meters. There is a similar plot for the normalized phase. On this scale the plots merge into one indicating that the attenuation is strictly a function of the normalized parameters. Note that for the case where the modeling apparatus straddled the two pipes we used the arithmetic mean of the two casing thicknesses in the normalization.

Figure 5 Bench model amplitude versus normalized frequency.

This last result is encouraging because it reduces the response to a single plot. From such a plot we can predict the response at any frequency with the knowledge of only one point on the curve. In addition, the plot seems to include the response for the straddled casings, which is how the full scale tool will likely be deployed. Note that we should be cautious because this plot was made using only two pipes with similar electrical conductivity and magnetic permeability.

As expected, numerical models suggest that this is an oversimplification. These studies show that for close source-receiver separations and low frequencies the EM response of the casing is primarily a function of the product of the magnetic permeability and the square of the pipe thickness and that it is insensitive to the casing conductivity or frequency.

We illustrate this with the plot displayed below. Here we display the amplitude response for two casings with different permeability and conductivity values but the same permeability-conductivity product. The curves are similar but do not coincide, indicating that the normalization shown in Figure 5 is insufficient for pipes of different permeability.

This means that we cannot use a sensor placed adjacent to the source or receiver to obtain exact casing compensation data for the long offset sensor.

The adjacent sensor can be used to measure variations in the casing effect during logging and provide information on the variation of casing properties but it cannot be used for exact logging data adjustment without an additional correction function.

Figure 6 Numerical model amplitude spectra using casings of different μ and σ but a constant μ - σ product.

A.3 Discussion

Although encouraging, the results of this task are incomplete. For example, the bench data collected thus far are made with small sources and sensors in which the measurements closely correspond to the loop sources used in numerical codes. In contrast, a full scale system uses a long (2m or more) multiturn source which may not be equivalent to the loop sources used in the numerical models. The response of this new system must be simulated prior to the implementation of casing compensation schemes. In addition, the field levels are likely to be much higher in a full scale system which may cause nonlinearities in the response.

The final design of the casing compensation system is clearly not complete but the work above suggests that a system involving the measurements of fields adjacent to the source and receiver antennas will produce data to separate casing and formation effects. The goal is to develop a

method to compensate for casing effects in real time, during the logging operations

We plan to continue this work in the next phase of the project using the full scale apparatus and surface casings. We will also physically measure the conductivity, thickness and magnetic permeability of the full scale pipes to provide ground truth for the casing analysis schemes. This will help us test the design of the casing compensation systems and determine their effectiveness.

Part B Numerical Model Results

Preliminary models indicate that through-casing measurements are possible at frequencies up to 200 Hz. To achieve the same percentage of formation signal as conventional logging tools the source receiver separation must therefore be much larger. In this section below we apply numerical models to investigate the capabilities of extended logging tools and discuss techniques to improve resolution.

Numerical calculations were made by Dr. David Alumbaugh of Sandia Laboratories using numerical codes EM1D and EM3D developed at U. C. Berkeley and at Sandia National Laboratories. The object of the study was to calculate the response of an extended logging tool operating to various layered structures. Here we are attempting to detect and resolve conductive and resistive target layers with thicknesses that range from 0.5 to 8 m. We assume that the effect of the steel casing has already been removed from the logging data.

B.1 Resolution of layered structures with an extended logging tool

In Figure 6 we plot the EM response of a 10 m logging tool to a 0.2 S/m layer layer that ranges in thickness from 0.5 to 8 meters; the logs are plotted at the midpoint of the 10 m logging tool. The host rock conductivity is 0.1 S/m and the layer is centered at a depth of 1000m. The plot clearly shows the imprint of the 10 m source-receiver separation but much less clearly the depth of the target layer, its thickness or conductivity. For layers less than 4m thick the plots are almost identical. The response becomes smoother but more distinct for the thicker layers.

Initial analysis of these data suggest that the extended logging tool may resolve the conductivity -thickness product of the thinner layers but not the conductivity and thickness of these layers separately. The general rule is that the target layers are only readily distinguishable if their thickness is at least

one half of the source-receiver separation. For this tool that would limit the resolution layers at least 5m thick.

The situation is more hopeful if we examine the differences between the response in more detail. Notice that the curves differ slightly at depths near 995m and 1005m, where the receiver and source coils encounter the target layer. These slight differences may be of some use in discriminating between targets.

We can accentuate the differences by computing the vertical gradients of the field, or the differences between adjacent measurement points. In Figure 7 we plot the 0.5m vertical gradient, in percent, for target layers with thicknesses of 1 2 and 4 meters. The plots are considerably more distinct than the corresponding logging profiles in Figure 6. For example, the gradient for the 4 m layer shows a peak at approximately 992 whereas the 1m layer gradient peak is smaller and positioned at a depth of approximately 994 m. Note the region of zero gradient near a depth of 1000 m on all of the plots. This suggests that when the logging tool straddles the target layer the response is independent of the source or receiver position.

Figure 6 Out-of-phase response of a 10 meter logging tool to a three layer model where the center layer is of varying thickness. The conductivity of the middle layer is 0.2 S/m and the frequency is 80 Hz.

Clearly, the vertical gradients accentuate the differences between thin layers, allowing for some discrimination between models. For models consisting of closely spaced thin layers, however, the gradient plots can be quite complex and difficult to unravel. This suggests that more work is required before these gradient may be routinely used in data analysis.

For operation in steel casing we feel that it is desirable to calculate gradients rather than to measure them using two closely spaced sensors. Measuring the gradients would most likely accentuate variations in the

casing pipe rather than formation variations. We feel that a superior tactic is to first measure the absolute field, correct them for the casing effect and then compute the gradient.

Figure 7 Vertical magnetic field gradient of 10 m logging tool for 0.2 S/m layers 1,2 and 4m thick centered at a depth of 100m.

B.2 Signal and Noise Considerations:

Another goal of the numerical modeling is to establish the noise threshold of the new logging device. That is we wished to examine signal

from formation layering as compared to the sensor noise level. We assumed a coil noise of 1 femptoteslas, a source moment of 1 A-m² and required the signal from the target layer to exceed this level to detect the layer.

This is illustrated graphically in Figure 8. Using a 0.1 S/m background medium we wished to determine the sensitivity of the 10 meter logging device to formation layering deviating from this background. A range of models were calculated using layer thicknesses from 0.1-100 m and conductivities from .01 to 1 S/m. The contours show signal levels from the target layers of conductivity and thicknesses corresponding to the axes. The gray area is where the target layer signals fall below the 1 femptotesla threshold. The plot shows that layers as thin as .02 m can be detected with this device and the layers become easier to see as the conductivity deviates more from 0.1 S/m background. Note that the conductive layers on the right of the plot are easier to detect than the resistive layers on the left side of the figure.

Figure 8 Layer detectability diagram for a 10 m logging device operating at 80 Hz. The shaded region is where layers are undetectable.

This plot suggests that the 10 m logging device will be quite sensitive to a wide range of formation layering. However, as shown above, detecting the signal from layer is not equivalent to resolving its conductivity and thickness

Part C: Tool Design

In this section we describe the preliminary design of the SCIL logging tool. We first give the design philosophy, provide an overall view of the major features and then show the construction and testing schedule.

In our phase I final report (Wilt, 1997) we outlined several criteria for successful induction logging within steel casing. These were based on numerical model results and some field data; we repeat these specifications below.

1. The tool must operate at low frequencies (less than 500Hz)
2. The tool must have a source-receiver separation exceeding 5 m.
3. The EM response of the casing must be evaluated separately from logging measurements.
4. The EM response of the casing must be known at the logging frequencies and subtracted from the measurements.

C.1 General Specifications

The SCIL induction logging tool is schematically shown in Figure 9. It features a transmitter module and a receiver section that hangs below the source on a variable-offset semi-rigid cable. Both source and receiver modules have monitoring sensors and electronics to track the EM effect of the casing adjacent to the tool. The source-receiver separation may vary from 5 to more than 30m. This allows for formation penetration of up to 30m or more. The tool will operate at 8 frequencies from 1 to 2,000 Hz. It is specifically designed for operation in steel cased boreholes but it will also operate effectively in open or fiberglass cased wells.

The source (transmitter) module features a very powerful inductive source for overcoming attenuation due to the steel casing. The receiver section has a three component magnetic sensor array designed for mapping near-well inhomogeneities such as fractures or faults.

The design of the SCIL tool follows the philosophy of several earlier prototypes developed at EMI. This philosophy is to place electronic and computational elements as close to the sensors as possible. This allows us to achieve the most accurate and precise measurements possible and still retain data acquisition flexibility. For example, the SCIL tool features a 32 Bit in-hole

Figure 9 Schematic overview of the SCIL tool.

computer to control the data acquisition through a programmable gate array and a digital electronic section that features a 24 Bit A/D for optimum dynamic range.

The SCIL tool is designed as a flexible prototype that may be used in a variety of field experiments. We do not envision that this particular tool is the final commercial version but many of the features and designs of the SCIL tool will be common to future versions.

C.2 Transmitter Module

The transmitter module, schematically in Figure 10, features a powerful antenna, operable from 1 to 2,000 Hz, a current driver to supply the signal and a digital electronics module for downhole signal processing.

The source antenna is roughly 1000 times more powerful than standard commercial logging sources to provide sufficient signal for long offset logging operations and to overcome the attenuation caused by the steel casing. It consists of approximately 1000 turns of wire around a 2m long 3 cm wide mu-metal core. This provides a moment² of between 100 and 2,000 A-m². The transmitter can broadcast at 8 frequencies, from 1 to 2,000 Hz, controllable from the surface.

As shown in Figure 10 a monitoring coil is positioned 0.5 meters above the transmitter antenna. This coil is designed to monitor the EM signal adjacent to the transmitter; it is therefore very sensitive to the casing effects but insensitive to the formation. Measurements from this coil will be used in casing compensation procedures.

Attached to the source module in a separate stainless steel thermal dewar is the transmitter electronics package. This section consists of 4 modules each with a separate independent function. These are, from bottom to top, the driver module, tuning capacitors, digital electronics section, and power supply.

The current waveform is generated in the signal driver module and sent to the source coil. The driver uses the internal clock and a power supply switching circuit to efficiently create a square wave signal. At frequencies below 50 Hz this signal is transmitted intact; above 50 Hz the source is resonant tuned, using capacitors from module 2, to compensate for inductive losses. The resulting signal is a sine wave. Current levels up to 3 A are

²The transmitter moment, a measure of the source strength, is the product of the effective crosssectional area, the number of turns and the current flowing through the wire

SCIL Transmitter Module

Figure 10 Schematic representation of the transmitter section of the SCIL tool.

possible but during routine logging the maximum current is roughly 0.1 A. Higher currents are used at large source receiver separations and at frequencies above 50 Hz, where casing attenuation effects are severe.

The digital module consists of electronics to control the timing and frequency of the transmitter driver and to digitize and average signals from the transmitter flux monitor and casing monitoring receiver. The data flow is controlled by an in-hole computer. Signals are transmitted to the surface using short haul modems.

The power supply module converts the 300V surface power supply into supply lines for the antenna driver and the electronic circuits within the tool. Because heat dissipation is an important consideration the tool head itself is used as a heat sink for the power supply.

The transmitter section has been designed to withstand pressures of up to 4 km and temperatures in excess of 125 °C. This is sufficient for operations in the vast majority of oil industry boreholes.

C.3 Receiver Module:

The receiver section is attached to the source with a semi-rigid cable (Figure 11). In this design the cable actually traverses around the source to avoid inductive coupling by the powerful antenna.

We have chosen a three component receiver antenna for the sensor module. The receivers were designed to have maximum sensitivity at approximately 200 Hz, this allows for signal measurement at frequencies where the casing attenuation is highest. Although gradient coils were considered in our proposal, numerical and bench models suggest that these coils would primarily measure casing irregularities rather than formation effects. With the 24 bit data acquisition and the casing compensation software the field gradients are more accurately calculated from the sensor coils than they could be measured using gradient coils.

Notice that within the antenna casing is a small transmitter in addition to the primary receiver antenna. In a similar manner to the receiver coil located on the transmitter, this source is used for mapping the EM casing effect near the receiver during logging operations.

Above the antenna module is the receiver electronics section. Similar to the transmitter electronics, this section consists of four removable modules each with an independent function. From bottom to top the modules are the

SCIL Receiver Module

Figure 11 Schematic representation of the receiver section of the SCIL tool.

analog electronics, digital electronics, mechanical compensator and power supply.

The analog module consists of amplifiers and filters for the sensor array and a current driver for the small transmitter. The amplifiers are similar to those on the commercial EMI coils but they are optimized for better response at low frequencies. The source driver is simply the clock synchronization signal.

Above the amplifiers is the digital module which is used for A/D sampling, signal averaging and data transmission to the surface. This module is identical in design to the transmitter digital section, however, there are many more channels to sample. Data acquisition, processing and transmission to the surface is controlled by the integrated downhole computer.

The receiver can withstand pressures in excess of 4 km and temperatures of up to 175 C.

C4 Surface Station:

The surface station module, located in the logging truck, supplies power to the system, controls the communication and data flow and reads the tool depth through a wheel encoder. The data acquisition PC is attached to this surface station using the serial port.

The surface station communicates with both the transmitter and receiver modules. It uses short haul modems for data flow and has the capability of synchronizing both of the clocks.

C.5 Software Development

There are three software components for SCIL system. These are data acquisition and control software, data processing codes and interpretation software. The codes form an integrated package that covers the range from tool deployment to log interpretation.

The first series of codes developed are the acquisition software and tool firmware. These modules control the data flow, storage and logging operations. The firmware is code written for the in-hole computer, an INTEL based 386 "PC on a stick". This software controls timing, data acquisition and signal averaging. The firmware also controls the digital sampling of all field components. The firmware is stored on flash RAM on the borehole computer and the design allows for this software to be upgraded from the surface. The

logging software is written for a laptop PC and its main function is to read the depth encoder, control the data flow, and for storage and display of logging data. This software also controls the communication between transmitter and receiver modules and sets the data acquisition parameters such as transmitter frequency and the number of signal averages per record.

Data processing software includes modules for data editing and calibration, rotation of horizontal receiver sensors (using the integrated fluxgate magnetometers and accelerometers) and software for casing compensation. These codes are implemented in the field during or immediately after logging operations. The codes allow for data quality checks and some simple data interpretation and display. They also prepare data sets for the more detailed 2D and 3D imaging interpretation.

Imaging software consists of 2D and 3D inverse codes to fit the collected data. The codes are under development at Sandia National Laboratory and should be ready during the field testing phase of the project.

C.6 Construction and Testing Schedule

The timeline shown in Figure 11 provides the schedule for tool construction and testing during the first 20 months of the project; at present the project is at the 8 month mark.

Much of the manufacturing activity has already begun and many of the parts with long lead times have already been ordered. We expect to have completed the main manufacturing and be testing the device at the time of the next report at the 14 month mark.

Conclusion and Final Remarks

This report concludes the first, and in many ways, the most crucial phase of this SBIR II project. Here the preliminary experiments have been completed and the tool design has been set. In the next phase tool construction and assembly will be completed. According to our schedule the completed tool should be ready for testing by the end of this calendar year.

The construction stage will be followed by an extensive testing phase and finally a series of field trials. Note that many of the fundamental experiments on the EM effects of steel casing will continue throughout the course of this project, though at a lower level.

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Figure 12 Timeline for development of the SCIL tool.