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an automatic magnetic observatory system

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Abstract. A digitally recording magnetometer system is designed to replace the standard photographic magnetographs at geomagnetic observatories. The instrument can operate for up to 80 days without attention. Provision is made for immunity to brief power failures.

The elements D, H, and Z are derived from a 3-component fluxgate magnetometer in which all three detectors operate in near-zero field. A simple proton magnetometer measures F.

Voltages proportional to the values of the three elements D, H, and Z are sampled in quick succession by a digital voltmeter, once per minute. Each minute, a measurement of F is also made. The four measurements are recorded on digital magnetic tape. Each ten minutes, the date, time, and station identification are also recorded. A strip-chart recorder produces a visual indication of the variations in D, H, and Z.

The performance of the system is estimated from a comparison of hourly mean values with those of the St. John's Magnetic Observatory.

Résumé. On a conçu un système de magnétomètre à enregistrement numérique pour remplacer les magnétographes photographiques réguliers utilisés dans les observatoires géomagnétiques. Cet instrument peut fonctionner seul pendant 80 jours. Des mesures ont été prises pour remédier aux brèves pannes de courant.

Les éléments D, H et Z sont dérivés d'un magnétomètre à solénoïde à noyau saturable à trois composantes dans lequel les trois détecteurs fonctionnent dans un champ magnétique presque nul. Un magnétomètre à proton mesure F.

Les tensions proportionnelles à la valeur des trois éléments D, H et Z sont relevées en succession rapide à toutes les minutes par un voltmètre numérique. A chaque minute, l'appareil mesure aussi F. Les quatre mesures sont enregistrées en numérique sur une bande magnétique. A toutes les dix minutes, la date, l'heure et l'identification de la station sont aussi enregistrées. Une enregistreuse à bandes indique visuellement les variations produites dans D, H et Z.

On évalue le rendement de ce système en comparant sa moyenne horaire d'indices avec celle de l'Observatoire magnétique de St. John.

Introduction

The Automatic Magnetic Observatory System, hereafter called the AMOS, is designed to replace the standard photographic magnetographs at geomagnetic observatories. Figure 1 is a block diagram of the instrument. Four components of the geomagnetic field are measured. These four may be either the elements D, H, Z, and F or X, Y, Z, and F, depending on the orientation of the magnetic sensors.

Two types of record are produced. A strip-chart recorder continuously records the values of D, H, and Z (or X, Y, Z) relative to appropriate baselines. The other record is on digital magnetic tape. On this record the AMOS records the quasi-instantaneous values of all four elements, with a sampling rate of once per minute. No baselines are involved here except for the element D. The recorded value of D is the instantaneous displacement of D from some arbitrary but fixed baseline close to the mean value of D. In addition, each 10 minutes, the day of the year, the hour of the day, and the minute of the hour are recorded. Following this, a seven-figure station identification number is put on the tape. One tape record then consists of 10 minute-samples of each of the four elements, plus the date and time, and the station identifier. All digital data is in 4-line, bindary-coded-decimal format. Appropriate inter-record gaps are generated after each record so that the tape may be read by digital computers.

The recorders can accommodate sufficient supplies of paper or tape to permit the AMOS to operate for up to 80 days without attention. Provision is made to operate the digital clock from a 12-volt automotive battery whenever power-failures occur. In this way, although no data is recorded during power-failures, when power is restored the data will be properly timed. The entire AMOS may also be operated by a dc-to-ac inverter for complete immunity to power-failures.

A separate but related system has been developed whereby the operation of an AMOS located at some distant point may be monitored by means of connections to commercial telephone circuits (Andersen, 1973).

Basic design considerations

A fluxgate magnetometer was chosen as the basic instrument for several reasons. This type of magnetometer uses only solid-state electronic components. There are no relays or other electromechanical parts. This results in a relatively simple and rugged instrument with a good reputation for reliability. In addition, this instrument can operate successfully in the presence of radio-frequency transmitters, electromechanical switches and other sources of electrical noise.

The basic output of a fluxgate magnetometer is an analog voltage proportional in polarity and magnitude to the magnetic field component along the axis of the field-cancelling coils. In a 3-component instrument each of three geomagnetic elements is continuously represented in this way. The analog outputs are completely independent of one another. Thus at any instant, the analog voltages are valid, real-time representations of the values of the field components existing at that time. This real-time output, with each component being independently represented is of considerable significance. A number of other automatic observatory systems have been proposed in which the component values are calculated from a series of time-spaced measurements. Unless the magnetic field is relatively constant over the course of these measurements,

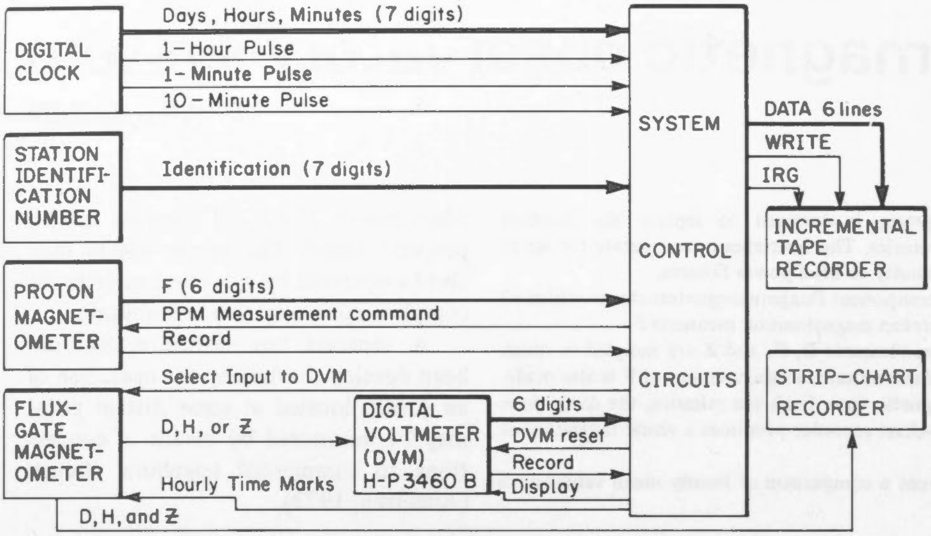


Figure 1. Block diagram of automatic magnetic observatory system (AMOS).

appreciable errors can result (Serson, 1969). For many of the Canadian observatories the level of magnetic activity is so great that this would be an almost constant source of error with these types of instruments. The 3-component fluxgate completely obviates this problem.

Another significant advantage of the 3-component fluxgate instrument is its ability to accommodate very large variations in the magnetic field without the need for adjustments to tuned circuits, bias currents, and oscillator frequencies as is necessary with systems based on proton precession frequency measurements.

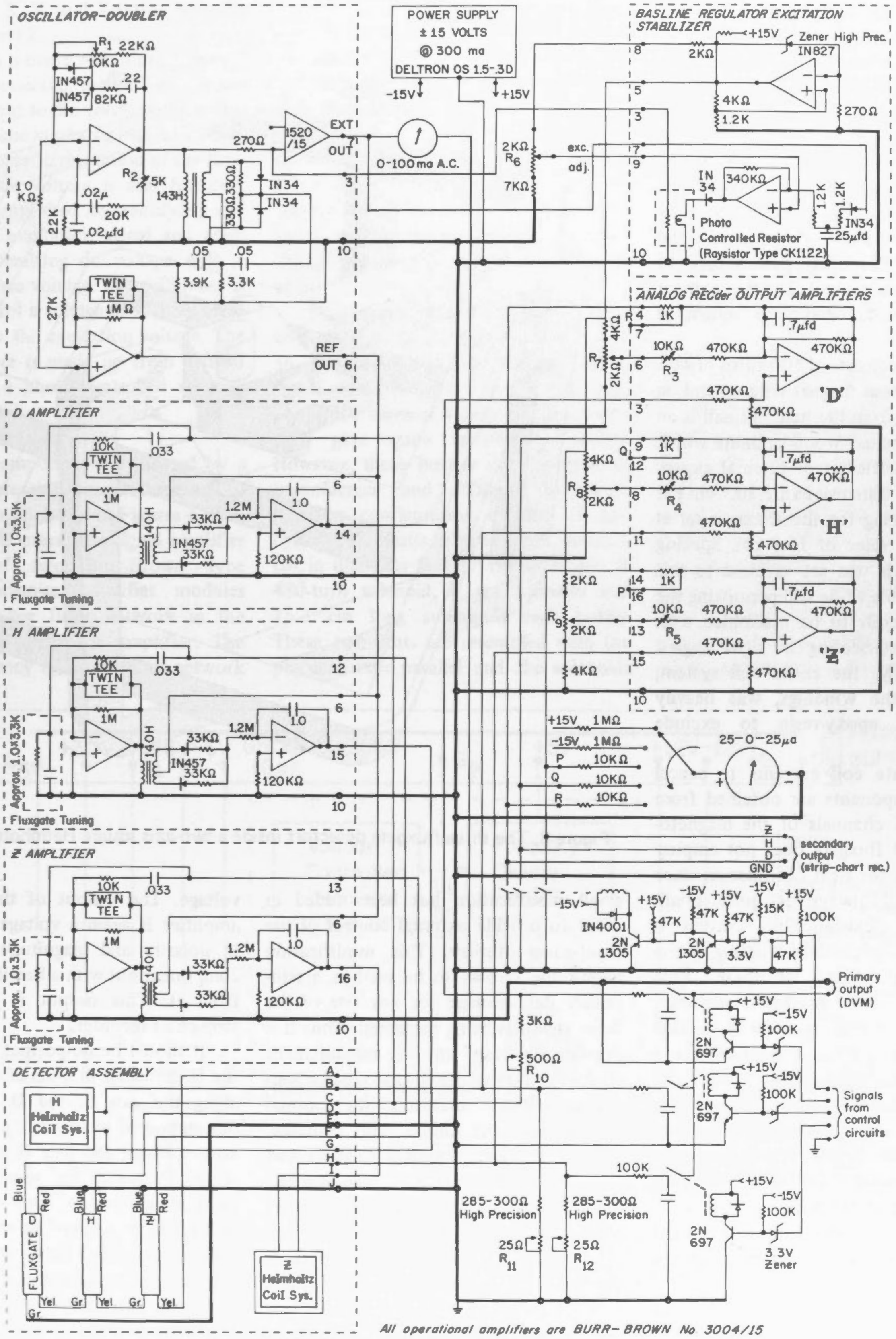
There is however, one serious deficiency with the fluxgate instrument. The long-term stability is hardly good enough for a primary observatory instrument. This instability results from changes in the zero offset arising from permanent magnetization and other effects within the fluxgate detector. This drift in zero offset is particularly troublesome since it may be non-linear with time, or even discontinuous. To obviate the deficiencies of the fluxgates, a simple proton precession magnetometer (PPM) measuring only the total field F, is incorporated into the system. While this instrument is much more sensitive to electrical noise, and is generally less reliable than fluxgates, it does offer the significant advantage that, if it can be made to work at all, the resulting measurement can be relied on to an accuracy of better than one gamma. It is almost completely insensitive to changes in temperature, detector alignment, or foundation shifts. Furthermore, the basic output is a frequency, which is easily converted to an accurate digital representation of the field value. In addition, a proton precession magnetometer is a recognized absolute standard in itself. There are no calibrations or baseline measurements involved with its operation.

By frequently comparing the value of F as measured by the PPM with the value of F calculated from the component values supplied by the fluxgate, a very good check is made on the performance of the fluxgate. In practice, the basic measurements of the field components are made once each minute. Thus a check on the performance of the fluxgate can be made as often as once per minute. In this way, non-linear drifts as well as discontinuous shifts of the zero offset are easily detected. It has been found by experiment that the changes in zero offsets are approximately proportional to the field being measured. Thus by applying corrections to the fluxgate measurements porportional to the mean values of the components, it is possible to achieve accuracies quite satisfactory for a primary observatory instrument (DeLaurier *et al.*, 1973).

The primary recording medium chosen for the AMOS is digital magnetic tape operating at a density of 200 bits per inch. Some justification may be in order for the choice of magnetic tape instead of paper tape or cards, and for the choice of the low bit density rather than the more usual 556 or 800 bits per inch. Magnetic tape affords a high speed, computer-compatible recording medium with sufficient storage capacity to permit operation of the AMOS for up to 80 days with standard size reels of tape. In addition, this medium presents less problems with storage. It is also quite durable, being able to withstand many hundreds of passages through tape-handling machines without deterioration in performance. Since the AMOS will be operating in less than ideal laboratory conditions and since it requires several weeks to write one reel of tape, there is much danger of the tape being contaminated with dust, and of being subjected to many changes in temperature. For these reasons it seemed wise to use the lowest density possible and thus be most immune to skew problems and bit-loss arising from these adverse conditions. Another advantage of the low density is that by immersing the tape in a liquid suspension of iron oxide powder, the actual transitions of magnetization on the tape can be made visible to the naked eye and in fact readable with low-power microscope. This facility has been of great help in detecting and correcting instrument malfunctions. Finally, magnetic tape recorders employ fewer electro-mechanical parts than do card or paper tape punches and should therefore prove the most reliable of the three recording media.

Measurement of D, H, and Z (X, Y, Z)

An electrical magnetometer of the fluxgate type is shown in Figure 2. The theory of operation of this type of magnetometer has been explained by Serson (1957), and Trigg *et al.* (1971). In the design used here, the method of



All operational amplifiers are BURR-BROWN No. 3004/15

Figure 2. Circuit diagram of three-component fluxgate magnetometer as used in AMOS.

cancelling the various field components is unique in some respects. For maximum stability and accuracy it was decided that all three fluxgate detectors should operate in near-zero field, both axially and transversely. To achieve this, it was necessary to mount the detectors in the middle of a dual-axis, square Helmholtz coil system. One pair of coils is used to cancel the horizontal component of the earth's field, the other pair is used to cancel the Z component. The two pairs of coils are nested together as shown in Figure 3.

Each coil consists of 600 turns of #25 enamelled copper magnet wire wound on a form made from Permali. Permali is an epoxy-impregnated wood-laminate which has a low coefficient of thermal expansion. The coil dimensions are 30.5 cm per side. Coil-spacing for the Z axis is set at the optimum value of 16.8 cm. Spacing for the H axis was set as close to this value as possible while still permitting the two sets of coils to be assembled with their axes intersecting at right angles. After assembly, the entire coil system, particularly the windings, was heavily coated with epoxy-resin to exclude moisture.

Appropriate coil currents to cancel the field components are obtained from the H and Z channels of the magnetometer. The D fluxgate does not employ external coils for field cancellation since this field will always be quite small. Instead, the field-cancelling current is applied to the secondary winding of the fluxgate itself. Each of these three currents is passed through a precision resistor in order to generate a voltage which is proportional in magnitude and polarity to the value of the component being cancelled by that current. The resistors are of such values that the voltage-to-field factor for each component is exactly 10·0000 volts for 100,000 gammas of field.

These three analog voltages form the primary output of the fluxgate magnetometer. This output is used with a five-figure digital voltmeter (DVM) to produce a digital output for use with the magnetic tape recorder. The DVM is a Hewlett-Packard model 3460B to which a small modification has been added in order to provide external control of the front-panel display. This modification allows the display to be used as a temporary data storage for any one of the three channels being measured. Thus it is possible to "trap" any one measurement in the front-panel display for visual observation without affecting the normal operation of the AMOS. This combination of fluxgate, digital voltmeter, and tape recorder provides a geomagnetic recording system with a dynamic range of ±70,000 gammas in all components.

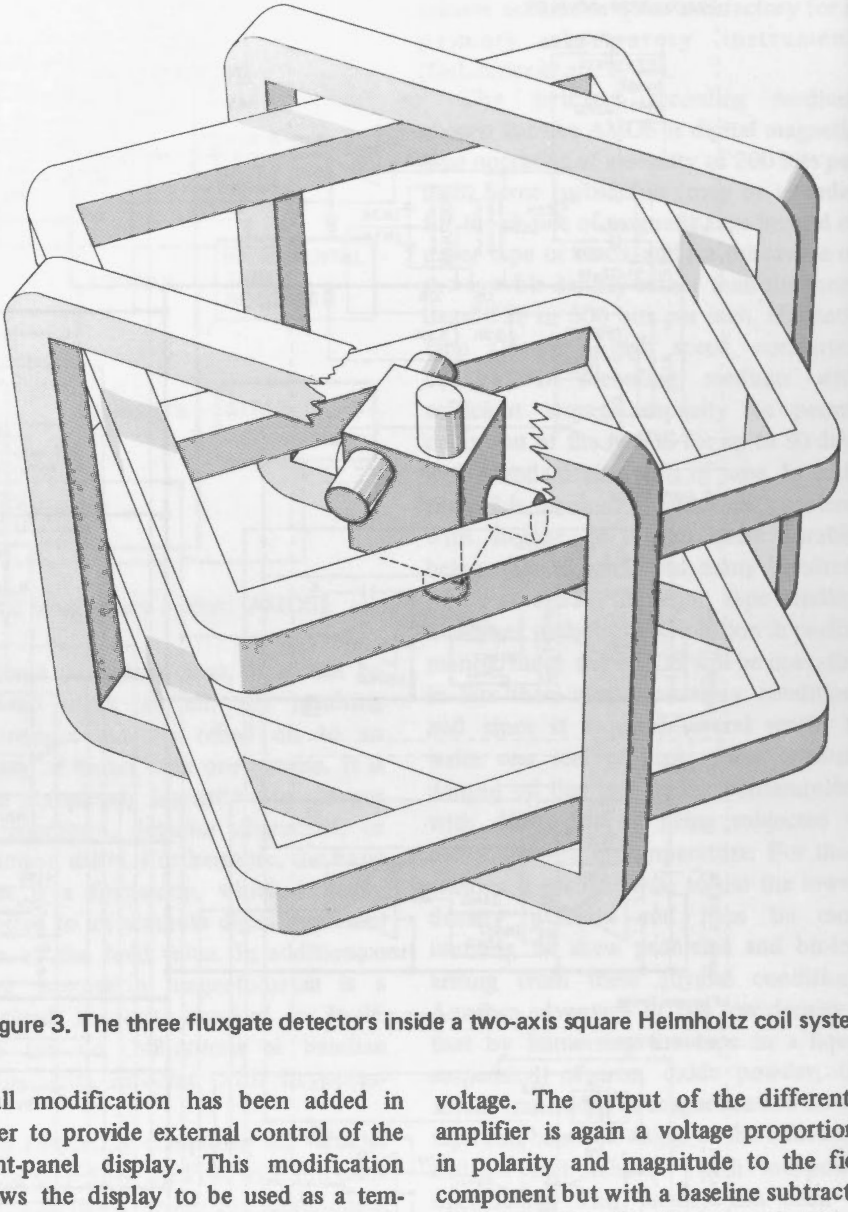


Figure 3. The three fluxgate detectors inside a two-axis square Helmholtz coil system.

A secondary output is obtained from the fluxgate magnetometer by feeding each of the primary analog voltages into one input of a unity-gain differential amplifier. The other differential input is supplied with a stable but adjustable dc voltage. The output of the differential amplifier is again a voltage proportional in polarity and magnitude to the field component but with a baseline subtracted from it. This output is used with a strip-chart recorder.

It should be noted that the output of the D channel is in units of magnetic field along the axis of the D fluxgate, the orientation of which is fixed. Thus the D output is not the true D in the strictest sense. However, for most observatory locations the mean value of H is sufficiently large and the fluctuations of D sufficiently small that the difference between the D output and the true D is negligible. In locations where these conditions do not prevail, it is customary to orient the detector assembly in geographical coordinates and measure the components X, Y, and Z rather than the usual D, H, and Z.

Provision is made within the magnetometer for connecting each channel of the primary output to the voltmeter, and also for hourly time-marks on the secondary output. Automatic regulation of the flux-gate excitation voltage is also featured. This is accomplished by rectifying and filtering the excitation signal and comparing the resulting dc voltage with a stable reference voltage. The difference is used to control a voltage divider which in turn controls the excitation voltage. The voltage divider is made up from a fixed resistor and a photo-controlled resistor.

Measurement of F

The F component is measured by a proton precession magnetometer of simple design, as shown in Figures 4, 5, 6, 7, and 8. The precession signal amplifier consists of two Burr-Brown type 3001/13 low-noise amplifier modules with a twin-tee filter network in the feedback loop of each amplifier. The centre frequency of the twin-tee network is selected for the precession frequency corresponding to the mean value of F for the station in question. Additional tuning of the signal amplifier is provided by a capacitor across the amplifier input terminals, that is, by tuning the precession signal pick-up coil. This yields an overall Q of about 25, or a useful bandwidth corresponding to a field range of ±2,500 gammas. The tuning elements are easily changed to accommodate any mean value of F.

Two types of detecting head have been used. A toroidal plastic bottle with an outside diameter of 15 cm and an inside diameter of 4.5 cm wound with about 600 turns of #20 enamelled copper wire gave quite satisfactory results. However, these bottles are expensive to manufacture and difficult to repair. Another configuration consists of two cylindrical plastic bottles, each about 6 cm in diameter and 17 cm in length. A 480-turn solenoid, 6 cm diameter and 15.3 cm long surrounds each bottle. These two units are assembled with the physical axes parallel and the solenoids connected in series opposition. This configuration is much easier to manufacture and repair than the toroid type, and the performance is at least as good. A number of liquids have been used to fill the bottles. Among these are water, kerosene, JP-4 jet fuel, alcohol, and ethyl glycol. The most satisfactory fluid used thus far is an automotive windshield washer additive consisting mostly of methyl-hydrate. In situations where electrical noise has been a problem, it has been found very helpful to surround the detector assembly with a cubic shield about 600 mm per side, made from aluminum sheet about 1.6 mm thick.

Since the precession signal is of the order of 2,400 Hz for Canadian observatories, and persists for only 2-3 seconds after polarization, it is not possible to achieve the required accuracy of one part in 50,000 by direct counting of the precession signal. To achieve the desired accuracy, a phase-lock circuit is employed here (Serson, 1962). In this circuit, a voltage-controlled oscillator is electronically adjusted to a frequency which is

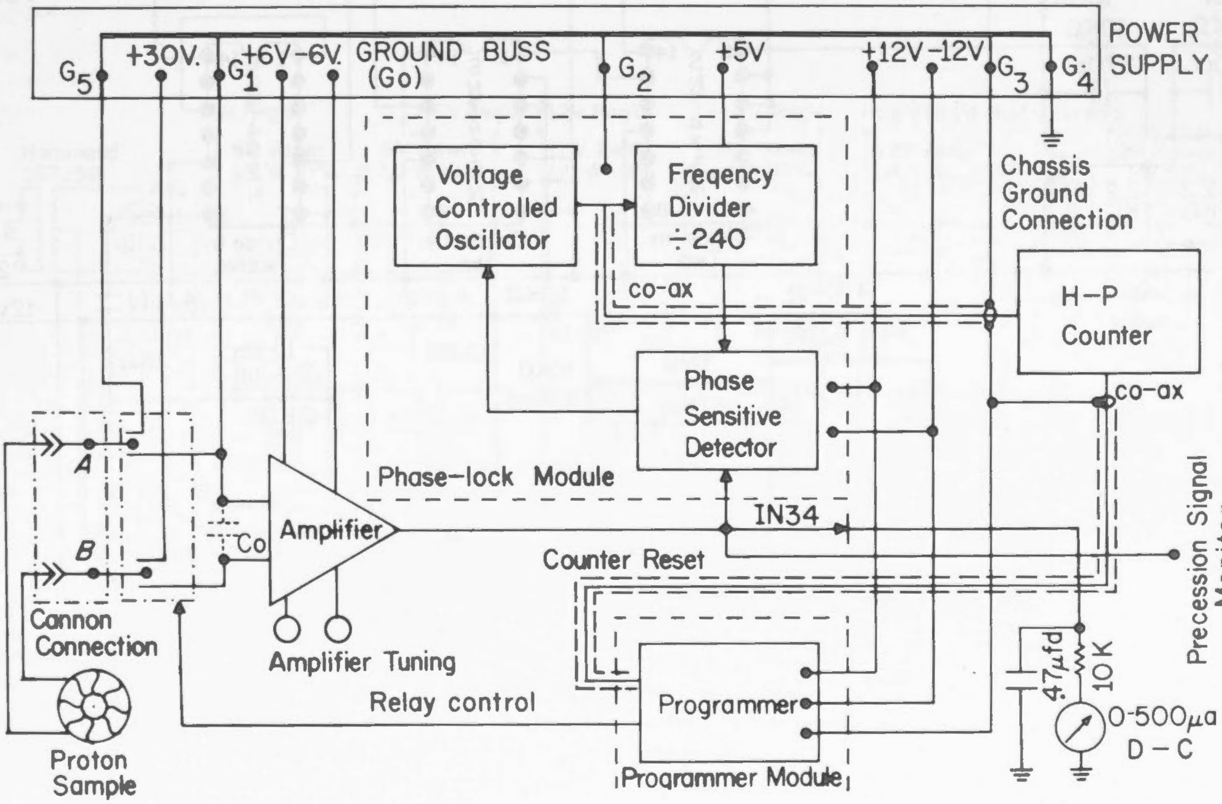


Figure 4. Block diagram of proton-precession total-intensity magnetometer.

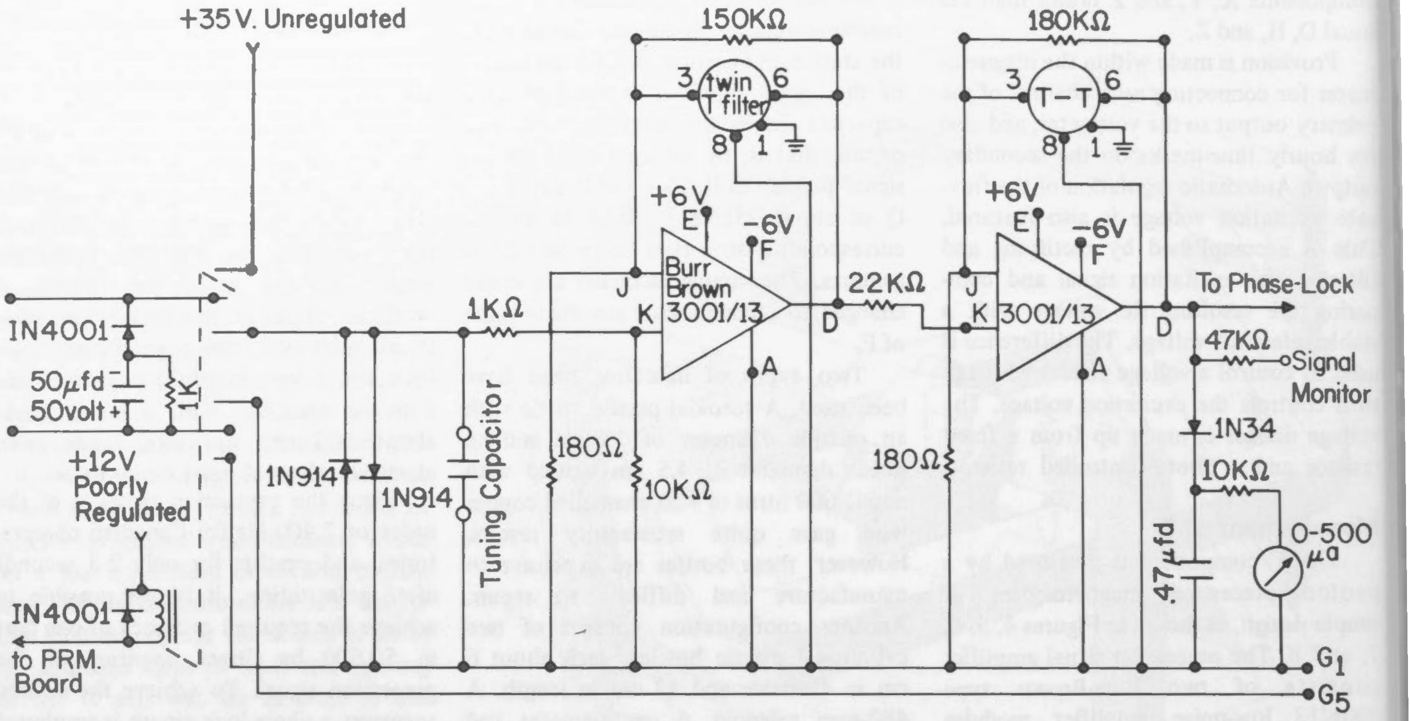


Figure 5. Polarizing circuit and signal amplifier for proton-precession magnetometer.

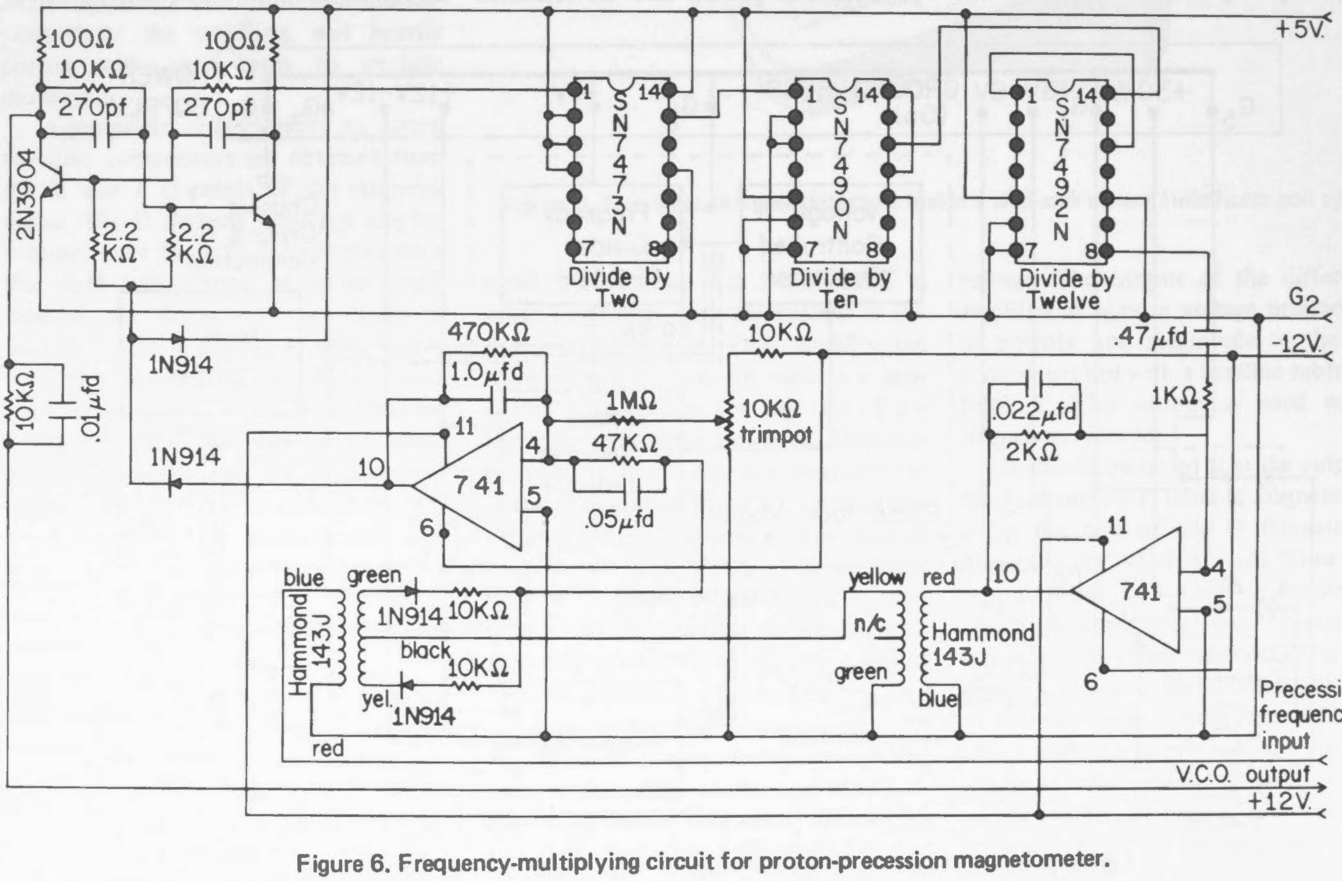


Figure 6. Frequency-multiplying circuit for proton-precession magnetometer.

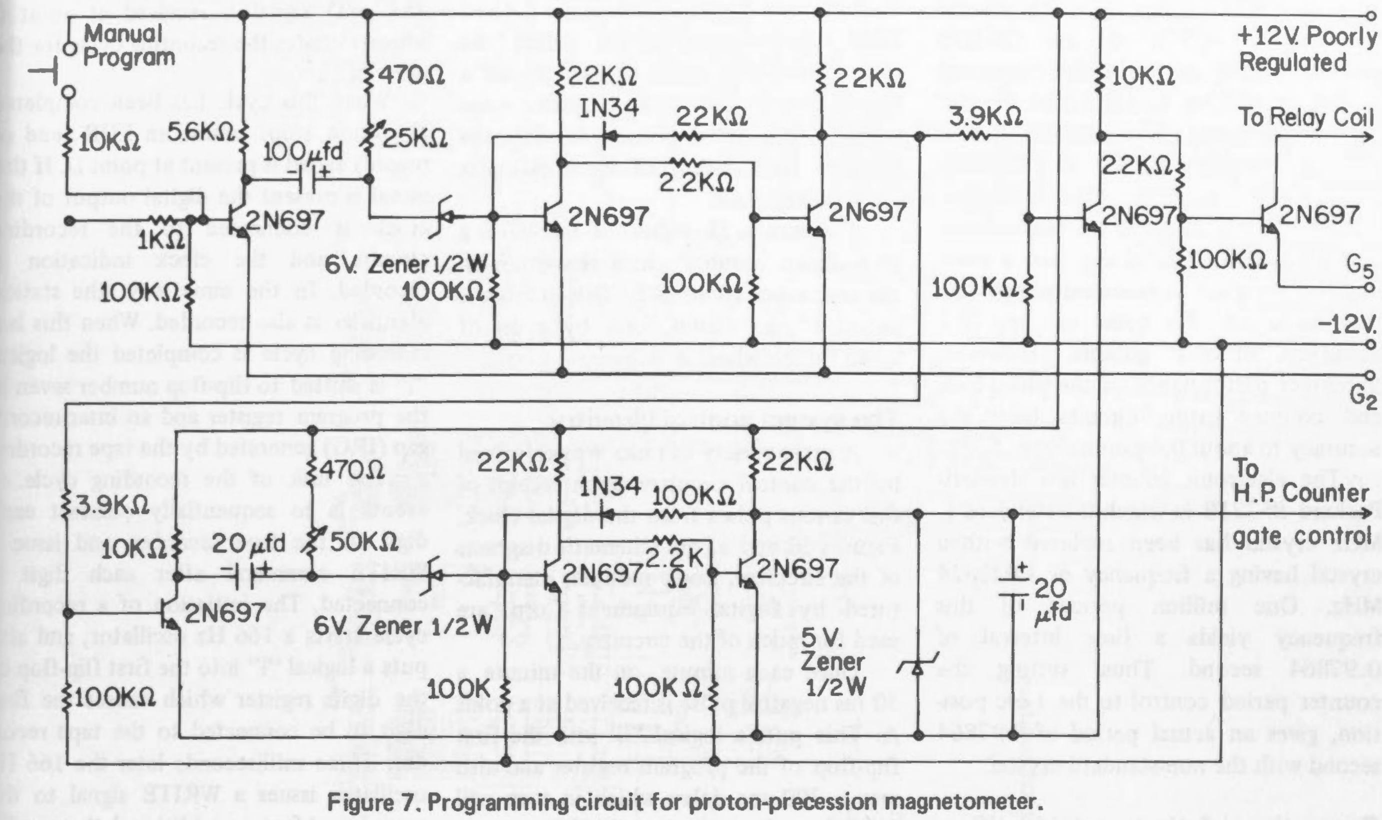


Figure 7. Programming circuit for proton-precession magnetometer.

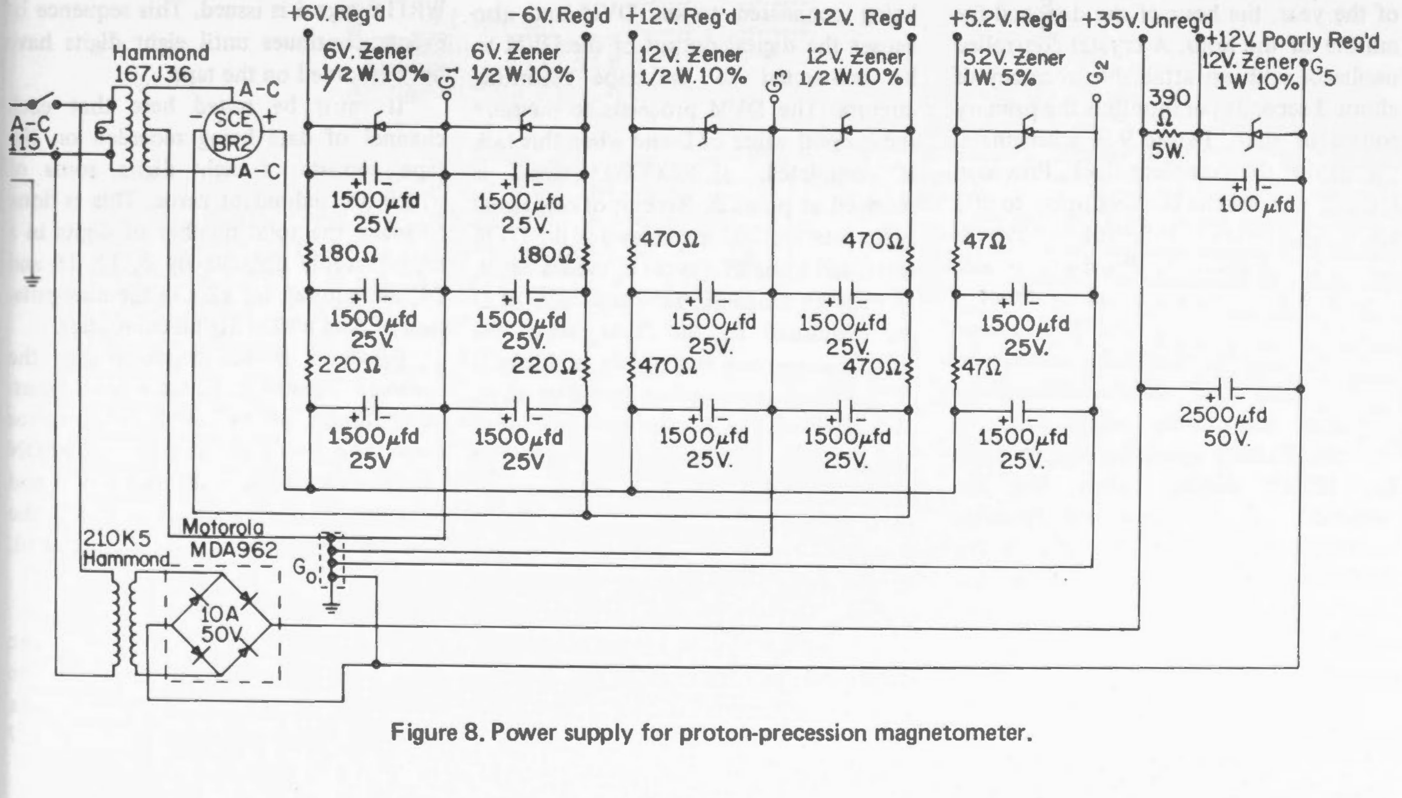


Figure 8. Power supply for proton-precession magnetometer.

exactly 240 times the precession frequency. Now since the precession frequency is 4257.6 Hz for 100,000 gammas of field, the multiplied frequency is 240 x 4257.6 = 1,021,824 Hz for 100,000 gammas. This frequency will yield 1,000,000 cycles in 0.97864 second. By counting this multiplied frequency for a period of 0.97864 second with a six-figure digital counter, a readout is obtained corresponding to the magnitude of F, with an apparent accuracy of 0.1 gamma. However, imperfect performance of the phase-lock and counter gating circuits limit the accuracy to about 0.4 gamma.

The electronic counter is a Hewlett-Packard #5221B in which the standard 1. MHz crystal has been replaced with a crystal having a frequency of 1.021824 MHz. One million periods of this frequency yields a time interval of 0.97864 second. Thus, setting the counter period control to the 1-sec position, gives an actual period of 0.97864 second with the non-standard crystal.

Generation of time and identification codes

A digital clock was designed to encode seven digits representing the day of the year, the hour of the day, and the minute of the hour. A crystal controlled oscillator with an attainable accuracy of about 3 seconds per month is the primary source of time. Figure 9 is a schematic diagram of the complete clock. Provision is made to reset the DAYS display to 001 after day number 365, 366 or 999 as selected by a switch. Provision is also made for operating the clock from a 12-volt automotive battery. When power fails, the clock automatically switches to the battery, and then automatically recharges the battery when power is restored. Battery operation will not light the NIXIE display tubes, but the remainder of the clock will function normally. This feature is useful in the AMOS in that should the power fail, the clock will continue until power is restored. Thus all recorded data will be properly timed.

Numerous control pulses of various durations and polarities are also produced by the digital clock for use in the AMOS control circuitry. These pulses are derived from negative-going signals within the clock. One such signal is used to set a flip-flop. A second signal, occurring some suitable time later, is used to reset the flip-flop. The output of the flip-flop is the required pulse.

The station identification number is a seven-figure number which is written on the tape every 10 minutes. This number is encoded into digital form by a set of seven thumb-wheel switches.

The system control circuitry

A great variety of tasks are performed by the control circuitry upon receipt of the various pulses from the digital clock. Figures 10 and 11 are schematic diagrams of the circuitry. Logic modules manufactured by Digital Equipment Corp. are used for much of the circuitry.

Once each minute, on the minute, a 50 ms negative pulse is received at a point A. This puts a logical "1" into the first flip-flop of the program register and also sets a 200 ms delay which in turn will reset the voltmeter when the delay resets. Putting a logical "1" into the first flip-flop of the program register results in the D channel of the fluxgate magnetometer being connected to the DVM and also causes the digital output of the DVM to be connected to the tape recording circuits. The DVM proceeds to measure the current value of D and when this task is completed, a RECORD signal is received at point B. Receipt of this signal again sets the 200 ms delay for the DVM reset, and initiates a cycle of events which records on magnetic tape the value of D just measured by the DVM. When the recording cycle is completed, the logical "1" in the program register is shifted to its second flip-flop. The current value of H and then of Z is measured and recorded in similar fashion as was the D value.

Following the completion of the Z recording cycle, the logical "1" is shifted to the fourth flip-flop in the program register. This connects the digital output of the proton precession magnetometer (PPM) to the recording circuits and commands the PPM to make a measurement of F. This takes 4-6 seconds. When the measurement is completed a RECORD signal is received at point C which initiates the recording cycle for the value of F.

When this cycle has been completed all action stops unless an EOR (end of record) signal is present at point D. If this signal is present the digital output of the clock is connected to the recording circuits and the clock indication is recorded. In the same way, the station identifier is also recorded. When this last recording cycle is completed the logical "1" is shifted to flip-flop number seven in the program register and an inter-record gap (IRG) generated by the tape recorder.

The task of the recording cycle of events is to sequentially connect each digit to the tape recorder, and issue a WRITE command after each digit is connected. The initiation of a recording cycle starts a 166 Hz oscillator, and also puts a logical "1" into the first flip-flop of the digits register which causes the first digit to be connected to the tape recorder. Three milliseconds later the 166 Hz oscillator issues a WRITE signal to the recorder. After an additional three milliseconds, the logical "1" is shifted to the second flip-flop in the digits register and after a further three milliseconds, another WRITE signal is issued. This sequence of events continues until eight digits have been recorded on the tape.

It must be noted here that each channel of data being recorded on the tape consists of eight digits, some of which are redundant zeros. This is done to make the total number of digits in a record evenly divisible by 8, 12, 16 and 24, as required for ease in the manipulation of data within digital computers.

Provision is also made within the control circuitry to control the front-panel display of the DVM. This involves clamping to ground the NEON TRANSFER signal within the DVM and releasing it only during the time the channel to be displayed is being measured.

Magnetic tape recorder

Two models of recorder have been used with the AMOS; the Precision Instrument #PI1177 and the Digidata #142OH. These machines record on 7

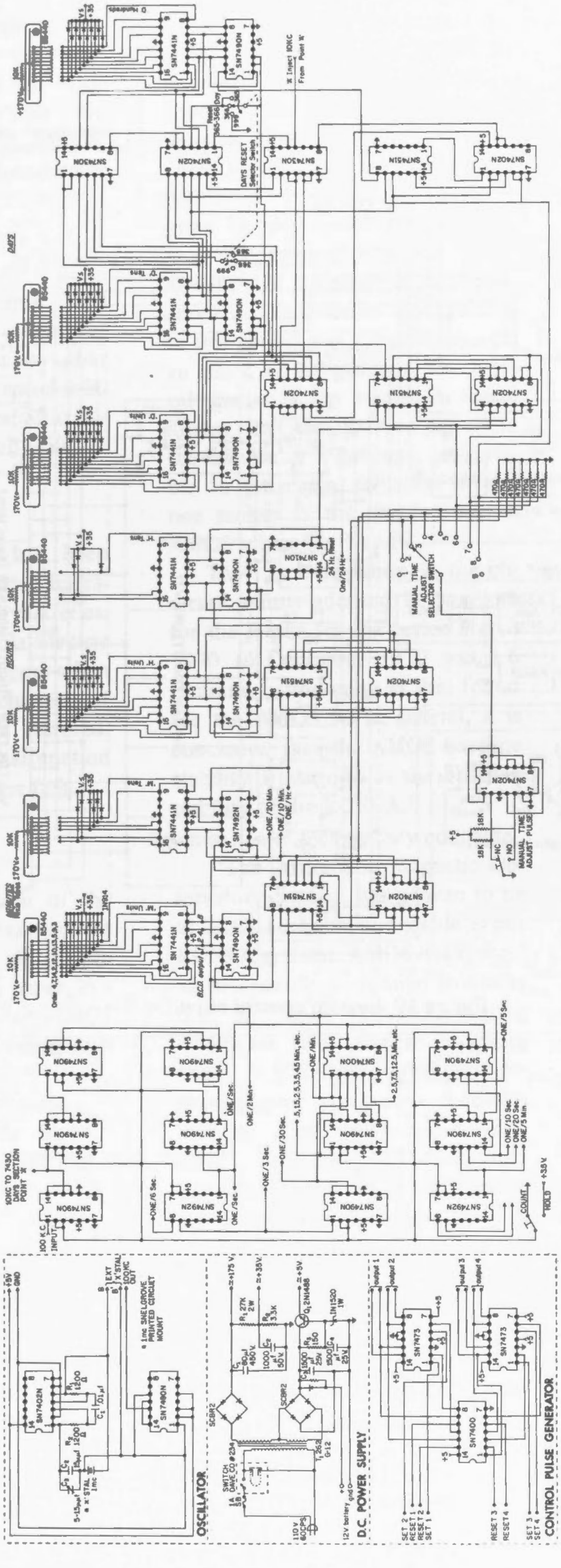


Figure 9. Digital clock and timer.

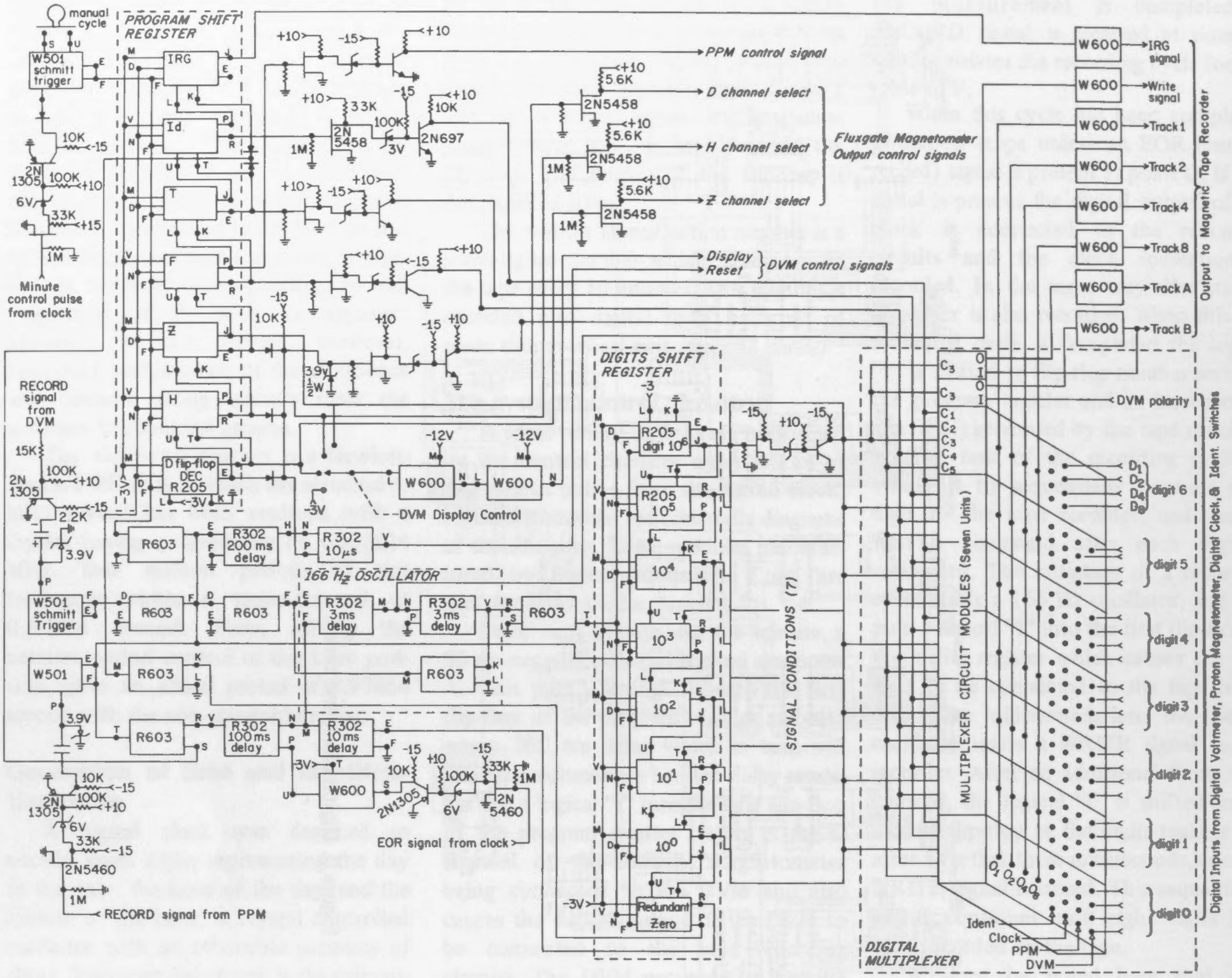
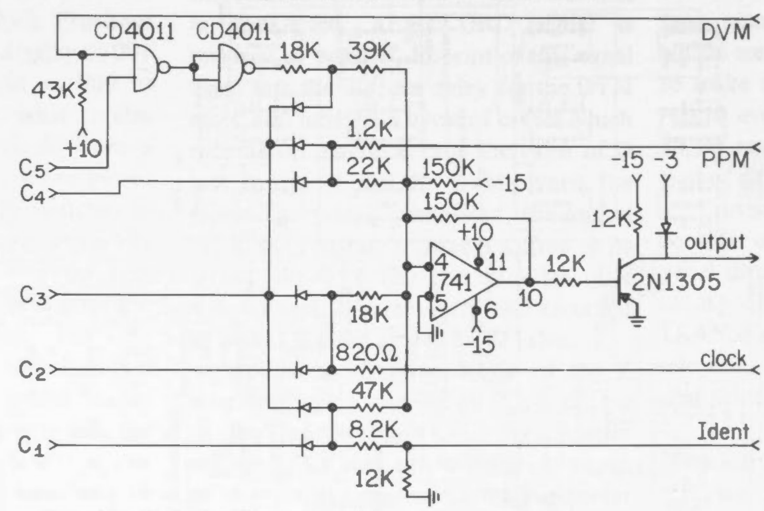


Figure 10. System control circuit.



- Four identical circuits per module.
- All control inputs (C_1–C_2) are common to the circuits within a module.
- All diodes are IN914.

Figure 11. Control circuit detail.

tracks at 200 bits per inch. Tape motion is incremental. Formatting of the inter-record gap, the file mark, and the load-point gap, is performed within the recorder. Both horizontal and vertical parity indications are automatically generated.

Strip-chart recorder

The strip-chart recorder now used with the AMOS is the Texas instrument Servo-Riter II. However, almost any other recorder could be used. Chart speed is 20 mm per hour and sensitivity on all channels is usually 1,000 gammas full scale.

Stand-by power supply

One AMOS installation has been equipped with a dc-to-ac inverter operating on large automotive-type batteries. This unit, manufactured by Sola Electric Co., features automatic switch-over when power fails and automatic recharging of the batteries when power is restored. Switch-over is so fast that no malfunction of the AMOS occurs when power fails.

Performance

A very extensive evaluation of the AMOS performance has been carried out by J.M. DeLaurier *et al.*, all of the Geomagnetic Division. In their paper, in a section entitled *Comparison of AMOS data with Absolute Field Measurements* they write,

> "AMOS data at all stations are regularly compared with the absolute field measurements by plotting the AMOS D baseline and the corrections required to reduce AMOS H (X, Y), Z values to the field measured at the absolute piers.
>
> For example, a careful comparison has been made between the corrected AMOS D, H, Z values and the absolute field observations at St. John's observatory for the 12-month period March 1970 to February 1971. For H and Z the differences between the absolute observations and the corresponding AMOS values were plotted, and the straight line segments were fitted to the points. In the interval from March to December 1970, for 84 absolute (QHM) observations, the correction necessary to reduce the AMOS H to the absolute pier, as given by the best straight line fit, was 3.3 gammas with an r.m.s. deviation of 1.6 gammas. The mean adopted correction to the AMOS Z in this period was 5.1 gammas with an r.m.s. of 1.6 gammas. The typical scatter in any month in determining the AMOS D baseline was 0.6 minute or 3 gammas, comparable to the r.m.s. deviation in any one month in the absolute minus AMOS values for H and Z.
>
> The r.m.s. deviation in the observed minus adopted H baselines for the Ruska for the period March 1970 to December 1970 was 1.6 gammas, or the same as that found for the AMOS H. In general, it is concluded that the AMOS baseline stability is as good as the baseline stability of the RUSKA."

Again in a later section they conclude,

> "The Automatic Magnetic Observatory System has proven to be at least as reliable and stable as our RUSKA systems. AMOS has recorded successfully such large storms as that of August 4-5, 1972, during which the field changed by more than 1,800γ/min whereas our photographic equipment failed to monitor such a disturbance. The direct recording of one-minute values on digital tape is an improvement over the manual scaling or digitizing of photographic traces."

Since late 1969, the Geomagnetic Division has built and installed a total of eight AMOS. Two more installations are planned for 1973. The most persistent sources of malfunction have been the digital voltmeters and the magnetic tape recorders. Usually the malfunction is traceable to the electro-mechanical items such as cooling fans, microswitches, reel motors, and relays.

The voltmeters must be calibrated on a regular basis, nominally every six months.

Miscellaneous information

The power consumption of the system is nominally 500 watts. During the time that the proton magnetometer is polarizing, an additional 100 watts is required. Overall weight is just under 200 kgm. Excluding the fluxgate detector assembly and proton sample, the dimensions of the system are about 140 cm high, 55 cm wide, and 55 cm deep.

Acknowledgments

It is a pleasure to thank Dr. P.H. Serson and E.I. Loomer of the Geomagnetic Division for their interest and encouragement during the development of the AMOS. They have also made numerous suggestions for improvement of this paper.

The author is much indebted to J.M. DeLaurier, E.I. Loomer, G. Jansen van Beek, and A. Nandi, also of the Geomagnetic Division, for permission to quote extensively from their paper on the evaluation of the AMOS.

References

Andersen, F. 1973. Telephone verification system for automatic magnetic observatories, *Pub. Earth Physics Branch,* Vol. 44, No. 5.

DeLaurier, J.M., E.I. Loomer, G. Jansen van Beek, and A. Nandi 1973. Editing and evaluating digitally recorded magnetic components at Canadian observatories, *Pub. Earth Physics Branch,* Vol. 44, No. 9.

Naval Ordnance Laboratory, 1942. The fields of square coils, singly and in pairs, *Nav. Ord. Lab.* Report 574, United States Navy Yard.

Serson, P.H. 1957. An electrical recording magnetometer, *Can. J. Phys.,* 35, 1387.

Serson, P.H. 1962. A simple proton precession magnetometer, *Geomagnetic Laboratory* Report No. 62-1.

Serson, P.H. 1962. Proton precession magnetometer, U.S. Patent No. 3,070,745.

Serson, P.H. 1969. Equipment with digital recording possibilities, (Abstract) *Int. Assoc. Geomagnetism and Aeronomy,* Bull. No. 26, 103, 1969.

Trigg, D.F., P.H. Serson, and P.A. Camfield, 1971. A solid-state electrical recording magnetometer, *Pub. Earth Physics Branch,* Vol. 41, No. 5.