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A Magnetic Induction Technique for Mapping Vertical Conductive Fractures: Electronic Design

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A MAGNETIC INDUCTION TECHNIQUE FOR MAPPING VERTICAL CONDUCTIVE FRACTURES: ELECTRONIC DESIGN

by

J. A. Landt, A. R. Koelle, M. A. Trump, and J. D. Nickell, Jr.

ABSTRACT

This report is the last in a series that describes the preliminary design of an instrument capable of mapping conductive fractures deep below the surface of the earth. Earlier reports dealt with theoretical analysis, the general status of the instrument development, and materials vendor searches. Here, attention is focused on the electronics design and prototype hardware to perform the mapping task. A phase-sensitive detector is described that has a sensitivity in the tens of nanovolts. Coil-switching circuitry is also described, as well as a downhole data link tailor-made for this particular instrument's needs.

I. INTRODUCTION

The orientation and location of vertical hydraulic fractures is of vital concern in the production of geothermal energy from hot dry rock.[1] Consequently, the Los Alamos Scientific Laboratory (LASL) has been keenly interested in fracture mapping techniques in support of their geothermal hot dry rock demonstration project. Many fracture mapping techniques have been considered and attempted, as summarized in "Status Report of the Vertical Conductive Fracture Detector."[2] The basis for the operation of this technique is the same as that used in the commercial induction logging instruments.[3,4] A theoretical treatment of this new magnetic induction technique is provided in "A Magnetic Induction Technique for Mapping Vertical Conductive Fractures: Theory of Operation."[5]

II. OPERATIONAL REQUIREMENTS

The vertical conductive fracture detector senses eddy currents induced in the fracture by a transmitting coil contained in the instrument, much like the operation of commercial induction loggers. The eddy currents can be detected by measuring their magnetic field with a receiving coil. The received signal (voltage in the receiving coil) is given by

$$V_r = CI\sigma t \cos^2 \beta \quad , \qquad (1)$$

where C is a constant depending on coil design, electrical frequency, etc., σ is the electrical conductivity, and t is the thickness of the fracture. β is the angle between the plane of the fracture and the plane of the coils, and I is the current in the transmitter coil. The present coil designs and expected fractures will produce a received voltage of 0.2×10^{-6} V with a drive current of 100 kHz and 10 mA.

The fracture orientation is found by rotating the coils and finding the angle β for which the signal is maximum. This mapping involves several elements:

(1) Determine the orientation of the instrument case as a reference, provided by the earth's natural magnetic field.

(2) Rotate the coils to determine the greatest received signal. This rotation can be accomplished electronically, involving no mechanical motion, if two identical coil sets oriented at right angles to each other are used.

The environmental operating requirements are 275° C and 7 x 10^7 Pa (10 000 psi). At the present state of the art, these requirements dictate the use of a thermally protected pressure housing for the electronics.

The coils must be located in a nonconductive housing, and the borehole fluid must be displaced in the vicinity of the coils. These requirements lead to major mechanical complexities, which have been addressed in a separate report.[5]

III. CONCEPTUAL DESIGN

A block diagram of the instrument is shown in Fig. 1. A separate report[6] covers materials considerations, hydraulic system design, and conceptual mechanical design. Here, emphasis will be given to the electronic subsystems.

A typical measurement scenario is:

(1) Position instrument at desired depth.
(2) Inflate bladder by supplying power to "inflate" wire pair.
(3) When motor current indicates stall (bladder expanded), disconnect power to inflate wire pair.
(4) Turn experiment "on" by supplying 150 Vac, 60 Hz to experiment power wire pair. The experiment will automatically sequence through a set measurement procedure. Magnetic north, as well as several outputs proportional to fracture eddy currents, will be measured and sent to the surface.
(5) When desired, turn "off" experiment by removing the power to the experiment power wire pair.
(6) Deflate bladder by supplying power to "deflate" wire pair.
(7) When motor current indicates stall, remove power from deflate wire pair. Instrument may then be repositioned at another depth.

To conserve energy and extend downhole operating time, power to each subsystem will be turned off if that subsystem is not being used.

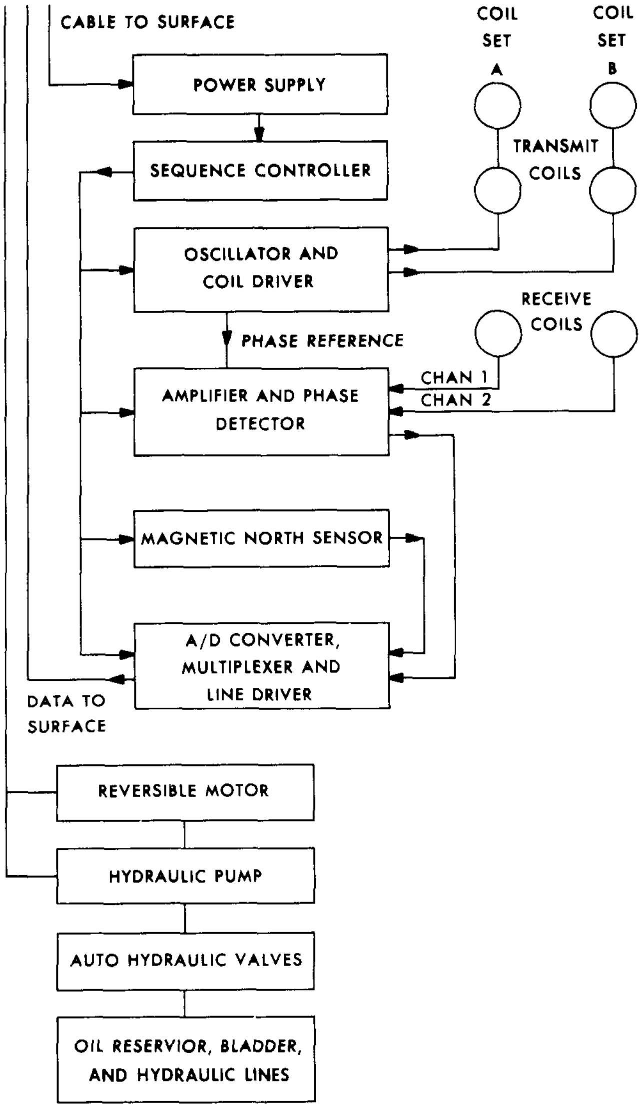


Fig. 1. Vertical conductive fracture detector.

The experiment [item (4) above] consists of several parts, each controlled by the sequence controller that starts automatically when it receives power.

(a) Measure magnetic north direction.
(b) Transmit in coil set A and receive in channel 1.
(c) Transmit in coil set A and receive in channel 2.
(d) Transmit in coil set B and receive in channel 1.
(e) Transmit in coil set B and receive in channel 2.

(f) Receive in channels 1 and 2 with no coils transmitting.

(g) Reverse polarities on several of the items b through e and repeat the measurements.

Measurements b through e permit a "synthesized" coil rotation to be performed mathematically, which yields the desired angle β of the fracture. Measurements f and g provide data on electronics performance and allow some measurement errors to be corrected.

IV. SPECIFICATIONS

The specifications and general considerations of the electronic subsystems are

A. Power Supply

PURPOSE : To provide dc power for the experiment.

SUPPLIER: Semiconductor Circuits, Inc., 306 River St., Haverhill, MA 01830, or equivalent.

INPUT : 150 V, 60 Hz from surface.

OUTPUT : ±6 Vdc, ±12 Vdc mA total output.

SIZE : Must fit within a 7.1-cm- (2.8-in.-) diam tube.

OPERATING REQUIREMENTS: Must provide well-regulated and filtered dc outputs; will consume as little internal power as possible. All electronic equipment is to be powered from this device so that grounding and shielding requirements of the other subsystems must be considered. The experiment will be turned on by applying the 150 Vac from the surface to the power supply, which in turn provides power to the signal processor and sequencer.

B. Sequence Controller

PURPOSE : To sequence through the experiment, each new state being set automatically upon command from the signal processor.

SUPPLIER: LASL design.

INPUT : ±6 Vdc, ±12 Vdc, +6 V pulse from signal processor.

OUTPUT : Appropriate voltages and currents to set the necessary relays, switches, and equipment to the proper state. Also send the processor an indication of the state that was set.

SIZE : Must fit in a 7.1-cm- (2.8-in.-) diam tube.

OPERATING REQUIREMENTS: Must reset when power is turned on, then step through experiment when commanded by the processor. The sequence of the experiment will be determined before detailed design of the sequencer. Time between states will be 4 s. At least four devices will be controlled.

C. Oscillator and Coil Drivers

PURPOSE : To provide a stable, well-controlled drive coil current.

SUPPLIER: LASL design.

INPUT : ±6 Vdc and ±12 Vdc, controls from sequencer.

OUTPUT : ~ 10 mA, 100 kHz, feeding a series resonant coil of several mH inductance. Also a reference voltage in phase with the drive current.

SIZE : Must fit in a 7.1-cm- (2.8-in.-) diam tube.

OPERATING REQUIRMENTS: Specifications on stability of amplitude and frequency to be set later, but most likely within several per cent. Either of two coils will be driven with either polarity upon command from the sequencer.

D. Amplifier Phase-Sensitive Detector

PURPOSE : To provide a dc output proportional to the received signal in phase with the transmitting coil current.

SUPPLIER: LASL design.

INPUT : ±6 Vdc, ±12 Vdc, twisted pair from receiver coil of signal approximately 0.2 μV.

OUTPUT : -6 to +6 Vdc corresponding to received signal in phase with the transmitter coil current.

SIZE : Must fit in a 7.1-cm- (2.8-in.-) diam tube.

OPERATING REQUIREMENTS: The desired signal will be in the range of 0.01 to 1 μV in the total signal of possibly several microvolts. Phase errors will be set later upon analysis of the experiment, but should be less than 2-3°.

Readings will be taken at least once every 4 s. Input power and switching will be controlled by the sequencer. Two channels of different gain may be used to cover a larger dynamic range than would be available with one channel.

E. Coil Sets

PURPOSE : To induce eddy currents in the conductive fracture and measure the resulting magnetic field.

SUPPLIER: LASL design.

INPUT : 10 mA, 100 kHz.

OUTPUT : Signal from fracture.

SIZE : Must fit within bladder and dielectric housing, overall o.d. is 15.2 cm (6 in.). Maximum length of dielectric space is 1.5 m (~ 5 ft).

OPERATING REQUIREMENTS: To provide a signal proportional to the eddy currents in the fracture. Appropriate grounding, shielding, and bucking will be determined. Two sets of coils with perpendicular magnetic moments are required. These two sets should be identical.

F. Magnetic North Sensor

PURPOSE : To find magnetic north.

SUPPLIER: Various off-the-shelf items are under consideration.

INPUT : 14-34 Vdc at 35 mA.

OUTPUT : One or two channels, 0 to +5 Vdc, +2.5 Vdc nominal, 0-500 Hz response.

SIZE : 3.1 cm (1-1/4 in.) by 3.5 cm (1-3/8 in.) by 10.1 cm (4 in.). The Schoenstedt device requires gimbals and will fit in a 6.4-cm-(2-1/2 in.) diam tube. The Humphrey device has a built-in gimbal but requires housing modification.

OPERATING REQUIREMENTS: Other equipment should be turned off. No dc currents near the device; dc motors may require magnetic shielding. Dewar and pressure housing must be nonmagnetic. Present devices are self-contained but need thermal protection.

G. A/D Converter, Multiplexer, and Line Driver

PURPOSE : To receive and digitize analog data and send it uphole for recording and data analysis.

SUPPLIER: LASL Design.

INPUT : ±6 Vdc, ±12 Vdc, 2 W, 16 data channels, -6 to +6 Vdc.

OUTPUT : Analog signals digitized to 12 bits and sent uphole at a rate of 4 measurements/s. Four seconds required for complete sequence. Sequence automatic. Flag provided for sequencer to indicate end of data sent.

SIZE : About 25.4 cm (10 in.^{3}) to fit in a 7.1-cm- (2.8-in.-) diam tube.

OPERATING REQUIREMENTS: Temperature held to 85°C maximum. Must drive 15 000 ft of cable. Cable is seven random insulated strands inside a steel jacket. Strand resistance, ~ 10 Ω/1000 ft. Interstrand insulation, 10 kΩ.

V. ELECTRONIC DESIGN

Electronic design and breadboarding have been completed on all of the electronic items listed previously, with the exception of the sequence controller. Consideration was given to the size and power requirements of each subsystem, but no ruggedized construction was started because the mechanical design was not yet complete. The results of these design efforts are given here.

A. Power Supply

An adequate commercial power supply module is the Model P2.12.200M from Semiconductor Circuits, Inc. It measures 6.4 cm (2.5 in.) by 3.2 cm (1.25 in) by 8.9 cm (3.5 in.), and will supply 12 Vdc. Output regulation is ±0.01%, with a line voltage variation from 105-125 Vac at 50-400 Hz, at a current of 200 mA. The ±6 Vdc will be derived from the ±12 Vdc with a simple transistor regulator.

B. Sequence Controller

Detailed electronic design of this item will be postponed until the mechanical design has begun.

C. Oscillator and Coil Drivers

Two main parts to the circuitry for measuring eddy current signals are (1) the 100-kHz coil drivers and associated 100-kHz generator and drive controls, and (2) the 2-channel input high-gain 100-kHz receiver amplifier, which includes a phase-sensitive detector and postdetector low-pass filter and amplifier. The two circuit blocks are connected together, in addition to the eddy current coupling to be detected, by the 100-kHz reference phase signal generated in the driver section and used in the phase-sensitive detector.

The 100-kHz working frequency is generated in an XR2206 integrated circuit shown in Fig. 2. This device is basically an RC oscillator, in which the timing capacitor is charged and discharged with constant current sources between two voltage limits

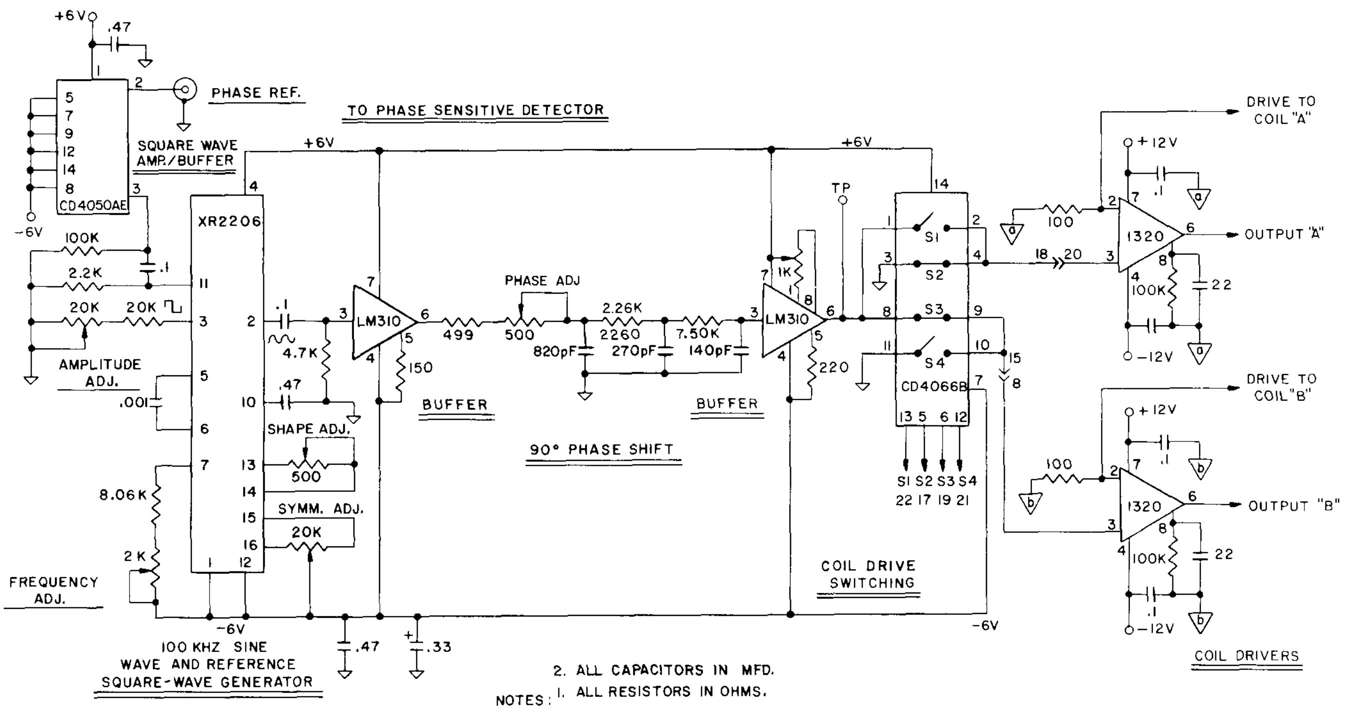


Fig. 2. Oscillator and coil driver circuitry.

sensed by a pair of internal voltage comparators. This process generates a triangular wave and a square wave. The square wave is taken out on pin 11 and passed through one section of the CD4050, which acts as a buffer amplifier, and the output is used as the 100-kHz phase reference for the phase-sensitive detector in the receiver section. The triangular wave is converted into an approximation of a sine wave inside the XR2206 by a shaping circuit. The sine-wave shape is optimized by means of the external symmetry and shape adjustments.

The sine-wave output from pin 2 of the XR2206 is passed through an LM310 voltage follower, which acts as a buffer between the XR2206 output and the following low-impedance circuitry.

The sine wave is then phase shifted by 90° in a three-section RC phase shifter, which also acts as a low-pass filter to remove much of the residual harmonic distortion in the signal. The 90° phase shift is necessary since the phase-sensitive detector requires that the square-wave phase reference signal be in phase with the sine-wave phase component to be measured, and the XR2206 produces the square-wave and sine-wave output in phase quadrature. There is no practical way to phase shift the square wave, leaving as the only alternative to phase shift the sine wave.

The output of the phase-shift network is again buffered in an LM310 and then passed to the coil-driver stages through a CD4066, which is a CMOS quad-analog switch. Two sections of the CD4066 are used with each coil driver to either pass through the sine-wave signal or to ground the input. The CD4066 switch control inputs, at CMOS logic levels, will come from the experiment sequencing circuitry.

The coil drivers are wideband op-amps operated in a voltage-to-current converter mode. The current sent to the transmitting coils is returned to the driver circuit through the return wire of the twisted-pair transmission line and is passed to circuit common through the 100-Ω resistor at pin 2 of the op-amp, which is the amplifier input. The amplifier action forces voltage balance between the sine-wave voltage input at pin 3 and the voltage produced by the current through the 100-Ω current sampling resistor at pin 2. The 1321 op-amp has sufficient voltage gain at 100 kHz to force this conversion with negligible phase shift and distortion.

The transmitting coil inductance, which is several millihenries, is series resonated at 100 kHz with a suitable capacitor to cancel its reactance as seen by the coil driver. The series resonant connection makes it possible to drive the coil with 10 mA at 100 kHz with only a few volts at the output of the amplifier to drive the current through the coil resistance, the sampling resistor, and the residual unbalanced reactance. The resonating capacitor is shunted by a 100-kΩ resistor to provide a dc path for the feedback sufficient to keep the dc level at the amplifier output from drifting too far off zero.

D. Amplifier and Phase-Sensitive Detector

Phase relationships at the 100-kHz working frequency must be very well controlled throughout the system, since the major means for separating the eddy current response from the signal directly coupled by transformer action between the sending and receiving coils is by the fact that they are in phase quadrature. Most of the direct coupled signal is balanced by means of the cancellation coils so that it will not overload the amplifier, but there will be a residual quadrature-phase signal remaining because of the limitation on cancellation that can be practically achieved and maintained. The phase-sensitive detector is used to reject the residual quadrature signal. The phase-sensitive detector also functions as a means for reducing the noise bandwidth of the amplifier by means of the low-pass filter placed after the detector. Such a reduction in the effective bandwidth of the receiver amplifier is necessary to allow detection of the eddy current signals, which are in the tens of nanovolts range. The use of the phase-sensitive detector and post-detector filter to reduce the bandwidth allows the main 100-kHz amplifier to be operated with a broad response centered about 100 kHz, and therefore, with only a gradual change in phase shift with frequency.

The receiver takes the outputs of the two sets of receiver coils, one at a time, through about 3.8 m (12 ft) of twisted pair line in a shield and terminated in about 100 Ω at the end of the lines, as shown in Fig. 3. The two sets of coil signals are individually amplified in a low-noise and very well balanced differential input stage, with a constant-current-emitter current source for good common-mode rejection and cascode output for low phase shift. Signal passage through these two input stages is controlled by turning the constant-current sources on or off by means of CMOS logic level signals from the experiment sequencer circuitry.

Ground reference for the coil signals is obtained by grounding the center taps of the coils to the shield common at the coils. No other ground is connected to the signal lines. It is expected that this configuration will avoid ground-loop-coupled

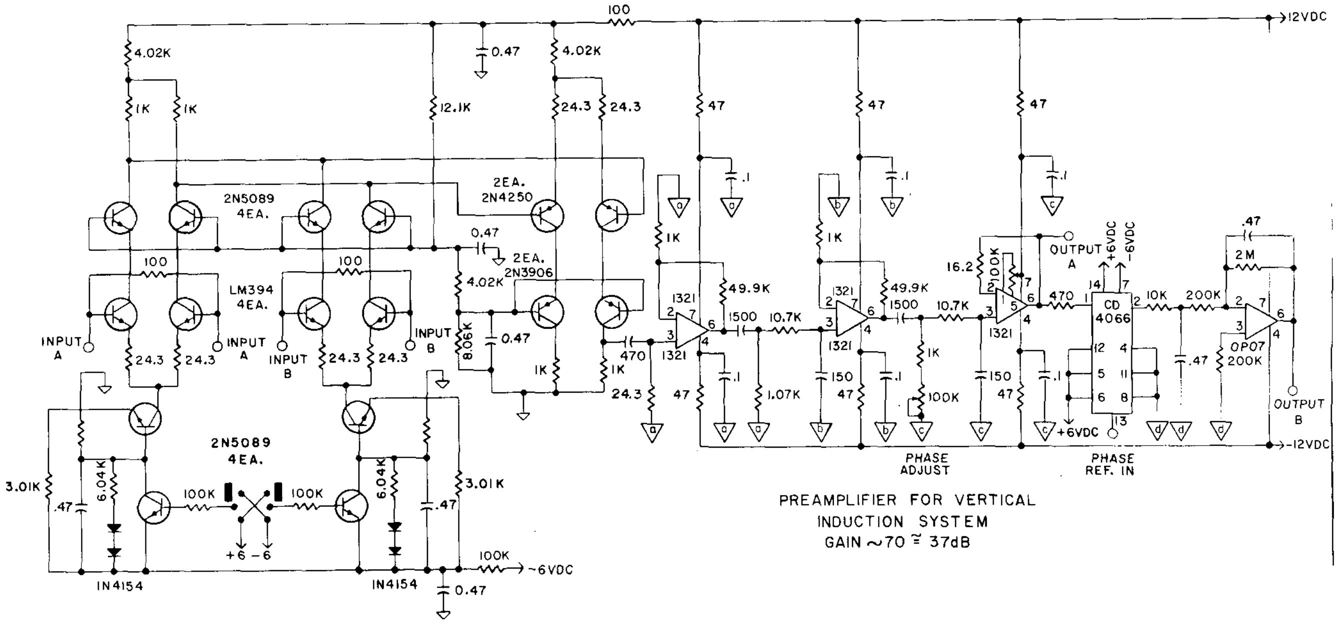


Fig. 3. Amplifier and phase-sensitive detector circuitry.

noise problems. The differential input configuration allows this type of connection to be used. The input device is an LM194, which is a very well balanced transistor pair. The use of a constant-current source for the emitter current and the inherently well balanced transistor pair results in high rejection of common-mode noise on the input signals.

The first-stage outputs are further amplified in another differential transistor pair with cascode outputs for low phase shift, and then taken off single ended with local ground reference to the main amplifier stages. The input amplifier configuration has, in addition to good rejection to common-mode input noise, good rejection to noise on the power supply lines. This is important to prevent phase shifts in the 100-kHz signal caused by feedback through the supply lines.

The two input stages give a combined voltage gain of about 40 dB or a factor of 100. The entire ac gain in the receiver is about 10^6 or 120 dB. Close control over the exact gain is not necessary, since the measurement made depends on the ratio of the outputs in the four measurement configurations rather than on the absolute level. Following the first input stage, the amplifier channel is common to all the measurement modes. The gains of the two input stages are mainly a function of the emitter current and the load resistors. Because the load resistor pair is shared by both input stages, the only separate elements controlling the gains are the emitter currents, and these are quite well controlled by the two constant generators.

The main ac amplification is done in three feedback stages using 1321 wideband op-amps. The first two stages provide 34-dB gain each and the last stage provides 24 dB. The 1321 stages each produce a few degrees of phase lag at 100 kHz because of the internal roll-off. The bandwidth of the amplifier is determined by the interstage coupling networks, which are set to produce both a low-frequency and a high-frequency corner at 100 kHz, each with a 45° phase shift in opposite directions for a net zero phase shift. The small phase shift from the op-amp stage itself is folded into the overall phase shift. One of the interstage couplings is made adjustable to allow trimming of the overall amplifier phase shift to zero at 100 kHz. The net frequency response characteristic is a rather broad response centered at 100 kHz, with 3-dB frequencies at 55 kHz and 190 kHz, rolling off at about 12 dB/octave at the skirts. The broad response, while undesirable from the noise viewpoint, ensures that the phase shift is not sensitive to drifts in the coupling components. Low-TC capacitors and resistors are used for the coupling, further ensuring stability of the phase response.

The phase-sensitive detector is one section of a CD4066RN CMOS quad-analog switch acting as a series switch between the last ac amplifier stage and the output filter. The detector passes through either the positive or the negative half of an in-phase 100-kHz sine-wave signal, and the dc level of the output is approximately 0.9 of the rms ac signal level. It was found that a half-wave detector was sufficient and much simpler to implement than a full-wave detector. The phase-detector input is directly coupled to the last ac amplifier stage output and sees any dc component in this signal. The last ac amplifier stage is provided with a dc offset control to zero the dc level in its output.

The phase-detector feedthrough from the switching input amounts to a few millivolts and is quite stable for a given device. This residual dc from the switching noise can be zeroed out with the offset adjustment in the preceding amplifier. The dynamic range of the phase detector is from a millivolt (determined by the stability of its zero level) to several volts. In practice, much of the dynamic range will be used to accommodate the amplitude of the quadrature phase signal, which may be several times as large as the in-phase component of interest. The dc output due to the quadrature phase signal will be zero, leaving only the output due to the in-phase signal component.

Some low-pass filtering is done right after the phase-sensitive detector. The main low-pass filtering is done in the output stage by the RC network in the feedback path. The amplifier used, an OP-07, has very good dc stability and provides a low-frequency gain of 10 with a single-pole low-pass roll-off with a 1-s time constant.

E. Coil Sets

To produce synthetic electronic coil rotation, two identical coil sets are required. Each set consists of three separate coils, and the planes of the coil sets must be oriented 90° from each other. Also, the center of each coil must coincide with the center of its perpendicular twin. The coils must also have metal shields around them (Faraday shields) except for a gap. The purpose of the shields is to eliminate the large, unwanted capacitive coupling signals that will be present otherwise.

Multiturn circular coils presented significant mechanical and electrical difficulties. Coil self-resonance was at a low frequency, which is undesirable. It was also difficult to adjust and shield the coils, and placement of required cable runs presented further problems.

A second construction technique was tried and has been more successful. This alternate arrangement makes more efficient use of space, permits easier adjustment of individual coils, allows installation of adequate shielding, and provides adequate space for cabling. Each individual coil was broken into two rectangular coils, each 7.6 cm (3 in.) by 15.2 cm (6 in.), wired in series and held 8.3 cm (3-1/4 in.) apart.

The transmitter and receiver coils were wound with 55 turns (5 layers of 11 turns), and the bucking coils contained seven turns. Each coil was series-resonated with capacitors held in place on the dielectric crossbar. These coils can be mounted perpendicular to an identical set more easily than the circular coils. Coil pairs were placed apart at vertical distances of 76.2 cm (30 in.) in the laboratory prototype. The center tap of the receiving coils was grounded, to be compatible with the receiver.

The laboratory unit was used to verify the analysis and to demonstrate the capability of measuring fracture direction without mechanical rotation. During these tests and demonstrations, it was found that grounding methods were extremely important and that the shielding provided by thin copper foil was marginal. It is anticipated that a good deal of attention to these details will be required as the actual construction begins.

F. Magnetic North Sensor

The vertical induction log requires a means of determining the orientation (azimuth) of the tool once it is downhole. It has been proposed that a flux-gate magnetometer, located in the tool, be used to measure the orientation of the tool with respect to the earth's magnetic field. If the assumption is made that the boreholes to be logged are all nearly vertical and that the magnetic fields in the rock are primarily caused by the earth's field, then a single-axis magnetometer located within the tool and in a plane perpendicular to the tool axis will be sufficient. For best accuracy the magnetometer should be free to remain in a plane perpendicular to the earth's gravitational field (pendulum mounting) and must be located in a portion of the tool free from magnetic effects or magnetic shielding.

The commercial instrument that most nearly satisfies the above requirements and those requirements imposed by the tool design is the Model FD06-0101-1 magnetic flux detector manufactured by Humphrey, Inc., of San Diego, California. This instrument requires an excitation of 28 Vdc at a maximum current of 200 mA. The output voltage is 2.5 times the sine of the heading with respect to magnetic north. Its upper operating temperature limit is 70°C. A complete list of operating characteristics is included on the enclosed drawing (Fig. 4). One basic limitation of this instrument is that zero output is obtained for north and south orientations.

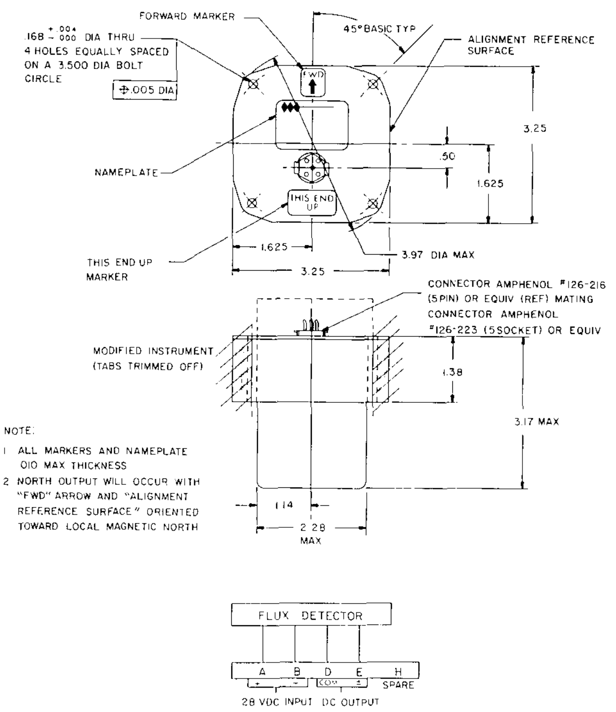
As supplied, the standard instrument exceeds one dimension (diameter) of the dewar proposed for the induction log. Harold Kries of Humphrey, Inc. has indicated that a modified flux detector can be supplied which will not exceed 5.8-cm- (2.28-in.-) diam over its entire length. The modified instrument could be supplied in approximately 8 wk at a cost of approximately $1500.

G. A/D Converter, Multiplexer, and Line Driver

1. Purpose. The downhole data link was designed to provide a serial data communication link between downhole experimental units and surface data-acquisition electronics. The unit is capable of receiving 16 analog signals, within the range of ±5.25 V and one 5-bit binary data word. Output information is in ASCII 7-bit code format and contains a carriage return (CR) and line feed (LF) as frame termination characters.

2. Description.

a. Physical. The unit is packaged to fit in a 7.1-cm- (2.8-in.-) diam tube and occupies approximately 25 cm^3 (10in.^3).



SPECIFICATIONS

*1.0	Input	
1.1	Voltage	28 Vdc ±10%
1.2	Current	200 mA maximum
*2.0	Output	
2.1	Function	Sine output
2.2	Voltage	Sine of the heading angle x 2.5 Vdc ±0.2 Vdc (when subjected to an earth's horizontal field of 0.25 G)
2.3	Angle	0° - N: 90° - E; 180° - S; 270° - W
*3.0	Accuracy	
3.1	North	Within 1° of earth's local magnetic north
3.2	Sine Function	Within 2° of input heading
*4.0	Repeatability	
4.1	North	Repeatable within 0.5° of earth's local magnetic north
5.0	Environmental	
5.1	Operating	
5.1.1	Temperature	-55°C to 70°C
5.1.2	Altitude	-1000 to 40 000 ft
5.1.3	Vibration	5 to 500 Hz, 0.036 in. D.A. or 5 G, whichever is the limiting value
5.1.4	Humidity	0 to 95% relative humidity at 32°C
5.2	Nonoperating	Normal transportation and storage
5.3	Pitch and Roll	±25°
6.0	Remarks	
6.1	Items marked with (*) are checked in production tests. Other items for reference may be checked on order by qualification tests.	

Fig. 4. Mechanical schematic of a Humphrey, Inc., flux gate magnetometer (electronic compass).

b. Electrical.

Basic operation: Refer to Fig. 5 for unit configuration and Fig. 6 for operational times.

A frame of output data is initiated by a 1-s frame synchronization during which time no data are transmitted. Following this frame synchronizing pulse a 16-channel multiplexer provides: (1) zero or +2.50-V calibration data, or (2) one of 14 analog signals to a 12-bit A/D converter. The A/D converter signals are converted into two data bytes (most significant data first), via 6-bit parallel tristate bus drivers (during BC1 and BC2 times, respectively). The data bus is received by a UART and converted to serial data transmitted in ASCII format at a 110-baud rate.

Following the 16 channels of analog (A/D) data, a 5-bit binary data word is received from the outside word and placed on the data bus during BC3 time. A sixth bit (MSB) of logical "1" is added to received binary data for format reasons, and the results are placed on the data bus via tristate bus drivers. These data are transmitted twice for redundancy.

The last two data words are: ASCII carriage return (CR, BC4 time) and line feed (LF, BC5 time). BC5 concludes the basic frame of data, transmission time approximately 4.6 s (including the 1-s frame synchronizing pulse). BC5 is buffered to produce end of frame (EOF) for use by external units.

c. Detailed Operation.

Major Timing Operations: Figure 7 shows in detail the action timing of the control signals with respect to each other.

A frame of data is initiated by a 1-s one-shot during which time data transmission is inhibited. This signal is used: (1) to trigger the A/D converter 60-μs initiate conversion pulse (IC), and (2) to provide a frame synchronizing pulse reset for the 16-channel MUX-control signals (C0, C1, C2, C3, and C4), and the DS and SC flip-flops.

The UART data strobe (DS) enters data into the UART input buffer when (1) the A/D conversion is concluded (ADCBZL) and (2) the UART output register is empty (TRMT). The DS pulse rate is divided by 2 to produce SC, which advances the MUX control scaler (C0 through C4). During C0 time, bus driver control signals BC1 and BC2 are produced and they place the A/D converter 12-bit data on the data bus lines BD0 through BD6. The most significant byte (MSB) is enabled during BC1 time, the least significant byte (LSB) during BC2 time. Thus, the MSB is serially transmitted first.

After 16 channels of analog data have been scanned, BC3 time is entered and the 5-bit binary data word is placed on the data bus. To insure that

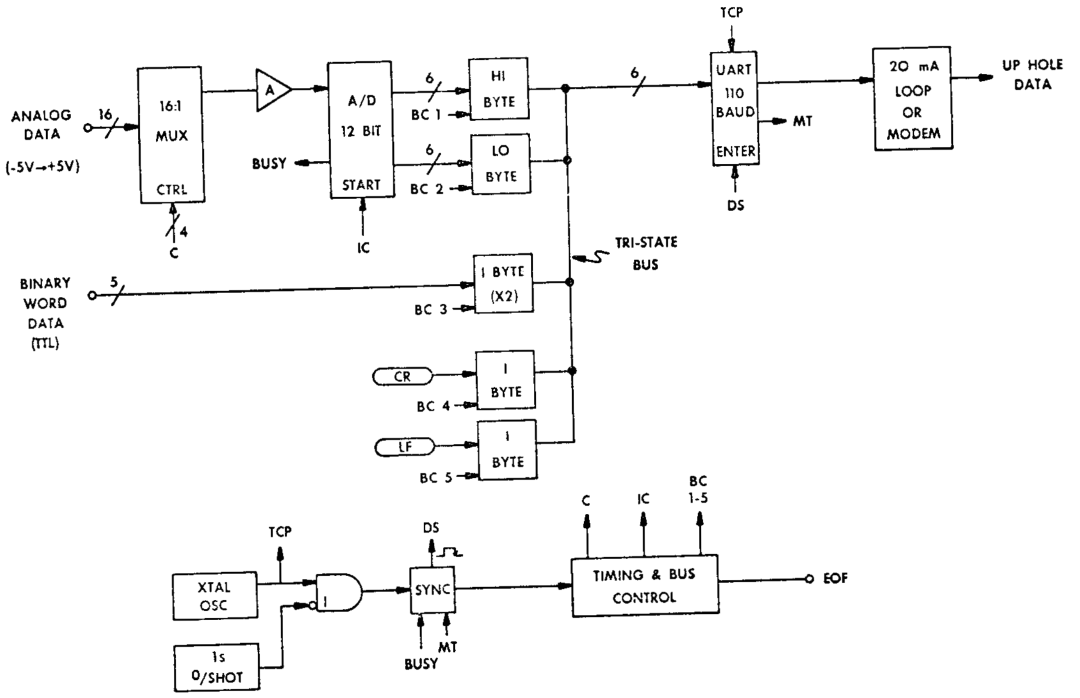
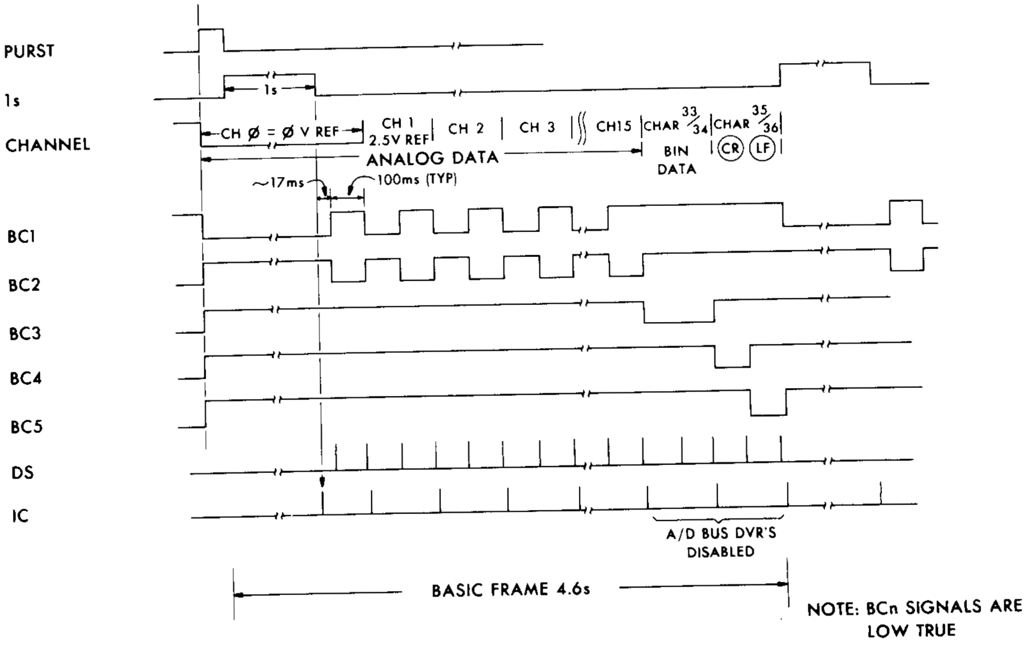


Fig. 5. Downhole data link.



NOTE: BCn SIGNALS ARE LOW TRUE

Fig. 6. Major timing.

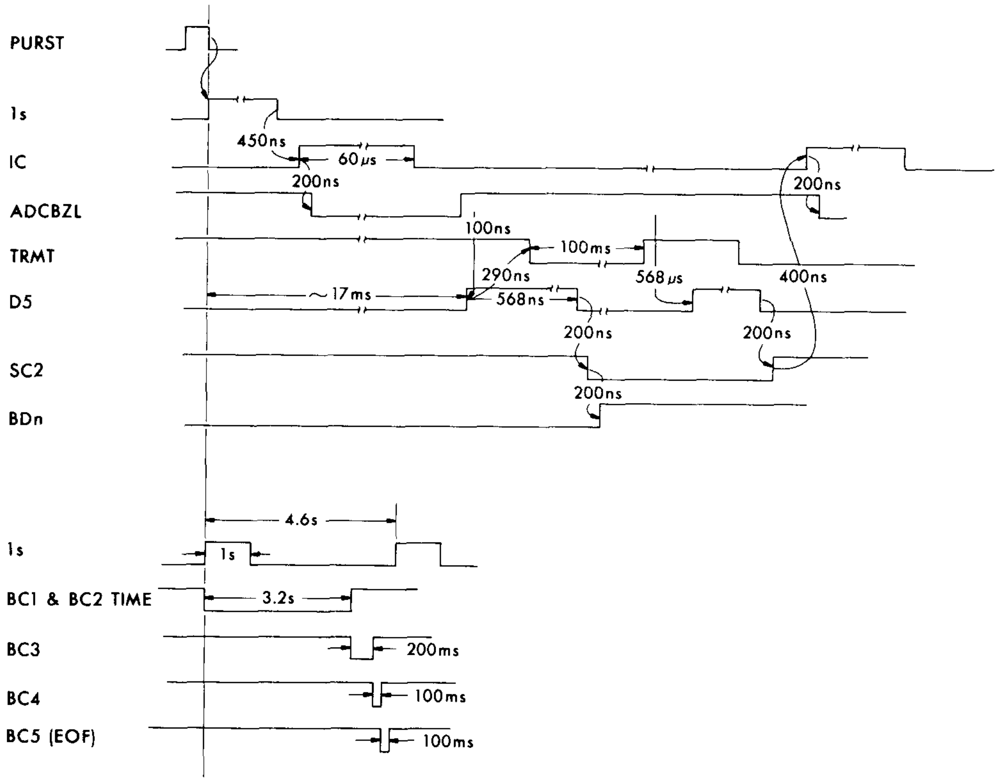


Fig. 7. Detailed timing.

ASCII control characters are not transmitted, bit 6 (BD5) is hard-wired to a logical "1." Thus, ASCII values of this data range from 040 through 077 (octal). These data are transmitted twice for redundancy.

Following BC3 time, the ASCII values for CR and LF are placed on the data bus during BC4 and BC5 times, respectively. An EOF signal is produced from BC5 for use by peripheral equipment. This signal is low-time DTL, capable of sinking 20 mA and sourcing +6 Vdc through 510 Ω.

Analog Data Amplifier: Incoming analog information (± 5.25 V range) must be converted into a 0- to +10 µA signal for analysis by the 12-bit A/D converter.

The 16-channel MUX analog output (MAO) is first buffered by a voltage follower to provide high-input impedance (< 10 M). Two amplifier sections, with a fixed overall gain of 0.75 subsequently perform the level conversion producing 0 to +10 µA for the A/D converter (A/D IN). Adjustments are provided to (1) adjust the amplifier to midscale (4.00 V) with 0.00 V input (POT 1), (2) adjust the amplifier gain to 0.75 (L.S. resistor), and (3) adjust the A/D converter signal current input (0 to 10 µA) (ADIN) (for MDO = 0.00 V) for an A/D output of 1000 (octal).

Serial Output Data Format: Serial output data from the unit are intended to be displayed on a standard 20-mA current loop teletype and/or received by a computer I/O interface capable of receiving serial ASCII 20-mA current loop data. The 20-mA source must be provided by the surface electronics to make the output buffer compatible with either an active or passive TTY terminal.

Analog Data: Format of the converted analog data has been chosen to eliminate unprintable TTY characters. This is accomplished by manipulation of bit 7 (BD6) in the transmitted ASCII word. (BD6 = BD5 x C4, where C4 is true during BC1/BC2 time). Thus, the data received by the TTY terminal always result in a unique printable character as a function of the analog input signal. The voltage represented by the printed characters is shown in Table I.

TABLE I

CHARACTER CONVERSION TABLE
VOLTAGE VS HI (LO) BYTE CHARACTER

HI Byte			LO Byte		
+Volts Char	Volts	-Volts Char	+Volts Char	Volts	-Volts Char
SP	0.00		@	0.000	?
!	0.16		A	0.005	
"	0.32		B	0.010	=
#	0.49		C	0.015	
$	0.66		D	0.020	;
%	0.82		E	0.025	:
&	0.98	Y	F	0.030	9
'	1.14	X	G	0.036	8
(	1.31	W	H	0.041	7
)	1.47	V	I	0.046	6
*	1.64	U	J	0.051	5
+	1.80	T	K	0.056	4
,	1.97	S	L	0.061	3
-	2.13	R	M	0.066	2
.	2.33	Q	N	0.071	1
/	2.46	P	O	0.076	
	2.62	O	P	0.082	/
1	2.79	N	Q	0.087	.
2	2.95	M	R	0.092	-
3	3.17	L	S	0.097	,
4	3.28	K	T	0.102	+
5	3.44	J	U	0.107	*
6	3.61	I	V	0.112	)
7	3.77	H	W	0.117	(
8	3.94	G	X	0.122	'
9	4.10	F	Y	0.127	&
:	4.26	E		0.132	%
;	4.43	D		0.137	$
	4.59	C		0.143	#
=	4.75	B		0.148	"
	4.92	A		0.153	!
?	5.08	@		0.158	SP

To use this table, first determine the printed characters (high and low byte) for the desired analog channel then sum the voltages represented by the characters.

Binary Data Word: The last two printed characters on a line represent the 5-bit binary data word received by the system. Bit 6 (BD5) is hard-wired to a logical "1" so that all values of the word are printable characters. This information is transmitted twice for redundancy. Thus, the ASCII values range from 040 (octal) for a binary word value of 00000 to 077 (octal) for a binary word value of 11111. Printed characters range from SP through ?. An example is shown in Fig. 8.

d. <u>Uphole Transmission Link</u>. Two techniques are available for transmitting serial data uphole. The most straightforward is to transmit 20-mA ASCII data. Circuitry required for this technique is a pair of transistors, the output stage capable of sinking 20 mA.

There is some uncertainty concerning RFI that may interfere with sensitive downhole units (that is, the magnetometer) from switching the 20-mA current. A second scheme would reduce this problem, but lack of experimental data results makes judgment difficult.

The second technique relies on modulating a low-speed modem transmitter with the serial data from the UART (SO). The modem output is a sine wave whose frequency is a function of the modulation information. A logical "1" produces 2025 Hz and a logical "0" (marking) produces 2225 Hz. Demodulation of the modem signal will be done on the surface and the 20-mA loop signal for the TTY terminal is provided in the demodulator package.

3. <u>Electrical Specifications</u>.

a. <u>Input Signal Conditioning</u>. The integrated circuits used in the downhole data link are C-MOS. Input terminals that interface with the outside world have nominal protection in the form of (1) 1kΩ

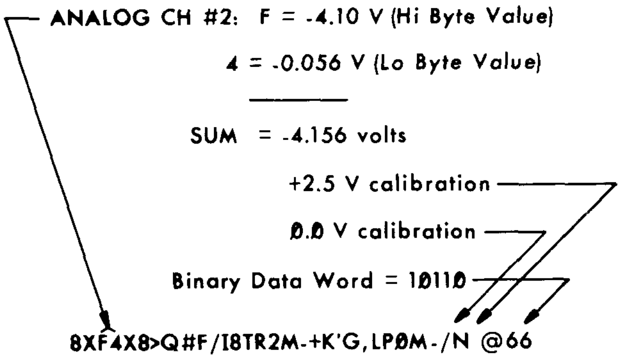


Fig. 8. A TTY line example.

series resistors in the analog input section and (2) 1kΩ series resistors with diode clamps to +6 and ground in the binary data word section.

Input voltage levels should be limited to (1) ±7 V to the analog section, and (2) +7 and -1 V to the binary data word section. Input impedance to both sections, within the above ranges, is >10 MΩ.

b. Input Power. Input power to the unit is:

+6 Vdc @ 30 mA
-6 Vdc @ -2.5 mA
+12 Vdc @ 1.5 mA
-12 Vdc @ -2.5 mA

Total input power < 250 mW nominal.

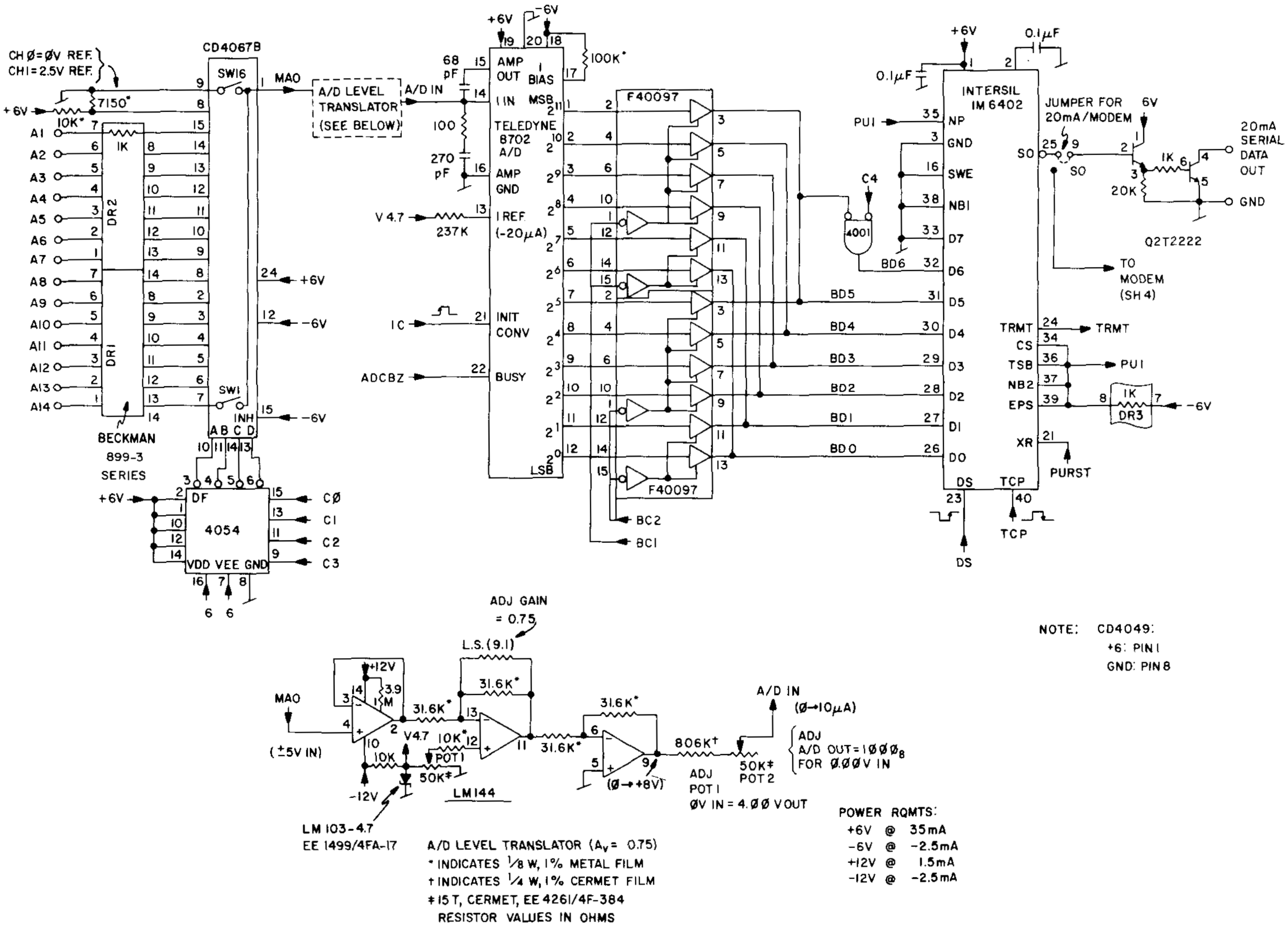
4. Circuit Diagrams. The circuit diagrams are provided in Figs. 9 through 12.

VI. SUMMARY

Several main items of electronic effort remain. First, the controller/sequencer must be designed. Because the experiment sequence and requirements will be influenced by the mechanical design as well as the analytical requirements, it was felt that sequencer design was presently premature. This design is straightforward and minimal once the actual experiment sequence is determined.

Second, a large amount of interfacing and check-out remains. Again, this effort depends in part on the mechanical design and components used. Interfacing the oscillator, coil driver, coil sets, and receiver has been accomplished.

Third, the ruggedized electronics must be built and tested. Again, this effort awaits mechanical design for sizes, cable routings, etc. No major problems are anticipated in this effort, however.



A/D LEVEL TRANSLATOR (A_v = 0.75)
* INDICATES 1/8 W, 1% METAL FILM
† INDICATES 1/4 W, 1% CERMET FILM
‡ 15 T, CERMET, EE 4261/4F-384
RESISTOR VALUES IN OHMS

NOTE: CD4049:
+6: PIN 1
GND: PIN 8

POWER RQMTS:
+6V @ 35mA
-6V @ -2.5mA
+12V @ 1.5mA
-12V @ -2.5mA

Fig. 9. Multiplexer and A/D converter circuitry.

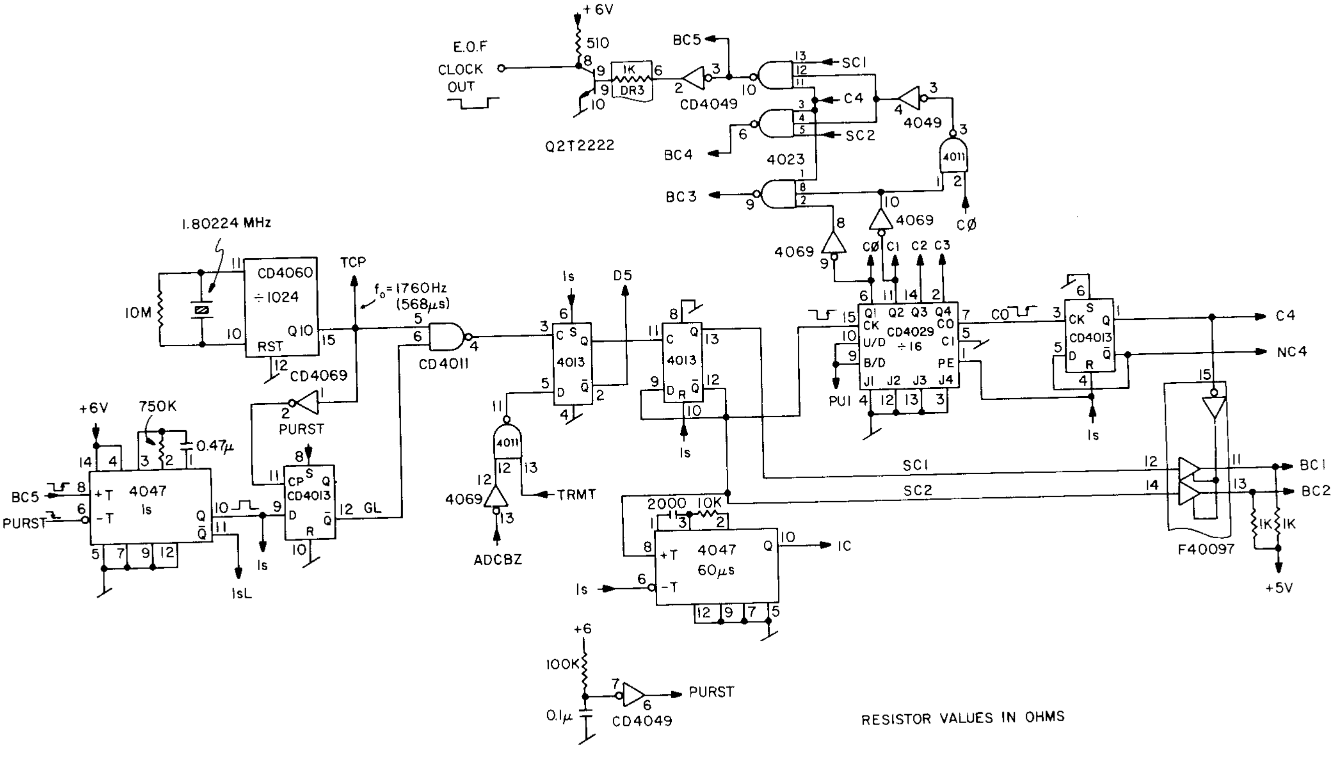


Fig. 10. Timing circuitry.

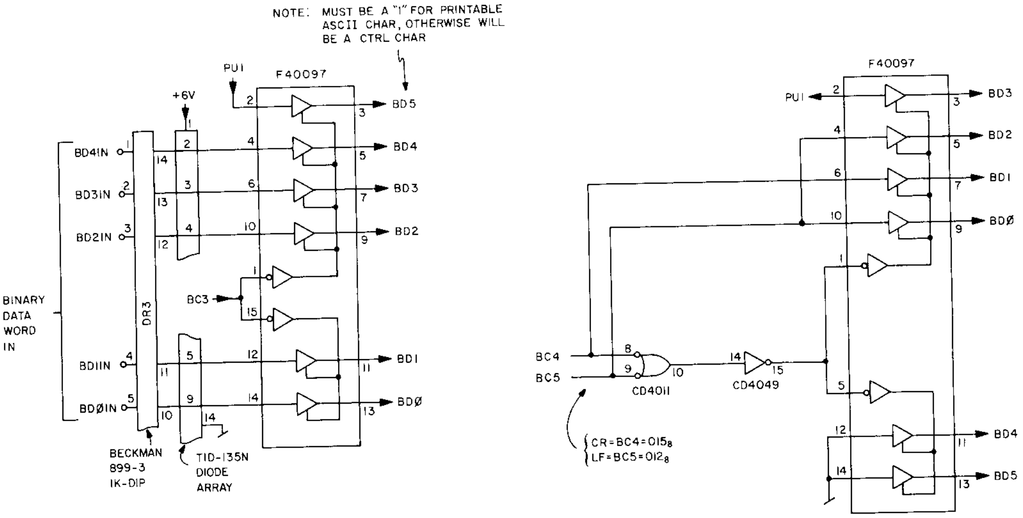


Fig. 11. Coder and line-driver circuitry.

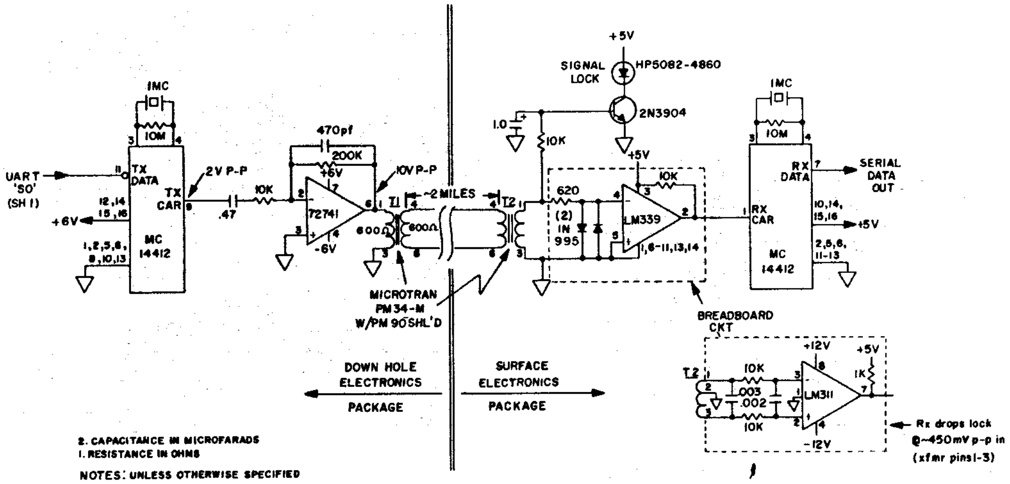


Fig. 12. Optional modem circuitry.

Last, the components must be mated to the mechanical housing, and the entire instrument will be performance tested before lowering into the intended hostile environment.

Figures 13 through 20 provide visualization of existing prototype hardware.

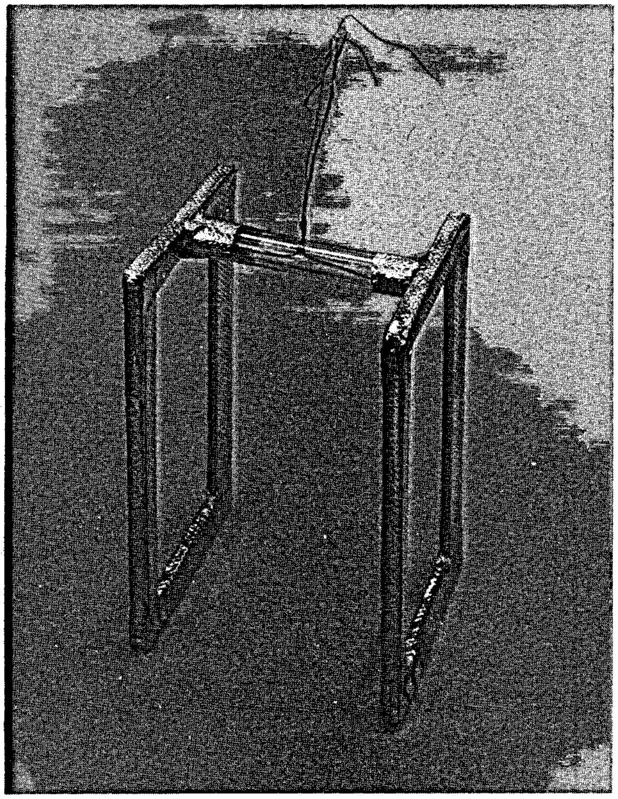


Fig. 13. A shielded rectangular coil set.

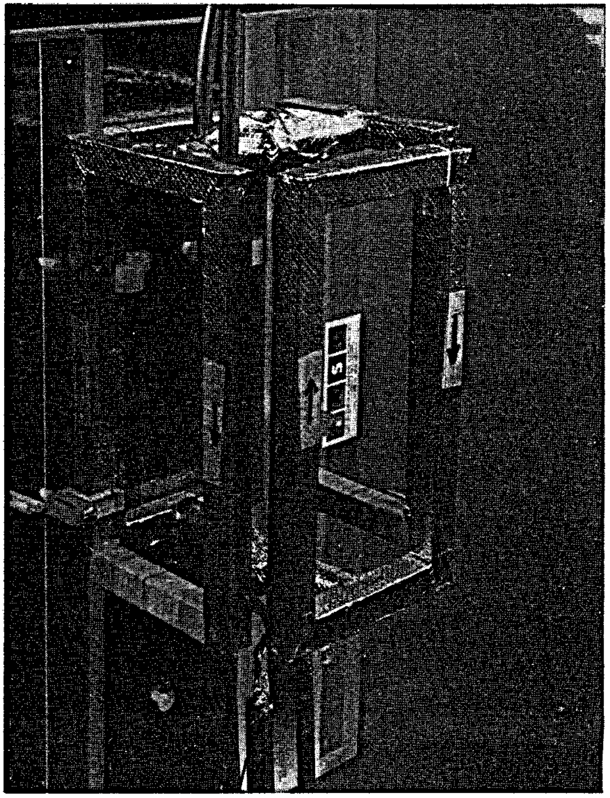


Fig. 14. Two shielded rectangular coil sets mounted perpendicularly to each other.

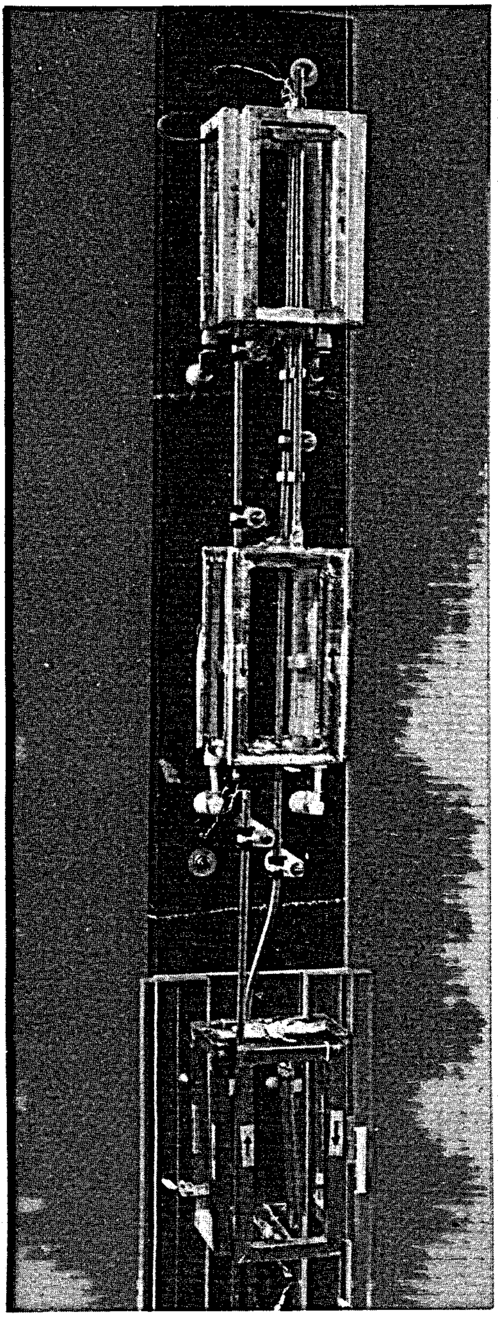


Fig. 15. Transmitting (top), bucking (middle), and receiving (bottom) rectangular coils for electronic rotation.

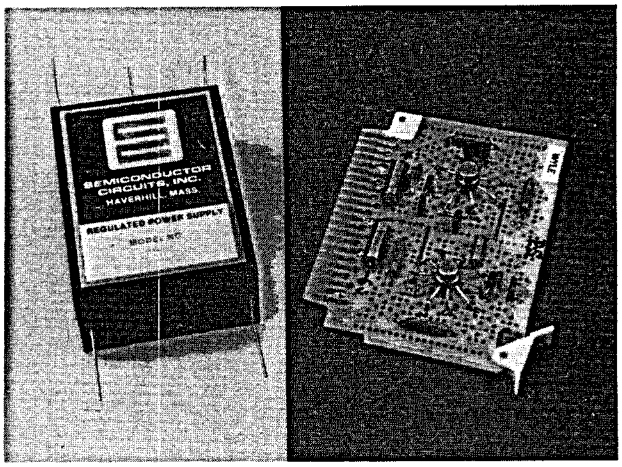


Fig. 16. Power supply and ±6-V regulator breadboard.

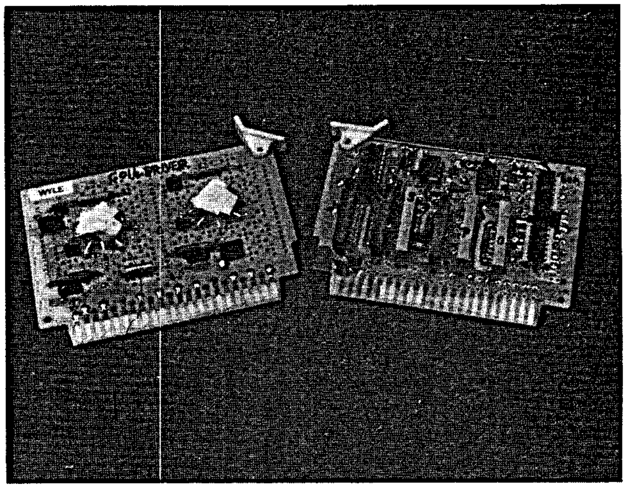


Fig. 17. Oscillator (right) and coil driver (left) breadboards.

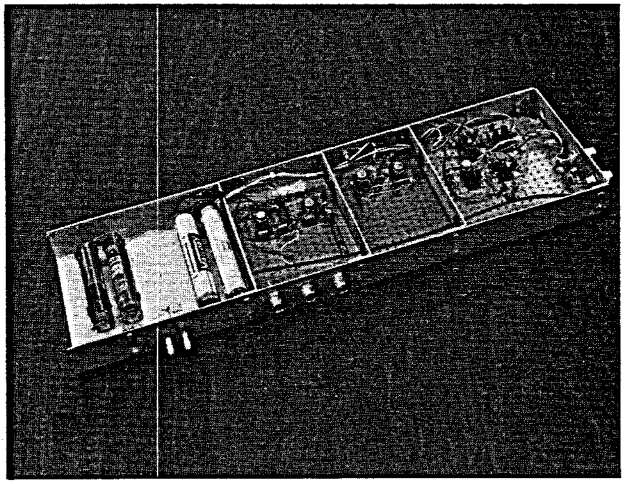


Fig. 18. Dual-channel amplifier and phase-sensitive detector breadboards.

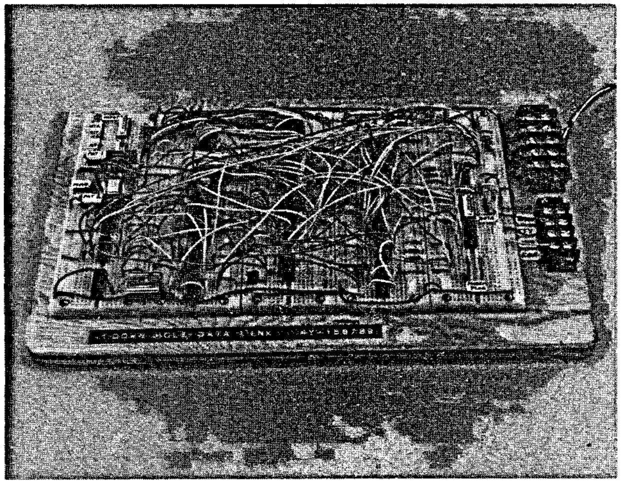


Fig. 19. A/D converter, multiplexer, and line driver breadboards.

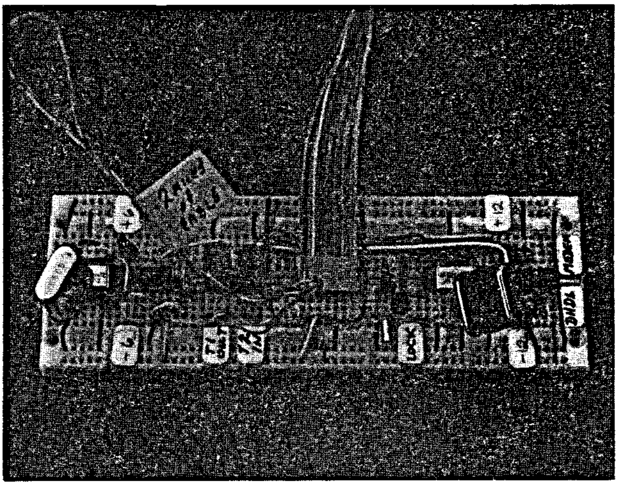


Fig. 20. Optional modem.

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REFERENCES

1. "The Los Alamos Scientific Laboratory's Dry Hot Rock Experiment: Engineering and Scientific Studies," a series of papers by LASL HDR staff presented at the 1976 Spring Meeting of the American Geophysical Union, Washington, DC April 12-15, 1976.

2. J. A. Landt, J. C. Rowley, J. W. Neudecker, and A. R. Koelle, "A Magnetic Induction Technique for Mapping Vertical Conductive Fractures: Status Report," Los Alamos Scientific Laboratory report LA-7049-SR, December 1977.

3. J. H. Moran and K. S. Kuntz, "Basic Theory of Induction Logging," Geophysics, December 1962.

4. H. B. Watt, G. W. Hammack, H. Guyod, P. A. Wichmann, L. E. Schneider, R. D. Wood, and D. W. Hilchie, Log Review 1 (Dresser Industries, Inc., Dallas, Texas, 1974).

5. J. A. Landt, "A Magnetic Induction Technique for Mapping Vertical Conductive Fractures: Theory of Operation," Los Alamos Scientific Laboratory report LA-7333-MS, July 1978.

6. R. W. Higgens, "Hydraulic System Design Aspects and Recommendations for an Induction Logging Tool," EG&G 1183-5078, EG&G, Inc., Los Alamos, New Mexico, April 1977.

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