ELECTRONIC INSTRUMENTATION USED IN BOREHOLE SURVEYING

by

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ABSTRACT

A directional survey of a borehole is based upon a series of measurements of an azimuth angle and an inclination angle made at successive stations along the borehole where the distance between the stations is accurately known. The measurements are made using a survey instrument containing two servo accelerometers, acting as inclinometers, a compass and the requisite instrumentation. The directional survey can be supplemented with temperature, diameter, pressure and other data. The electronic data acquisition package (DAP) designed and built in the University of Nebraska-Lincoln Physics Department Electronic Shop was first successfully used to log the Dye 3 Greenland borehole on June 7, 1986.

Two different survey tools are described, one using an Aanderaa Instruments compass and the other, three fluxgates arranged to measure magnetic field strength in mutually orthogonal directions, thus acting as a compass. In addition, two methods of powering the instrument, by battery and from a surface power supply, are described. The DAP uses a microprocessor which performs the data acquisition and control functions. The DAP data stream can include input from hole diameter, borehole fluid pressure, temperature and other functions in addition to that from the inclination and azimuth sensors. Caliper release is an example of a control function. Examples of the data sampling techniques, filtering and averaging, calibration of the electronics and sensors, and error analysis are given in detail. A modem circuit is used to transmit data to the surface, thus requiring only a coaxial cable for use in the logging. A BASIC program and Spreadsheet program used with a Portable PC computer for storing the logged data are discussed with numerical examples of the calculations required in borehole logging position determination.

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INTRODUCTION

Borehole directional survey equipment has been described by Gundestrup and Hansen (1) as used for the surveying of the borehole at Dye 3, south Greenland (2). Outputs from a compass, two servo inclinometers, and a thermistor were measured at the surface using a high accuracy digital multimeter and a rotary selector switch. In 1986 the Polar Ice Coring Office (PICO) survey tool was modified to include a battery powered microprocessor along with the original inclination and azimuth sensors used in previous surveys. This new electronic data acquisition package (DAP), designed and built in the University of Nebraska-Lincoln Physics Department, was first successfully used to log the DYE 3 Greenland borehole on June 7, 1986 and has since been used at DYE 3 in 1987 and at Byrd Station, Antarctica in January, 1988.

Inclination

The tilt or inclination angle of the survey tool is necessary in determining the tool position in a directional borehole survey. Several devices have been used to measure the inclination with respect to the vertical gravitational axis including single and multiple shot camera and plumb bob devices (3) (4). The PICO tool uses Schaevitz Servo Inclinometers (5), model LSRP-14.5°, purchased in pairs calibrated at -30°C (-22°F) and compensated for operation over the temperature range of 0°C (32°F) to -55°C (-67°F). The connections are solder pins and the units are stackable cylinders measuring 1.60 inches high and 1.43 inches in diameter. The solid-state electronics and servo sensor are totally enclosed within these sealed housings. Operated from a DC source, the output is an analog DC signal directly proportional to the sine of the angle of the tilt. In the level (horizontal) position, the DC output is zero. When tilted in one direction, the inclinometer output is 0 to +5V DC (14.5° tilt from the vertical) and when tilted the opposite direction the output is 0 to -5V DC (-14.5°). Two inclinometers are stacked with perpendicular tilt lines to give an inclination angle with respect to gravity vertical and a tilt direction referenced to the tool compass.

Azimuth

Azimuth is measured with a magnetic Aanderaa Compass model 1248 which has an allowable tilt of 12° and an accuracy of better than ± 2° (6). The compass was specially purchased unpotted and then gimbal-mounted with a range of 27° so that at inclinations of 0° to 30° the compass is horizontal. The 0° reading of the compass is aligned precisely with the inclinometers so that the tool rotation relative to magnetic north can be determined.

The Aanderaa compass acts as a potentiometer (resistance is 2 K-Ohm) with the compass needle as the wiper. The heading is determined by reading a ratio of the wiper voltage to the total potentiometer voltage when the needle is clamped steady. Thus the compass ratio is directly proportional to the rotation of the tool with respect to magnetic north and does not depend on the DC source across the potentiometer to remain constant over the entire hole survey. A wait of several seconds is required at each measurement level to allow the compass needle to settle from the tool motion in the hole.

DAP (Data-Acquisition Package)

The DAP is built using INTEL compatible CMOS 8085 microprocessor system integrated circuits (7). See Figure 1. The 8085 microprocessor is an 8-bit device that uses a multiplexed address-data bus scheme. The 8155 RAM-I/O device directly interfaces to this microprocessor and provides digital ports to activate the analog multiplexer, relays, various setup switches, and the cable slack switch. The 256 bytes of RAM memory in the 8155 chip is sufficient for the DAP since the data is averaged and stored as it is accumulated. An 8K byte 2764 EPROM provides the firmware used to acquire,

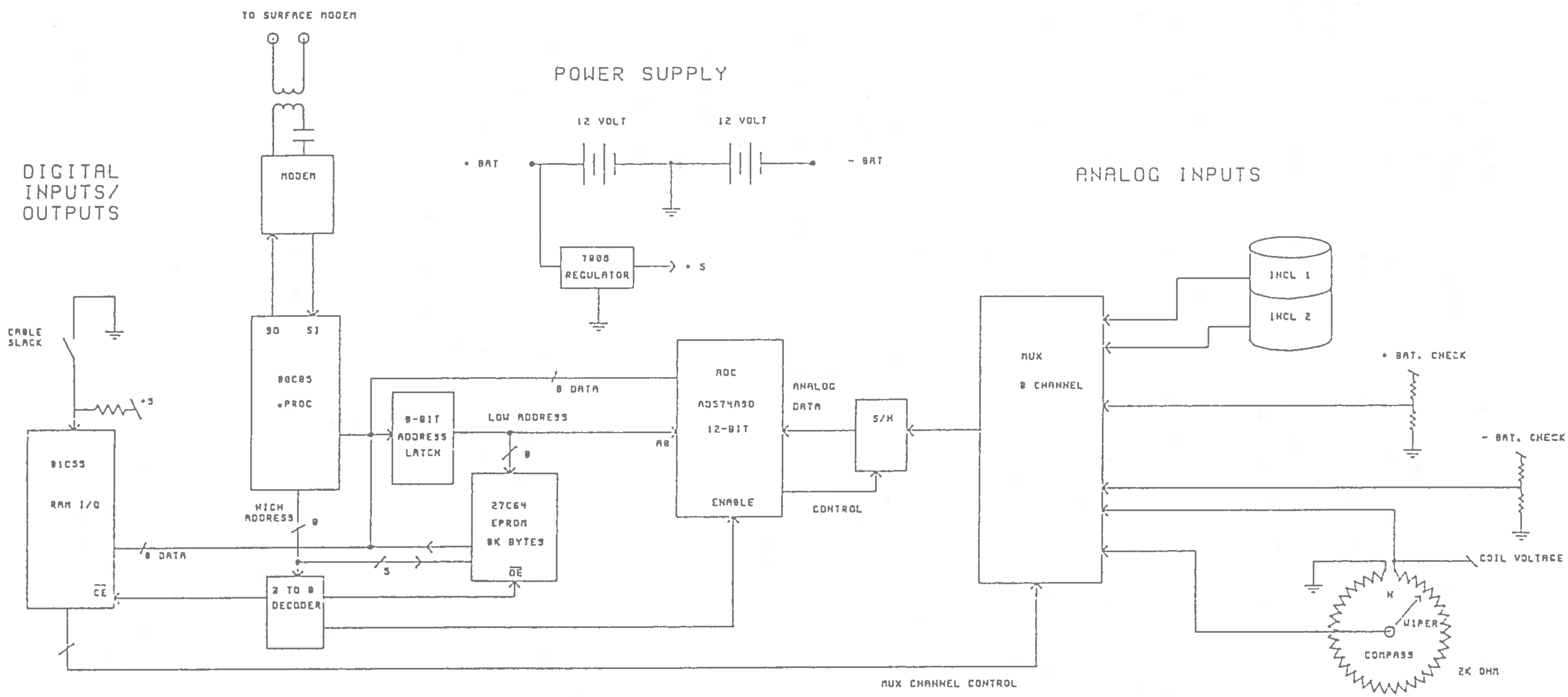

FIGURE 1. BLOCK DIAGRAM OF PICO LOGGING TOOL ELECTRONICS.

manipulate, and transmit data when requested by the surface computer.
Data is received and transmitted through serial in and out lines on the 8085 processor with a software bit detection scheme, eliminating the need for a separate UART type chip. The data is communicated to the surface via a transformer coupled 300 BAUD modem.

Data is accumulated by the DAP using an Analog Devices AD574AS 12-bit analog to digital converter (ADC) (8). The suffix AS is specified for -55°C to +125°C operating temperature range. The ADC is packaged in a 28-pin hermetically-sealed ceramic DIP and interfaces to the 8085 processor with an 8-bit path and an external address-bus buffer (that is shared with the EPROM). To insure that the signal to be measured remains stationary during the conversion time (about 25 microseconds) a sample and hold (S/H) circuit is used. The input signals are selected with an eight input multiplexer (MUX).

Software

The DAP is designed to be used with a 300 baud modem at the surface and some sort of RS-232 receiving device. The receiver could be a simple terminal, a speech synthesizer, or just a printer, but is usually an IBM compatible computer with a COM port available. With BASIC the data is read from the DAP with an OPEN COM statement and the INPUT command. The DAP is triggered by sending any character from the PC with a PRINT command. All characters are transmitted in ASCII, 7 bit, even parity, with 1 stop bit, at 300 BAUD and no handshaking is recognized.

Since the time required to position the tool at a given depth is longer then the acquisition time, the speed of a BASIC program is adequate. The DAP firmware (program in EPROM in the tool) sends a HEX data dump that is converted to variable values with a few simple lines of BASIC at the surface computer. A rather lengthy BASIC program has evolved which includes disk save and retrieve routines and other functions are handy in the field.

All of the transmitted raw data from the DAP is stored on floppy or fixed disk and a hardcopy is made as each point of the survey is taken. A small uninterruptable power supply (UPS) system is normally used in the event of a generator failure so that files may be properly closed and the PC turned off until after the generator is restarted.

The X, Y, and Z survey coordinates are calculated from knowing the inclination and the azimuth and the length of the cable paid out, which is either read from a serial device on the winch or entered by hand at each stopping station. See Figure 2. Data sent from the DAP becomes BASIC variables. The inclinometer voltages V1 and V2 are converted to the angle of inclination (I) tilted in a quadrant of the tool horizontal coordinate system. The azimuth AZ is the compass heading which is determined from the compass ratio R and the tool rotation AA in the hole. The distance the tool has traveled since the last point is S and the present X, Y, and Z coordinates are then calculated from the previous X, Y, and Z values.

Data Acquisition

Both digital and analog data is sampled by the DAP. The slack switch is an example of taking digital data, in this case a simple switch close. If the switch is closed, a bit on the 8155 I/O chip is pulled low and the DAP sends a "0" indicating that the cable has gone slack (the tool is at the bottom of the hole for example). If the switch is open, the bit is pulled high and the DAP returns a "1" to the surface receiver (as when the tool is hanging from the tower or is free in the hole).

Most of the DAP data is analog. The analog voltages are sampled with the AD574ASD analog to digital voltage converter through a multiplexer and sample and hold circuit. The devices to be read are the resistor networks indicating battery voltage, the compass ratio, and the inclinometer voltages, giving a total of 6 voltages to be measured. Since the compass requires a few seconds of settling time for the needle movement, the batteries and inclinometers are read first. A routine was designed that first selects the input voltage to be measured through the MUX, and then averages 4096 samples from the A/D converter. This may seem like a lot of samples but takes only 1 second per channel. Since the signals measured have noise that is greater then the bit resolution of the ADC (noise greater then 4.88 mV), the averaging helps to increase the resolution from the ADC 12-bits to an equivalent of about a 13.5-bit result (better then 1 part in 10000 or the equivalent of a 4-1/2 digit voltmeter). By the time the compass is to be read, 4 seconds have passed and the needle is hopefully pointing near magnetic north without oscillation and the compass ratio is read. The total acquisition time is about 6 seconds plus the time required to actually transmit the data, which is about 2 seconds. So for each hole station measurement, it takes about 8 seconds to obtain the position data once the tool has been placed.

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810 'GEOMETRIC CALCULATIONS
830 V1(J%)=INCL1:V2(J%)=INCL2     'VOLTAGES FROM INCLINOMETERS
840 S1=(V1(J%)+.003)/19.994       'OFFSET AND SPAN CORRECTIONS
850 S2=(V2(J%)+.053)/19.966
860 AB=ATN(S2/S1) * 180/PI        'TO FIND DIRECTION OF TILT
870 IF S1 < 0 AND S2 < 0 THEN AA=AB+180   'TOOL QUADRANT III
880 IF S1 < 0 AND S2 > 0 THEN AA=AB+180   'IV
890 IF S1 > 0 AND S2 > 0 THEN AA=AB       'I
900 IF S1 > 0 AND S2 < 0 THEN AA=AB+360   'II
910 I(J%) = FNB(SQR(S1^2 + S2^2))    'INCLINATION ANGLE
    FNB IS ARCSIN DEFINED EARLIER AS FNB(X)=ATN(X/SQR(1-X^2))
920 R=COMP(J%)                            'COMPASS RATIO
930 AC = .03 + (360.1 * R)                'OFFSET AND SPAN CORRECTION
940 IF AA < AC THEN AZ(J%) = (( AA + 360 - AC ) * PI / 180 )
950 IF AA > AC THEN AZ(J%) = (( AA - AC ) * PI / 180 )
960 AA(J%)=AA    'INDICATES TOOL ROTATION      AZ IS THE AZIMUTH
970 S = DEPTH(J%) - DEPTH(J% - 1)    'CABLE LENGTH PAID OUT
980 XLOC(J%) = XLOC(J%-1) + S/2 *    'X,Y,Z COORDINATES
((SIN(I(J%-1))*SIN(AZ(J%-1)))+(SIN(I(J%))*SIN(AZ(J%))))
990 YLOC(J%) = YLOC(J%-1) + S/2 *
((SIN(I(J%-1))*COS(AZ(J%-1)))+(SIN(I(J%))*COS(AZ(J%))))
1000 ZLOC(J%) = ZLOC(J%-1) + S/2 * (COS(I(J%-1))+COS(I(J%)))
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Figure 2 - Calculating hole coordinates from survey data in a BASIC program.

A New DAP Design

A new survey tool DAP has been constructed and is currently under test. The new tool takes its power from the surface instead of batteries and uses a fluxgate compass instead of an Aanderaa Instruments magnetic needle type compass. As with the original PICO tool, servo inclinometers are used to measure the tilt respect to the gravitational axis. There are major changes in the DAP firmware and a spreadsheet program is used in the surface computer to dramatically improve data observation in the field as the hole is logged.

Fluxgate Compass

In an effort to improve the azimuth readings, a fluxgate compass has been designed and is under test. Three orthogonally-oriented fluxgate sensors have been mounted in a fixture that matches an X and Y gate with the two inclinometer tilt lines and a Z gate with the tool vertical axis. The DAP reads three voltages proportional to the magnetic field sensed by each gate, and the surface computer normalizes these to give the normalized X, Y and Z magnetic components of the earth's field with respect to the tool orientation in the hole. Once again, the inclinometers are used to find the tilt and tool rotation, and the azimuth is calculated from both the inclinometer and compass values. The azimuth is given by the equation

$$\psi = \tan^{-1}\left[\frac{-(B_x \cdot \sin\phi + B_y \cdot \cos\phi)}{\cos\theta \cdot (B_x \cdot \cos\phi - B_y \cdot \sin\phi) + B_z \cdot \sin\theta}\right]$$

where B_x, B_y, and B_z are the normalized magnetic field components, Θ is the inclination angle, ϕ is the highside angle (the tool rotation), and ψ is the azimuth angle (9).

The fluxgate elements used are type LFG-A14 from Kelvin Hughes (10). These devices are constructed with excitation coils wound along lengths of high permeability wire. The excitation coils are then positioned side by side within a bobbin onto which a secondary sense coil is wound. These input coils are wired opposite and balanced so that with no external magnetic field present, the output secondary shows no output voltage. An external magnetic field lined along the axis of the element produces a voltage in the sense winding as one excitation coil is assisted and the other opposed. The output is proportional to the field and reverses polarity when the fluxgate element axis is inverted. The excitation frequency is set to 400 HZ and the resultant output pulse frequency is 800 HZ. This pulse is filtered and integrated to give a DC voltage output that is proportional to the magnetic field intensity (11).

Battery vs. Surface Power Supply Design

The use of batteries to power the DAP and sensors seemed at first very desirable. Batteries are DC with no ripple voltages and for the DAP design require no regulation except for the 5 volt supply. The voltages on the batteries are monitored with a simple voltage divider network so that the DAP can measure the battery voltage (the ADC has a maximum positive or negative input of 10 V DC). The cells connected for the positive 12 V DC always discharge quicker than the negative cells due to the imbalance caused by the 5 V DC requirement. Separate cells for the 5 V DC could be used, but the size and weight of the tool would be increased. As it is, the battery section is the longest and heaviest portion of the tool, containing twelve Gates lead acid batteries (type 0800-0004, X Cell, 2.0 Volt, 5.0 Ah) (12). The charge time of the batteries is typically overnight. Two chargers are used so that the negative and positive sides charge independently as required by their state of discharge. The chargers are wired so that they share a common ground and make it easy to apply a voltmeter to either the positive or negative side with respect to the common, or measure the total charge of the entire battery string from positive to negative. A good state of charge is better than 28 V DC. The cells drain to about 23.5 V DC after about 8 hours of logging (the imbalance gives about -12 and +11.5 V DC typically).

In an effort to make the tool smaller and weigh less, a surface supply has been designed, but has yet to be tested in the field. A 5 V DC regulator is used in the same way as with the battery supply and again an imbalance in the positive and negative voltage sources exists. Since the supply from the surface is abundant, a resistor is placed on the negative side of the DAP supply to help balance the load. Positive and negative 15 V DC is used instead of 12 volts since there is no space limitation as with additional battery cells. Modems at the surface and in the DAP are connected as before through audio transformers, but now the transformers must be able to handle the current supplied to the DAP circuit in addition to the audio signal. Two 18 Volt zener diodes are used to provide adequate input to the positive and negative 15 V DC regulators and are used to "take up the slack" in current that the resistor and regulators use from the unregulated DC surface source. If the zener diodes were not present, current pulses (and thus voltage pulses) appear at the audio transformers when the fluxgate cells are excited. Unfortunately, the fluxgates are excited at a rate of 800 Hz which is close enough to the modem frequencies that the transmission of spurious data is created during fluxgate activity. The installation of the zener diodes reduces the line pulses to where the modem devices successfully filter out the unwanted noise created by the fluxgate drive circuitry. Since the cable is usually long (over 2000 meters), the resistance of the wire causes a voltage drop, usually greater than the voltage needed by the tool itself. A surface supply capable of approximately 175 V DC and 2 amperes was built with the possible alternate use as a reamer motor supply. Ripple on the surface supply is approximately 3 % of the output voltage, which is easily handled by the DAP regulators.

Another design under consideration uses a 9 V DC zener diode and voltage converter modules to obtain ± 5 and ± 15 V DC supplies. Tests have not been completed on this power supply design, but the main advantages are one zener at a significantly lower voltage (thus requiring a smaller, safer surface supply, may be even solar panels) and no imbalance resistor to compensate for the 5 V DC drain on the positive supply side. This design might also prove good for use with batteries since only parallel 9 V DC cells are required.

New Sensor Additions

A caliper could be added to the PICO survey tool. The DAP could receive and decode a special character or message from the surface computer to trigger a caliper arm release solenoid. A DC-LVDT is available from Schaevitz Engineering that operates from a ± 15 V DC power source and has a ± 10 V DC output. This position transducer has been used with a separate PICO caliper tool using the survey tool battery pack and a surface voltmeter. The output voltage from the linear variable differential transducer (LVDT) could be connected to an unused DAP MUX channel and the hole diameter data sent as part of the data stream. Other calipers are described (1) (13) (14) and the electronic additions are small in comparison to the mechanical design required.

A pressure transducer is also easy to add to the DAP system and would be a desirable addition as part of a more complete PICO survey tool. The Paroscientific Digiquartz Pressure Transducer (15) has a digital frequency output and requires a single DC power source. A frequency-to-voltage converter or gated counter could provide the necessary interface to the DAP system.

CONCLUSION

The addition of the DAP to the PICO survey tool has greatly increased its adaptability to various transducers and eased the task of data acquisition in a harsh environment. Use of packaged software (such as spreadsheet programs) allows preliminary observations in the field so that decisions about the quality of the data taken can be made onsite. The versatility of a microprocessor-controlled survey tool greatly enhances the science of borehole logging.

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