THE UNIVERSITY OF NEW HAMPSHIRE

MAGNETIC FIELD OBSERVATORY

NUCLEAR MAGNETOMETER

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Acknowledgements

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NUCLEAR MAGNETOMETER

I Theory of Operation of the Nuclear Magnetometer

It has been known for some time that certain nuclei possess a magnetic moment and angular momentum. These nuclei precess at a frequency directly proportional to their environmental magnetic field strength. It has been found that the hydrogen nuclei, found in all hydrocarbons and in water, will precess at approximately 2000 cps in a magnetic field intensity of approximately 0.5 oersted. The relationship of magnetic field to precession frequency for hydrogen nuclei has been determined by the National Bureau of Standards (Driscoll and Bender, 1958) to be:

$$H = 23.4874\ (f_p)\ \text{gamma/cycle}$$

where H = field strength (in γ)

f_p = precession frequency (in cps)

$\gamma = 10^{-5}$ oersted $= 10^{-5}$ gauss (permeability = 1).

Because of the random orientation of nuclei in a normal liquid hydrocarbon sample, no detectable precession signal can be obtained in the earth's magnetic field. It is necessary first to polarize the sample, so that a sufficient number of nuclei will be processing together coherently and induce a detectable signal in a sensing coil. During the polarizing time, the magnetic moments of a certain percentage of these nuclei are aligned with the applied magnetic field. Abruptly removing this magnetic field allows the nuclei to precess freely in the earth's magnetic field. As described above, they will precess at a frequency which is directly proportional to the earth's magnetic field.

The phase coherence of the precessing nuclei does not continue indefinitely; after a short time the phasing starts to become random again. The result is exponential decay of the precession signal amplitude. The time required for the signal amplitude to decay to 1/e (e - 2.718) of its initial value is called the transverse relaxation time (T_2).

In addition to the initial polarization, there are several other requirements which must be met before a coherent precession will occur:

1. The direction of polarization must not be closely aligned with the total earth's field vector;

2. Polarization must be removed in a time that is short compared to the period of one cycle of the precession frequency in the effective field;

3. The hydrogen nuclei should be in a homogeneous field;

4. T_2 should be comparable to preset counter time interval (not a requisite for coherence, but does yield maximum signal-to-noise ratio).

This precession signal can be picked up by the same coil which produced the strong magnetic field and applied to the input terminals of a high-gain, bandpass amplifier.

The signal from the amplifier is fed into a preset digital counter where a preset number of cycles of the precession frequency form a time-gate. As the precession frequency increases, the time period of the gate decreases and vice versa. During the time-gate, a crystal controlled reference frequency of 100 kc/s is allowed to be counted by a time interval meter. Thus, the period of n cycles of precession signal is displayed at the end of the time-gate to an accuracy of 10 microseconds in terms of the 100 kc/s reference frequency. An indication of this period may be obtained by:

1. Observing the state of the display register indicator numerals;

2. Allowing the above information to drive the digital recorder (printer);

3. Allowing an analog of any three adjacent digital information bits (available at the printer plug) to drive the strip chart recorder.

Calculating Field Values

$$H = \frac{23.4874\ (n)}{N}$$

where n = number of precession cycles counted (present count-gate interval)

N = proportional count of reference frequency (number displayed)

Example

$$H = \frac{23.4874\ (\gamma/\text{cycle})\ n\ (\text{cycles})}{N \text{ in sec. from counter}}$$

$$H = X\gamma\ (\text{gamma})$$

Apparatus

A block diagram of the complete nuclear magnetometer is shown in Figure 1. This diagram shows the associated counting equipment necessary to display a time interval inversely proportional to the magnetic field.

At this laboratory a direct reading system is used to read out the field. This system is discussed in Appendix D. An analog-to digital converter is used to provide a graphic recording of the changing field (See Appendix C).

a) Coil Assembly

Since the rotating flux of the precessing protons links well with the polarizing coil, only one coil is needed for polarizing and pickup. Approximately 700 turns of # 16 copper wire are wound around a polyethylene bottle containing distilled water and alcohol (to prevent the sample from freezing). The supporting form for this winding is described in Appendix B. The relaxation time of the water sample can be increased by removing some or all of the dissolved oxygen which is paramagnetic. This can be done by vacuum distillation or by bubbling nitrogen through the sample for a period.

The polarizing field should be many times the earth's field of about 1/2 gauss. A current of four amperes is used for the polarizing field, and this current through the coil produces a field of more than 200 gauss.

The coil assembly is located in an area which is free from man-made magnetic disturbances. This area is about 200 feet from the electronics unit. The connecting cable is RG 57A/U which has a jacket of black polyvinyl chloride.

This jacket has good weathering and abrasion properties, and is noncontaminating. Therefore no attenuation should result with age.

b) Relaying

The input to the relaying circuit, shown in Figure 3, has a diode clipper to ground to reduce the positive transient caused by the collapse of the polarizing field. The polarity of the diode is such that it is back-biased by the polarizing batteries during the polarizing cycle but will conduct when the inductive transient appears. Thus, the energy contained in the magnetic field of the coil is transferred to the capacitor. This capacitor should have a large enough voltage rating to absorb nearly all of the energy without possible breakdown. The resistor should be small enough to overdamp the coil and to completely discharge the capacitor before the next read cycle.

Relay 1 (RLY 1) is driven by the timing circuit (Figure 2). The diode across the RLY 1 coil absorbs the transient that occurs when the coil is de-activated, and this prevents possible damage to its driving transistor. This relay initiates the polarizing cycle and switches relay 2 (RLY 2), which in turn grounds the preamplifier input to prevent oscillation during this part of the cycle, and resets the counting apparatus. A delay of about three milliseconds exists between the turnoff times of relays 1 and 2, due to the RLC time constant at RLY 2. If this delay is not long enough, a large transient appears at the preamplifier input. Although this does no physical damage to the input transistor, it will temporarily block the amplifier input and prevent the proton signal from passing.

The RLY 1 is a Sigma 42R0-500G-SIL with 5 ampere contacts, and RLY 2 is a General Electric #3S2791G200AS. Due to the heavy current at the normally open set of contacts on the polarizing side of the Sigma relay, an additional diode and RC network is incorporated in the part of the circuit it serves to reduce arcing at these contacts and to prolong the life of the contacts. The combined RC time constant must be sufficient to keep the coil current flowing long enough to break the contacts before any voltage develops across them.

c) <u>Timer and Switch</u> (<u>Figure 2</u>)

The timer is a unijunction relaxation oscillator. Switch 1 (SW 1), which is front-panel mounted, changes the RC time constant to provide a positive trigger voltage at approximately 15 and 60-second intervals. This fires the monostable which has a period of three seconds. The monostable can be fired externally (external timer) via rear panel connection, by pulling the base of the first transistor to ground, thereby applying a positive pulse.

The monostable turns on the 2N338 switch, and the collector current pulls in and holds the RLY 1 on for the monostable period.

d) Amplifier

The amplifier is a variable gain, variable bandpass type. Its component parts, preamplifier, attenuator, filter and main amplifier are shown in the block diagram of Figure 4. The input and output impedances of these blocks must be matched to maintain amplifier stability. The passband center frequency is set close to the mean value of the proton precession frequency and the bandwidth is sufficient to pass precession frequency associated with a $\pm$ 250 gamma magnetic disturbance.

The proton precession signal from the coil has a level of about 30 microvolts p-p. This level must be amplified by a factor of better than 3×10^5 to prepare it for counting. This means that the amplifier must have an overall gain of more than 3/10 million. The main amplifier gain will have to be sufficient to make up for the losses in the attenuators and the filter. Problems encountered in amplifiers of extremely high gain are noise and oscillations due to stray feedback.

e) Preamplifier (Figure 5)

Gain	3100 at 2420 cps	
BW	(3Db) $\pm$150 cps	f_c = 2420 cps
Gamma BW	$\pm$3525 Gamma	

The preamp is designed as a selective and very low-noise amplifier to amplify the output of the coil to a level at which the noise figure of any additional amplifier is not critical. An equivalent amplifier noise voltage of 6 microvolts was obtained by simulating the coil input load (including cable) with its equivalent dc resistance of 3 ohms.

Capacitor C5 couples the signal to the input winding of the transformer T1. Relatively high capacity has to be used at C5 in order that nearly all of the signal be coupled to the low impedance of the transformer.

The primary and secondary impedances of the transformer were chosen to match the impedance of the magnetometer coil at 2420 cps (200 to 250 ohms) to the input impedance of TR 4 (approximately 1 k). A triad TY-55X was used for this impedance match. The windings are 2000 ohms CT and 500 ohms CT, and one-half of each winding is used to give the desired impedance ratio. Physical placement of T1 with respect to T2 is critical since feedback oscillation can occur if they are placed physically too close together.

Transistor TR4 is a low-noise 2N220, p-n-p germanium transistor in a common-emitter, transformer coupled, tuned amplifier. R8 and R9 determine the base bias current. R15 and R16 serve to bias the emitter and limit the collector-to-emitter current to the recommended value of 400 microamps for the lowest noise operation. Capacitor C13 keeps the emitter at AC ground potential. Capacitor C6 grounds the cold end of the input transformer and insures that all signal voltage is developed across the base o TR4. Tuning is accomplished through series resonance of the secondary of T1 and the junction capacity of the base emitter junction of TR4. This junction capacity is proportional to the base current, and a rough adjustment of the passband location can be made by adjusting the dc base current. Thus, a higher base current will result in a greater capacity and a lower resonant frequency. Varying the base bias will also vary the collector current. This means that R15 and R16 will also have to be adjusted to maintain the recommended 400 microamps of collector current. C12 is used for fine adjustment of the center of the passband. R14 is effectively in series with part of the tuned circuit and can be used to control the Q, or the sharpness (bandwidth) of the passband.

Transformer T2 is a UTC DO-T1 sub-miniature that matches the high output impedance of TR4 to the low impedance of TR5. The primary and secondary windings are respectively 20,000 ohms and 800 ohms. C9 couples the signal to TR5.

Transistor TR5 is used in a common emitter configuration as an untuned voltage amplifier. This transistor is also a low-noise 2N220. R11, R12, R17, and R18 serve to bias TR5 for maximum gain and linearity. C14 bypasses R18. C15 serves three purposes. It helps further to shape the passband and to increase the signal-to-noise ratio by reducing the high-frequency response of the amplifier, and along with C10 it helps to set the output impedance of the last stage at 100 ohms.

Capacitor C10 couples the signal to TR6, another 2N220 in a common-collector configuration to give a low output impedance to isolate the input tuned stage from output load changes.

De-coupling resistors and shunt capacitors are inserted between stages to help stabilize the supply voltage to each transistor and to drain any supply line signal voltage that would cause feedback.

The preamp is encased in a copper box to reduce noise and cross-coupling circuit feedback.

f) Attenuator

The attenuator (Figure 6) is a variable "T-Pad," manufactured by Clarostat under part number CIT-100. Its input and output impedances of 100 ohms match the preamp output impedance and the filter input impedance. The minimum-loss pad matches the filter output with the amplifier input, which cannot be reduced much below 500 ohms. This pad has a voltage attenuation of about 3db.

g) Filter (Figure 6)

Insertion loss	5.36×10^{-2}	($f_c = 2420$ cps)
BW (3 db)	$\pm$ 10 cps	
Gamma BW	$\pm$ 235 Gamma	

The bandpass filter (Figure 6) is of the image-parameter design. The element value design equations are derived by assuming the network is terminated with impedances which vary as a particular function of frequency. These impedance functions can be satisfied only at the filter center frequency and it is important that they be satisfied. For this reason all of the input and output impedances are matched. The design equations for this filter were obtained from pages 174 and 175 of the FTR handbook of Reference Data for Radio Engineers (1943).

Filter Tuning - The center frequency of this filter is changed by varying the capacitors in the series arms. The center frequency can be changed 40 cps by varying C6 (Figure 6) from a maximum to a minimum.

Any large adjustment in center frequency, to accommodate a large change in porton precession frequency, must be made with the C_a (Figure 6) padder capacitors. Both capacitors should be changed by the same amount to minimize the insertion loss.

Front-panel adjustment of the filter center frequency can be made with the two C_b capacitors. Equal clockwise rotation of these capacitors will increase the filter center frequency (decrease the capacitance).

h) Main Amplifier (Figure 7)

Gain	3600 (f - 2420 cps)
BW (edb)	$\pm$ 400 cps
Gamma BW	$\pm$ 9400 Gamma

The purpose of the main amplifier is to increase the amplitude of the signals from the filter to a level acceptable by the readout equipment, namely the dual preset counter. The filter output is, of course, a function of the attenuator control setting. The normal filter output is about three millivolts. About 10 volts of signal are desired at the beginning of the signal decay.

The capacitor C1 is sufficient to pass the input and serves as a block for any DC component. C2 functions primarily as an input impedance adjusting device to set the amplifier input impedance at about 500 ohms and secondarily as a shunt to high frequency noise still present on the signal.

A common emitter voltage amplifier, Q1, has sufficient gain to insure saturation and cutoff in the next stage utilizing Q2. The second stage is identical in construction to the first, with the exception of R8 which is used to adjust the peak voltage values of saturation and cutoff in Q2. R6 and R7 are adjusted so that the amplifier clips symmetrically.

The purpose of the clipping is to remove noise that appears in the output as variations in amplitude of the signal. Since all of the information is contained in the frequency, preservation of the amplitude is not necessary. The waveform at the collector of Q2 is a square wave of fixed amplitude until the precession signal at the input to this stage has gone below the level necessary to guarantee clipping. This period of time has in a sense lengthened the precession frequency decay time.

The common-collector configuration, Q3, provides a high input impedance to the low-pass filter which passes along the fundamental of the clipped wave form. This fundamental is of constant amplitude as long as Q2 is in the clipping mode.

Another common-collector configuration, Q4, provides a fixed load for the low-pass filter when the output load may vary.

The R and C values in the -12 volt feed line serve, as in the preamp, to help stabilize the supply voltage and to damp any signal voltage that would tend to cause feedback.

The main amplifier is also encased in a copper box to shield it from external noise and cross-coupling feedback.

II Comments on Operation

a) Gain Adjustment

The system will break into oscillation if the overall gain is too high. The attenuator is used to set the gain to an optimum value. This optimum occurs when the output emitter follower just starts to square the peaks of the initial precession signal at about 11 volts.

b) Calibration

When any changes are to be made in the filter, a sine wave of known frequency can be coupled into the system through the biasing coils of the vector system (for information on this vector system, see Appendix A). This provides adequate signal for the sensing coil to pick up and send on to the electronics. A frequency counter should be used to set the frequency, since the filter tuning is critical. A change of one cycle in passband center frequency is the same as a shift of about 24 gammas in the magnetic field.

Peak the filter at a frequency corresponding to the mean value of the magnetic field. When the filter is at its peak corresponding to this field, the front-panel center frequency controls should be at or near their center position to provide adequate adjustment for long term changes.

c) Noise

Any long, conducting material, such as a wire, near the coil acts as an antenna and increases the amount of noise present on the signal. A break in the shield of the twin-axial connector will increase the noise level. If the electrostatic shield is not connected to the cable shield, a high level of noise will result.

On a quiet day the signal-to-noise ratio (s/n) of this instrument is between 25/1 and 35/1. Operation on a normal day might be as follows:

at the preamp output

peak output 150 millivolts p-p (at the start of the read cycle)

3/1 peak s/n ratio

at the amplifier output (attenuator set at 20)

peak output 11 volts p-p (at the start of the read cycle)

10/1 peak s/n ratio

A great deal of noise is picked up locally, from a low frequency (20 kc) submarine communications system used in the North Atlantic. This noise shows up in the output record, when counting over more than 1000 cycles of the precession signal, as erratic excursions on the order of 2 to 4 gammas.

Looking at the coil output with a scope this 20-kc coded signal had an amplitude of 100 millivolts. Also riding under this 20-kc signal were about 15 millivolts of 1 Mc which appear to be associated with the submarine communications station.

d) Coil

Never place the coil near any metallic material. The processing field of the protons will create eddy currents in this metallic material with a resulting reduction in precession signal level.

e) Power Supply - (Figure 8)

All electronics with the exception of the timer operate on minus twelve volts (-12 v). The power supply provides -12 volts regulated and +12 volts regulated. The ripple must be very low in the -12 volt supply for the high gain electronics. In order to accomplish this, a phase-shifting network is inserted in the control circuit to provide negative feedback for ripple reduction. R_p is used to seek a ripple null. R_1 controls the output voltage.

f) Data Readout

The precession frequency is read out with a time interval meter. In the apparatus diagram the readout equipment is shown as a dual preset counter and time-interval meter (TIM). The timer resets the dual preset counter which is set to count a certain number of cycles of precession frequency. After preset A cycles are counted, a pulse is generated which turns on the TIM; after preset B cycles are counted, another pulse is generated which turns off the TIM. Preset B minus preset A, divided by the TIM display, gives the precession frequency. This TIM display can be reset internally or externally by the timer. An analog of the last two TIM digits can be obtained by using the digital-to-analog converter described in Appendix C.

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Appendix A

1) The Vector System

By applying homogeneous bias fields to a proton precession magnetometer, vector magnetic field measurements of exceptional accuracy can be obtained. This system follows very closely the F - Δ D -ΔI magnetometer developed by Shapiro, Stolarik and Heppner (1960) from the idea of Bacon (1955). In this system of vector measurement there is no need for calibration, temperature corrections, or corrections for instrument drifts. The system accuracy is limited to ± 1 count in the precession frequency readout. Figure A1 shows the orientation of the Rubens coil which is used to provide the bias fields to obtain both declination and inclination measurements of the earth's field vector. This coil system consists of two orthogonal windings and is described in more detail later.

2) Declination Variations ΔD

To obtain this declination angle, field measurements must be taken of a vector sum of the earth's field and a bias field created at right angles to the earth's field in a horizontal plane. This measurement is made independent of coil or bias current by taking two measurements of opposite bias fields.

The change in declination, measured ΔD, is relative to the orientation angle of the coil. An absolute declination can be made through the algebraic addition of $D_o + \Delta D$ (D_o is the zero orientation of the coil) when the coil orientation is accurately known.

The equation for ΔD was derived by Bacon (1955) from the cosine law with the assumption that $(F_d - F)/F \ll 1$. This can be accomplished by limiting the bias field to a value sufficient to make $F_d = F + 100$ in gammas.

$$\Delta D = \frac{1.719 \times 10^3 \, (F^+_d - F^-_d)}{\text{Cos } I \left[F(F^+_d + F^-_d - 2F) \right]} \, 1/2 \qquad \text{(in minutes)}$$

where $I = I_o + \Delta I$ is the inclination field and 1.719×10^3 is the conversion from radians to minutes.

Although the zero orientation is not critical, there are advantages to making it such that F^+_d and F^-_d are nearly equal. These values can be made equal by rotating the coil structure in the horizontal plane. When ideally oriented, the readings over a period of diurnal variation will be such that the amount of time when $F^+_d > F^-_d$ is roughly equal to the amount of time when $F^+_d < F^-_d$; that is to say, that D_o is close to the mean declination.

3) Inclination Variations ΔI

The method used for inclination measurement is basically the same as that described for declination measurements. Again, the inclination ΔI is the algebraic sum of $I_o + \Delta I$ where I_o is the zero or fixed orientation. The I_o setting is determined, after D_o has been set, by tilting the coil until F^+_i and F^-_i are nearly equal when averaged over a diurnal cycle.

$$\Delta I = \frac{1.719 \times 10^3 \, (F^+_i - F^-_i)}{\left[F \, (F^+_i + F^-_i - 2F) \right] 1/2} \qquad \text{(in minutes)}$$

This relation is subject to the same assumptions.

4) Coil

A system of five, equally-spaced, square coils which provide a uniform magnetic field over a considerable volume (Rubens, 1945) are wound around two surfaces of a cubical aluminum structure. The conventional Helmholtz coil-pair provides uniform field at the center, but the region of high uniformity is small compared with the volume of space between the coils. (Figure A2)

As shown in the diagram, the spacing between loops is d/4 where d is the length of an edge of the cube. In this system a "d" of 36 inches was chosen. The currents are proportional to the numbers 19, 4, 10, 4, 19, and when the coils are in series, these numbers are proportional to the number of turns in the coil.

In the number of turns is exactly 19, 4, 10, 4, 19, then the axial field at the center of the system is 35.69/d oersteds/amp where d is the side length in centimeters.

Comparison of Rubens and Helmholtz Coils

Deviation of Axial Field from its Value at the Center of the System	Cubical Rubens Coil		Helmholtz Pair	
	Cylinder Length	Cylinder Diameter	Cylinder Length	Cylinder Diameter
1 part in 10^3	.45 d	.20 d	.10 d .15 d	.20 d .15 d
1 part in 10^2	.50 d	.50 d	.30 d .20 d	.25 d .35 d

5) <u>Windings and Resultant Field</u>

The windings used in this system are 19, 4, 10, 4, 19. For a bias field of about 3000 gammas we can obtain a $(F_d - F_d)$ of 100 gammas. To obtain this 3000 γ bias, 0.077 amperes must pass through the series coils.

6) <u>Bias Field Programming</u>

When the vector system is in use, the magnetometer is cycled externally (see Figure A3). A series of five cams is driven by a 1-rpm synchronous motor. The first cam provides five reset pulses for the magnetometer switching circuit of Figure A2. Each of the other four cams provides a bias current of the required polarity at the proper set of coils. The pulse from each of these four cams is given at the same time as one of the last four pulses of cam one. These cams are simply round aluminum discs with screws around the circumference to provide an elevated portion to trip a micro-switch. The cams make one complete revolution per minute, and only one set of necessary readings or measurements is taken.

7) <u>Data Readout</u>

When this vector system is being used, a digital recorder is obtained for:

1. F^{+}_{d}
2. F^{-}_{d}
3. F^{+}_{i}
4. F^{-}_{i}
5. Field Magnitude

This is done with time-interval counting equipment as described in the main part of this manual.

An analog recording of the field magnitude can be obtained by programming this reading last in the series of five. Since the time-interval meter is reset by the timer and switch of the magnetometer, this digital display will last more than 45 seconds and allow the recording instrument to make many points.

Appendix B

1) Nuclear Magnetometer Sample and Sensing Coil

The component parts of the coil assembly are shown in Figure B1. Parts 1, 2, and 5, are fabricated out of phenolic material to 3 3/4" diameter. Part 3, a polyethylene bottle holds the sample. This bottle slides inside of Part 4, which is an epoxy glass tube, 2 3/8" ID and 2 5/8" OD. The tube, 4" in length, is held centered by circular grooves in Parts 2 and 5. The parts are epoxied together, and #16 formvar-clad copper wire is wound on in 10 layers of about 70 turns each. A twin-axial conductor is connected to the coil. The other end is connected via coaxial fittings to the twin-axial cable leading to the electronics.

The entire assembly is covered with an electrostatic shield which is etched from 1/32" copper-clad epoxy board. The end parts of the shield are simply discs of the etched board. When the sections of shield are joined, care must be taken to introduce no closed loops, which are shorted turns in a magnetic circuit. The twin-axial cable shield is connected to the electrostatic shield.

The finished unit is covered with tape to protect it from its environment.

Appendix C

1) Digital to Analog Converter for Beckman/Berkeley Counter

This instrument is suitable for recording a slowly changing reading on any of the Beckman counters (Serson, 1962).

The analog circuit contains eight triodes which are used as switches, passing appropriately weighted currents through the resistor across the output terminals, depending on whether their grids are positive or negative. The plate swing of the four more critical triodes is limited accurately by silicon diodes (1N458) and the OG3 voltage regulator tube with the grids connected as shown in the circuit, the readout will be from the fourth and fifth digits of the Berkeley 7250R.

The potentiometers $R_1 \rightarrow R_4$ were used instead of fixed values in order to give a greater degree of linearity in the ten's digit column. This is done by adjusting these potentiometers to give analog readout proportional to their numerical magnitude times some constant.

Table #1

Decimal Digit Registered	1st Binary	2nd Binary	3rd Binary	4th Binary
0	0	0	0	0
1	1	0	0	0
2	0	1	0	0
3	1	1	0	0
4	0	1	1	0
5	1	1	1	0
6	0	0	1	1
7	1	0	1	1
8	0	1	1	1
9	1	1	1	1

"0" represents negative voltage
"1" represnts postive voltage or ground

Table #2

	1st Binary	2nd Binary	3rd Binary	4th Binary
	Pin # (Grid)	Pin # (Grid)	Pin # (Grid)	Pin # (Grid)
4th Highest Order Digit	16	15	14	13
Highest Order Digit	20	19	18	17

As an example, from table #1 we pick 2 as the decimal digit registered. The voltage at Grid #15 will be at ground or positive of ground to cause the tube to conduct and give us a current through the output resistor. By adjusting R_2 we can get the output voltage drop proportional with the registered digit times our constant. When the tube is conducting, the load resistor controls the amount of current which will flow. This same process will be used to get proportional readings with registered digits 1, 2, 4, 6. Pot R_1 for Digit #1, R_2 for #2, R_3 for #4 and R_4 for #6.

Potentiometer R_5 is used to control the current flow through the OG3 so the voltage across the OB2 will not go below that which is necessary to ignite it. The OB2 maintains a constant potential above ground. This in turn provides for more linear results because as more tubes conduct, the IR drop across the 5-k resistor increases giving a lower voltage on the tubes.

The potentiometer R_6 controls the range of output voltage. When adjusting $R_1 \longrightarrow R_4$ we can set this potentiometer to give us a constant of 0.1. By doing this a readout of $0 \longrightarrow 99$ will give us a voltage of $0 \longrightarrow 9.9$ volts.

Appendix D

Direct-Reading Proton Magnetometer

1) Theory of Operation

The direct-reading magnetometer circuit was originally devised by Serson, (1961) and the University of New Hampshire version is adapted from his description and circuits. The proton signal (about 2500 cps in 0.5-gauss field) is used to control the frequency of an 80 kc oscillator.

The oscillator signal is scaled by a factor of 32 giving a frequency of approximately 2.5-kc (Figure D1). The phase of this 2.5-kc signal and incoming magnetometer signal is compared in a phase detector. If the two signals are not exactly the same frequency, there will always be a constantly changing phase difference between them. This phase difference produces a sinusoidal voltage whose frequency is proportional to the difference in phase of the two incoming signals. This sine wave voltage or signal is often referred to as the error voltage. The error voltage is now fed back to bias the 80-kc oscillator. As the error voltage changes, a corresponding change in oscillator frequency occurs. Thus, if the oscillator frequency is high the error voltage will bias the oscillator so as to lower its frequency. This action continues until the frequency of the magnetometer signal and the scaled 80-kc signal are the same, resulting in a zero-phase difference. This condition is known as "locking in." Once the magnetometer signal has locked in, its frequency can be varied over a large range and the 80-kc signal is then counted for a certain calculated time interval, 7340 seconds* the readings will be directly in gammas.

* The precession frequency is 4257 cycles/sec gauss (1 gauss = 10^5 gammas). If the multiplication factor is 32, then the controlled oscillator frequency will be 136,000 cycles/second gauss and if this is counted for .7340 seconds the count will be 10^5, equal to the number of gammas in one gauss.

2) <u>Advantages of Direct-Reading Magnetometer</u>

Using this system to measure the frequency of the magnetometer signal has many advantages other than giving readings in gammas. By the very nature of the method used, an important discrimination against noise can be obtained. This excellent discrimination can be explained by the fact that the noise has no particular phase relation to the scaled 80-kc signal. Thus the 80-kc signal will respond only to the magnetometer signal. Large noise peaks that could cause distortion can easily be filtered. This particular unit has been tested, and it was found that with a 2:1 signal-to-noise ratio a resolution of one part in 50,000 could be obtained. Even with a signal-to-noise ratio of 1:1, consistently good readings were made.

A second major advantage of this system over the conventional (direct-counting) system is that a higher statistical accuracy is maintained. The reason is that, for the same length of time, more information is sampled than by the conventional system.

Third, more individual readings can be taken than with the conventional system in the same length of time. This results in a better sampling of the observed field.

3) Circuit Description

a) Magnetometer Amplifier (Figure D3)

This is a straight-forward audio amplifier with an emitter follower. The amplifier transistor is a 2N218. The gain of the amplifier is 10 or better. The emitter follower transistor is a 2N43. This emitter configuration is used to match impedances.

b) Phase Inverter-Detector (Figure D4)

The phase inverter is 1/2 of a 12AU7. Phase inversion is accomplished using equal plate and cathode resistors. The cathode is biased at minus 100 volts. This method of biasing is used to insure the proper bias on the following tube as it is wired as a direct-coupled amplifier. The outputs of the phase inverter and magnetometer amplifier are placed across a diode bridge phase inverter. The output of the phase detector is taken from the center tap of the magnetometer amplifier transformer. This output is then filtered and direct-coupled, amplified to 1/2 of a 12AX7. The signal then goes through a cathode follower. The ouput of the cathode follower is the error voltage.

c) 80-kc Oscillator (Figure D5)

The 80-kc oscillator is a symmetrical, free-running multivibrator. The error voltage is injected at the grids of the 12AU7 oscillator tube through a ganged 10-k variable resistor. The output is a square wave taken between the plate and ground. The purpose of the series

10 resistor and 500-uuf. capacitor is for removal of overshoot. The 80-kc signal then drives a 6C4 direct-coupled cathode follower. The cathode follower then drives the Time Interval Meter and scale of 32.

d) Scale Of 32 (Figure D6)

The scale of 32 is obtained by series connecting five scales of 2. The scale of 2 consists of a differentiating network, 2N329A pulse amplifier, and 2N247 bistable flip flop. The last scaler drives a 2N329A emitter follower and filter. The filter is a shunt LC circuit tuned to 2.5 kc. As the square wave of the last scaler is approximately 2.5 kc, it pulses the filter resulting in a sinusoidal output and voltage gain. This sinusoidal signal is the input for the phase inverter.

e) Automatic Resetting Circuit (Figure D7)

The input to the reset circuit is a 2N329A amplifier. This amplifier drives a 2N43 emitter follower. The emitter follower configuration is used here to achieve the proper current gain. The output of this voltage doubler is a dc level whose amplitude is proportional to the input magnetometer signal. When this dc reaches a certain level, it turns on the last 2N329A causing the relay in the collector circuit to energize. The energizing of the relay resets the counting equipment through the relay contacts. There is a 303 uf capacitor across the relay to hold the relay closed for the duration of the magnetometer reading. This capacitor also makes the circuit a bit sluggish so the relay will not close on the polarize portion of the signal. This circuit is to be used mainly with data reduction of tapes.

f) Power Supply (Figure D8)

The high voltage supply uses a 6 x 4 in a full wave transformer center-trapped configuration. The filter is condenser input design.

The low voltage supply uses four 1N96 in a bridge circuit. Again the filter is condenser input.

g) Clock Pulse Generator

The clock pulse generator is used to run the dual preset counter. The output of this circuit is a sine wave whose frequency is extremely stable. The circuit works as follows.

A signal from an 100-kc frequency standard is fed into a scale of 32 which is similar to that used previously. The output of the last scaler is again filtered to obtain a sine wave. The frequency of this sine wave will be exactly 3125 cycles per second. This signal runs the dual preset counter.

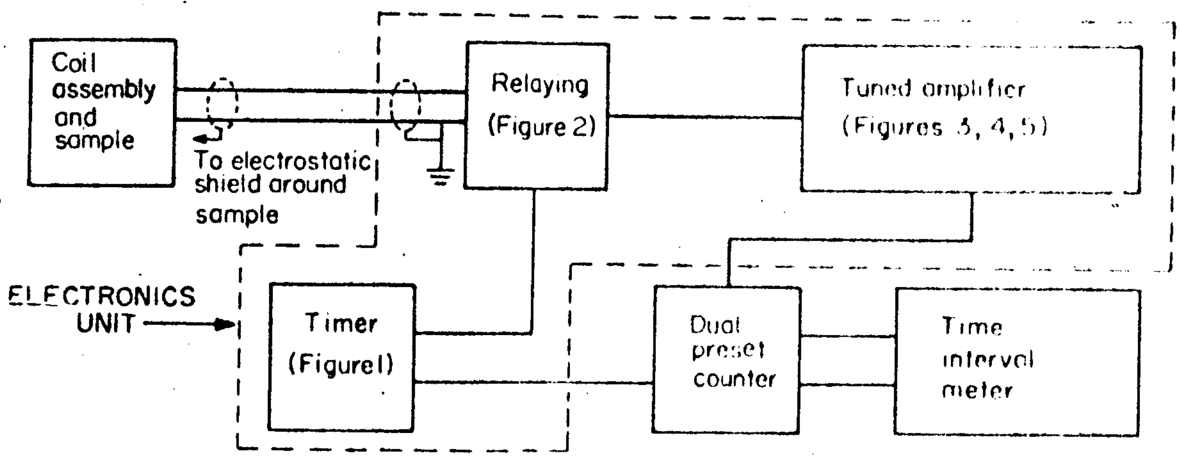
4) Operational Procedure

1. Connect unit as shown in figures 1.-2.
2. Turn on power switch and let warm up for five minutes.
3. Turn on all counting equipment.
4. Connect a magnetometer signal or its equivalent to magnetometer input.
5. Turn oscillator gain full on and set oscillator frequency control to its center position.
6. Connect an oscilloscope across the oscillator output.
7. While watching the scope, tune oscillator frequency control until the signal appears to be locked in.
8. After signal has locked set dual preset counter for 3125 cycles. The reading on the time interval meter will be the magnetometer input signal multiplied by 32.
9. Now set dual preset counter for 2294 cycles. The readings now obtained will be directly in gammas.
10. If, in step 7, the oscillator fails to lock, increase the magnetometer gain.

5) Operation of Automatic Reset

The automatic reset input is connected across the magnetometer amplifier output. To insure satisfactory operation the proper bias for the circuit has to be obtained from a very low ripple supply. It is recommended that batteries be used.

After making necessary connections, adjust the gain until the relay will just close with each magnetometer signal. If the gain is properly set only the magnetometer signal, not spurious noise such as that from the polarize relay operation, will reset the equipment.



NUCLEAR MAGNETOMETER SYSTEM BLOCK DIAGRAM

FIGURE 1

FIGURE 2— TIMER & SWITCH

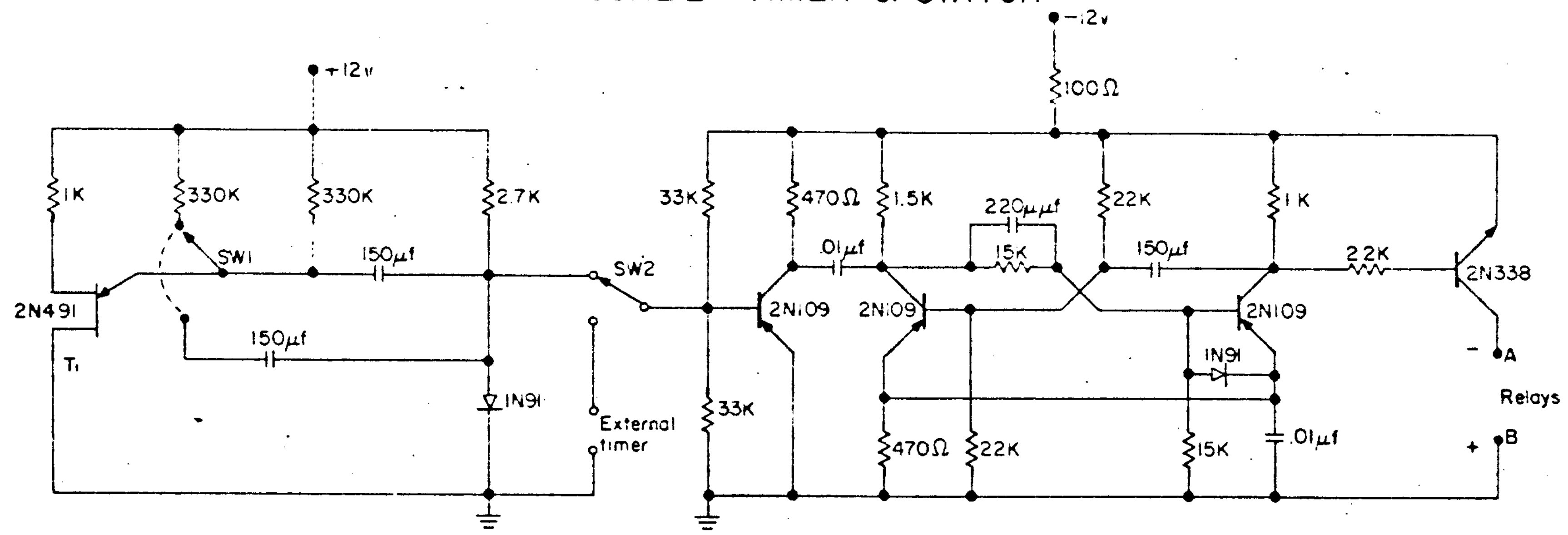
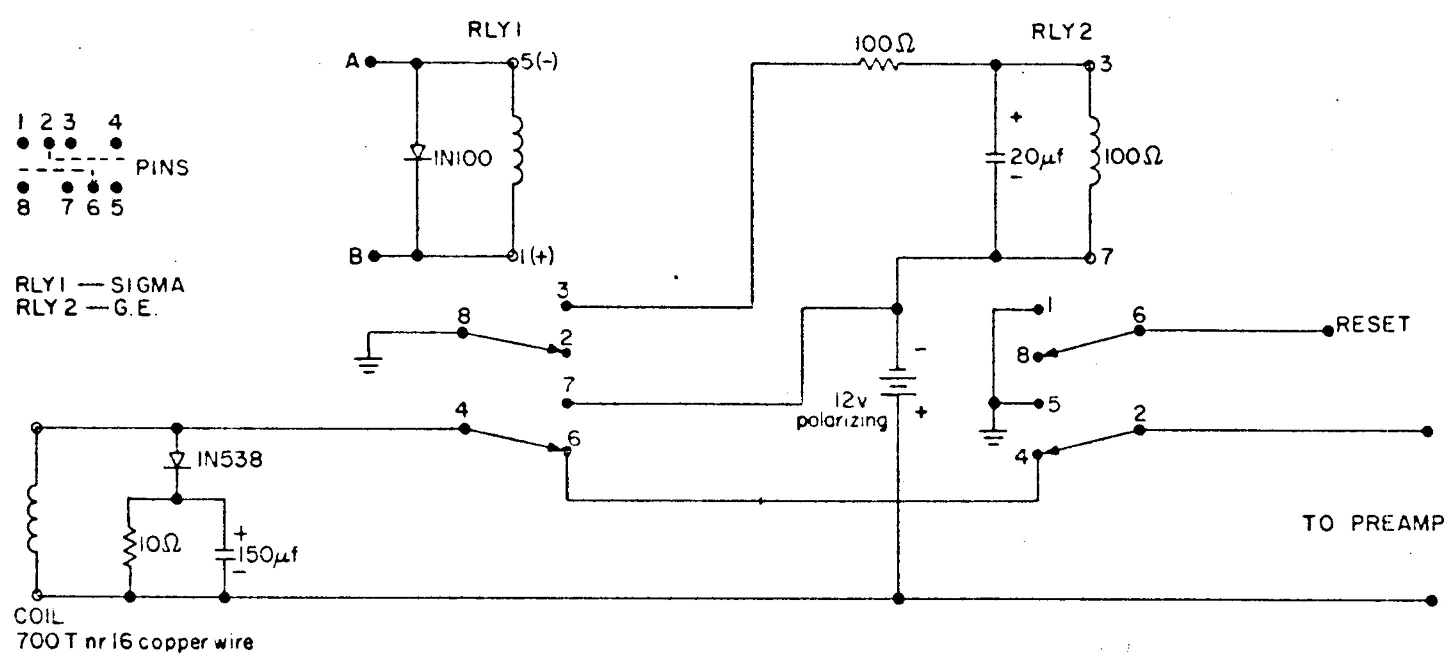
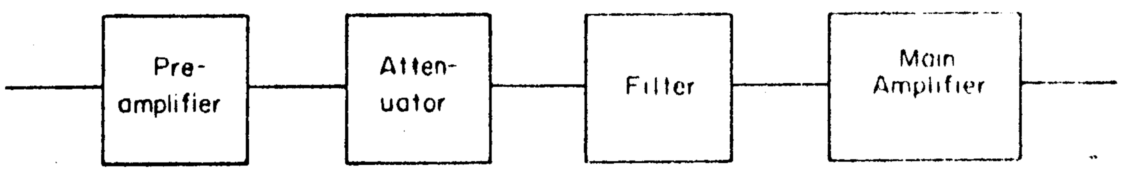


FIGURE 3 — RELAYING

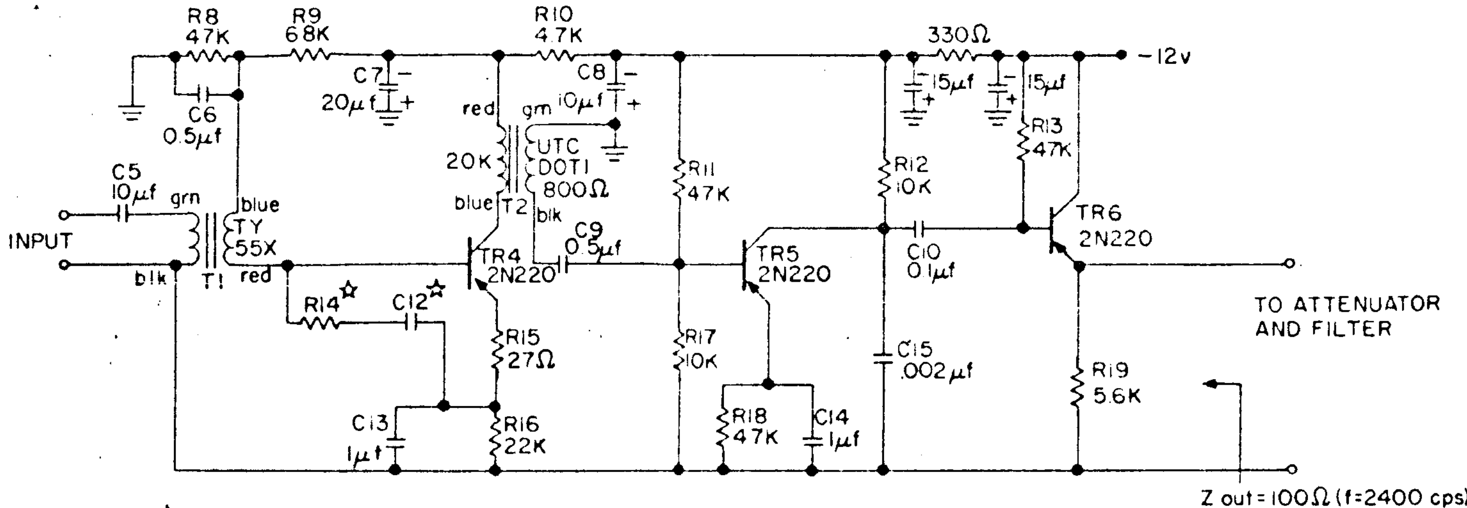




TUNED AMPLIFIER BLOCK DIAGRAM

FIGURE 4

FIGURE 5 — PREAMPLIFIER



☆Adjust for desired band width

FIGURE 6 — ATTENUATOR AND FILTER

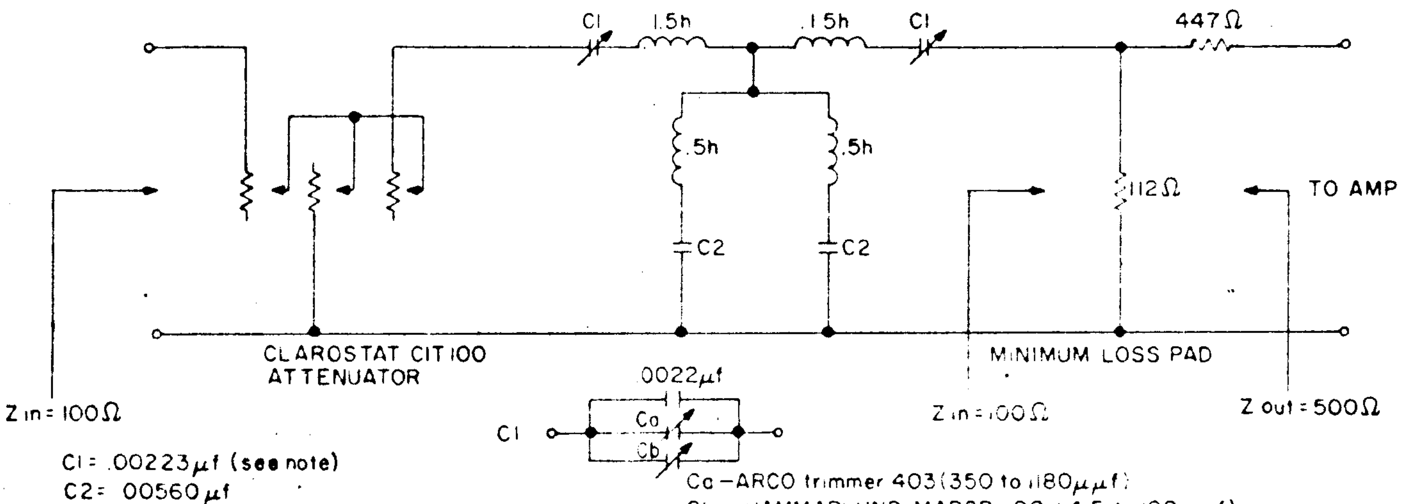
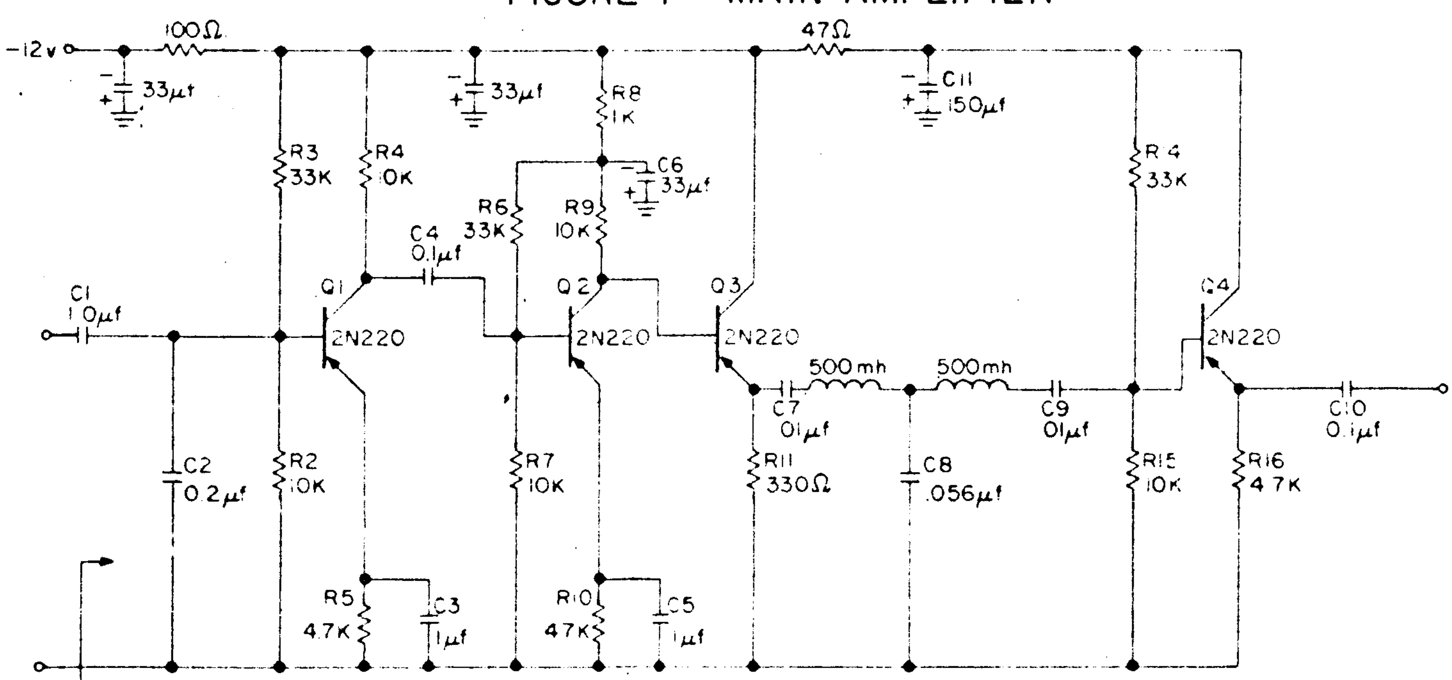
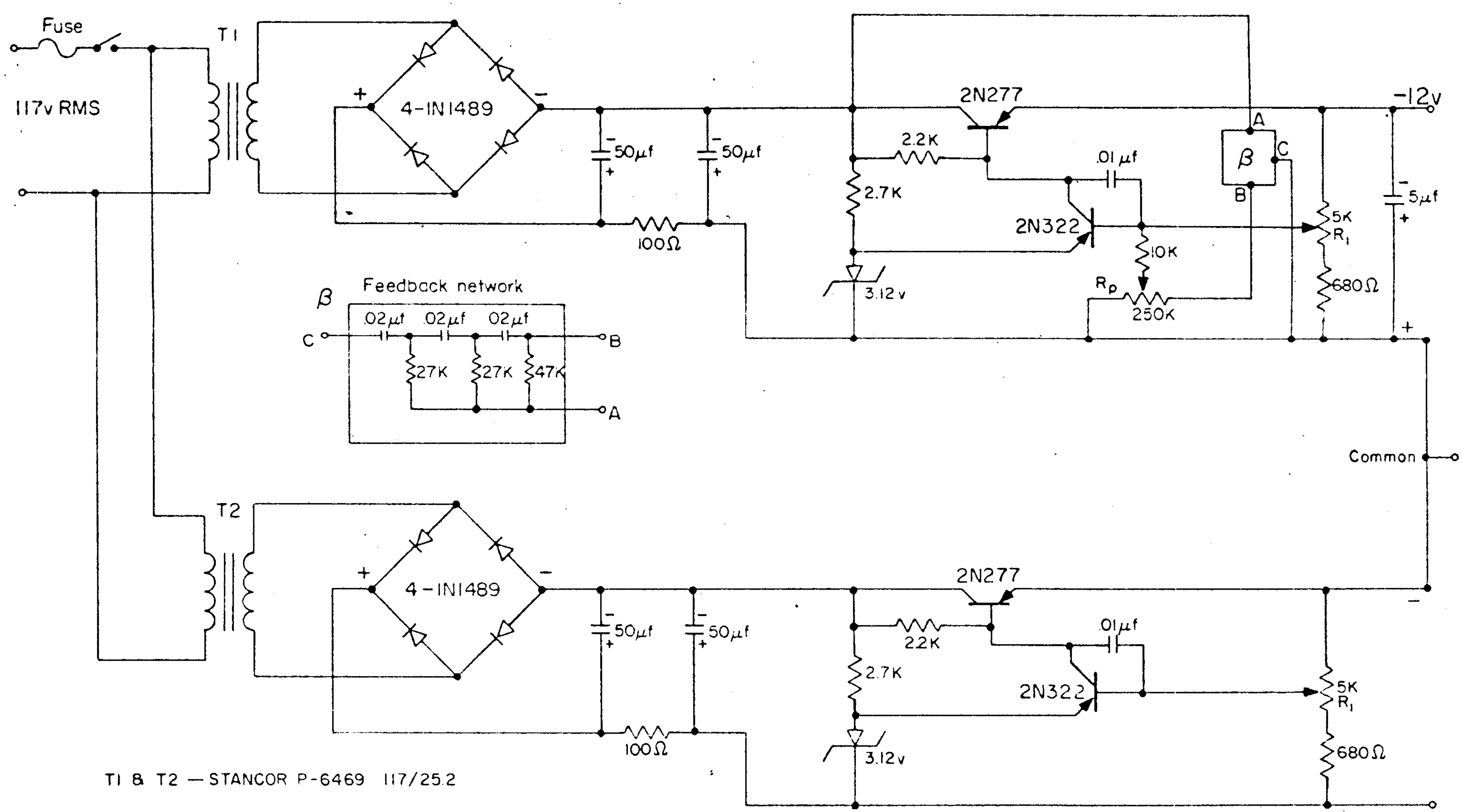


FIGURE 7 — MAIN AMPLIFIER



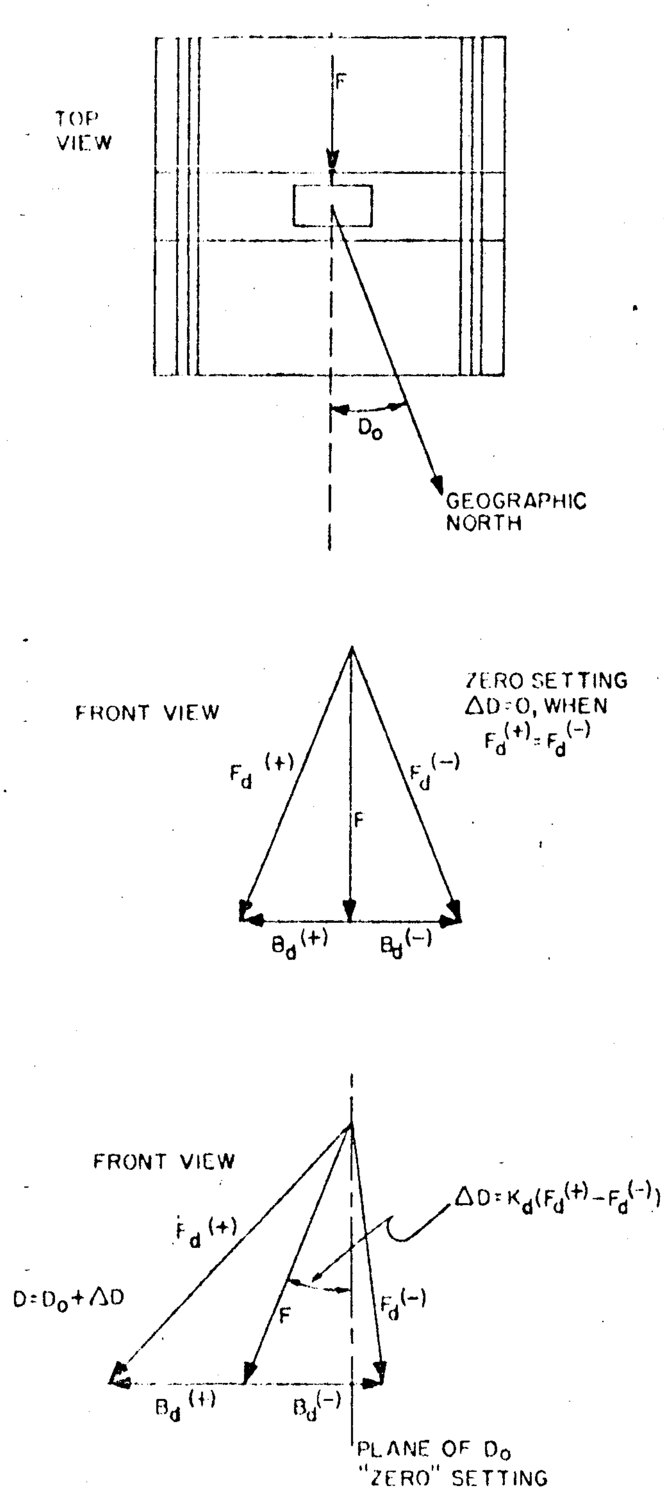
C_1 & C_2 adjusted for Z in ≈ 500Ω



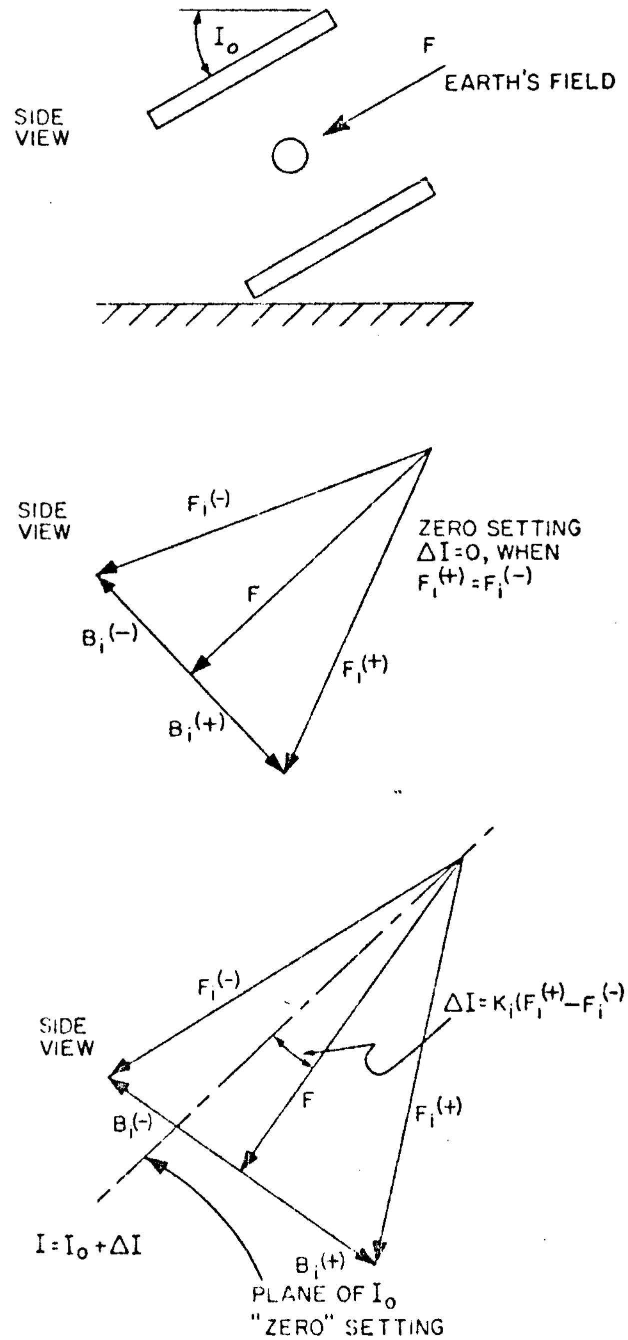
T1 & T2 — STANCOR P-6469 117/25.2

Diodes — IN1489

POWER SUPPLY
FIGURE 8

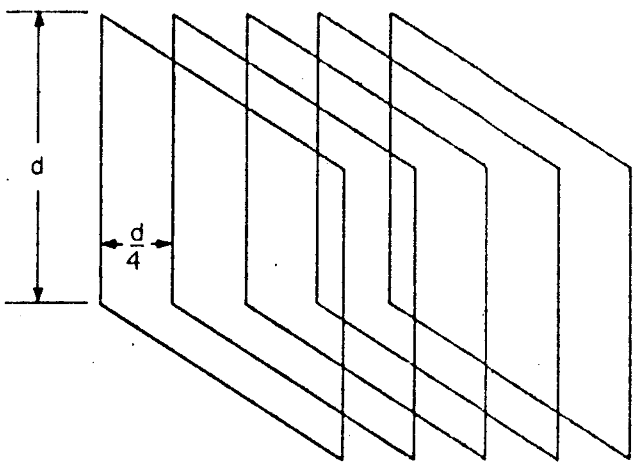


DECLINATION MEASUREMENT
(NORTH OF MAGNETIC EQUATOR)



INCLINATION MEASUREMENT
(NORTH OF MAGNETIC EQUATOR)

FIGURE A1

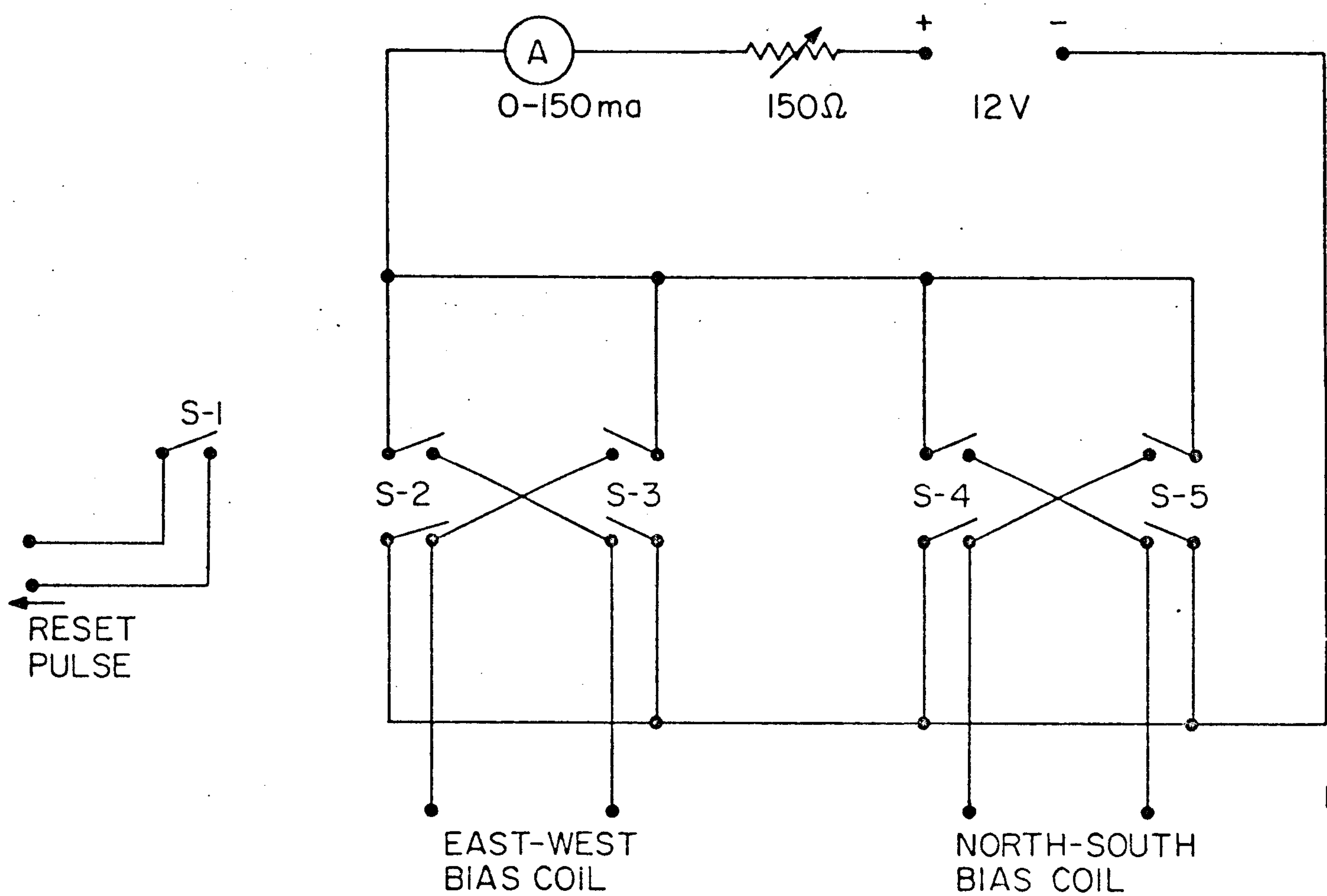


RUBENS COIL

One of two sets of coils to provide two orthogonal bias fields

19 4 10 4 19 Turns (Windings in series)

FIGURE A2

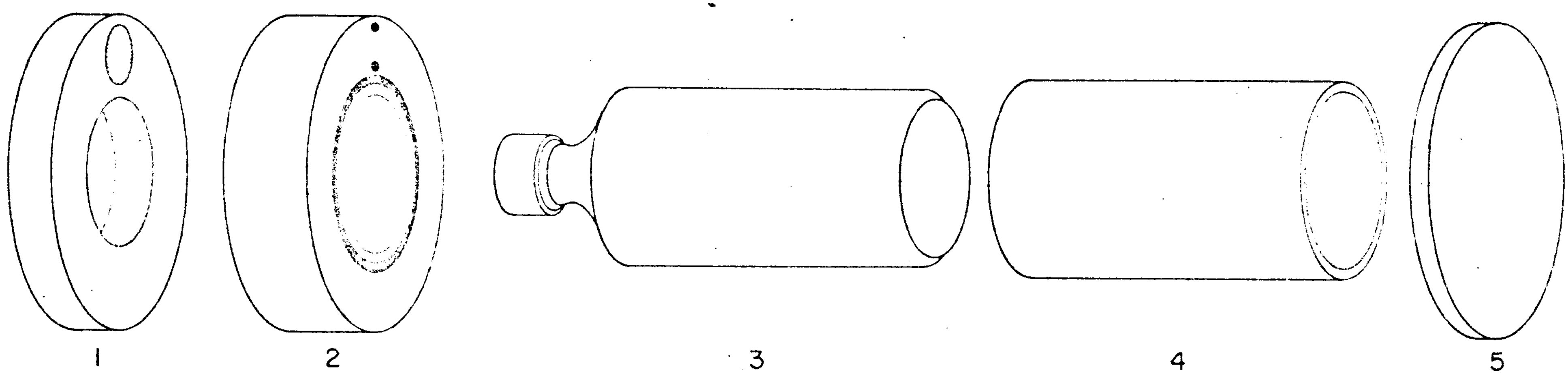


NOTE

1. Switches operated by 60cps, 1rpm synchronous motor driven cams.
2. Front panel switches in parallel with micro switches 1 to 5.

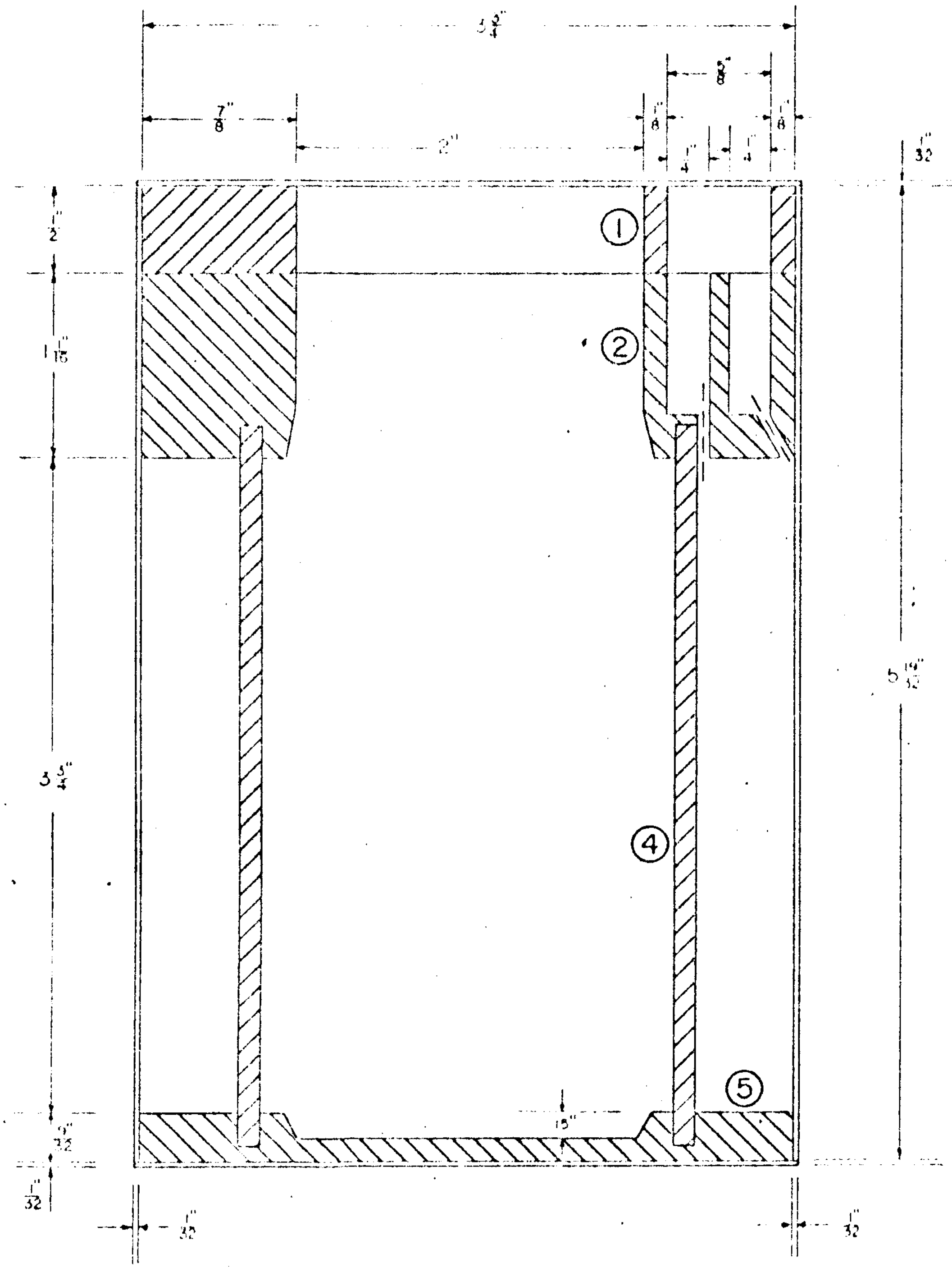
FIGURE A-3

BIAS PROGRAMMER FOR VECTOR MAGNETOMETER



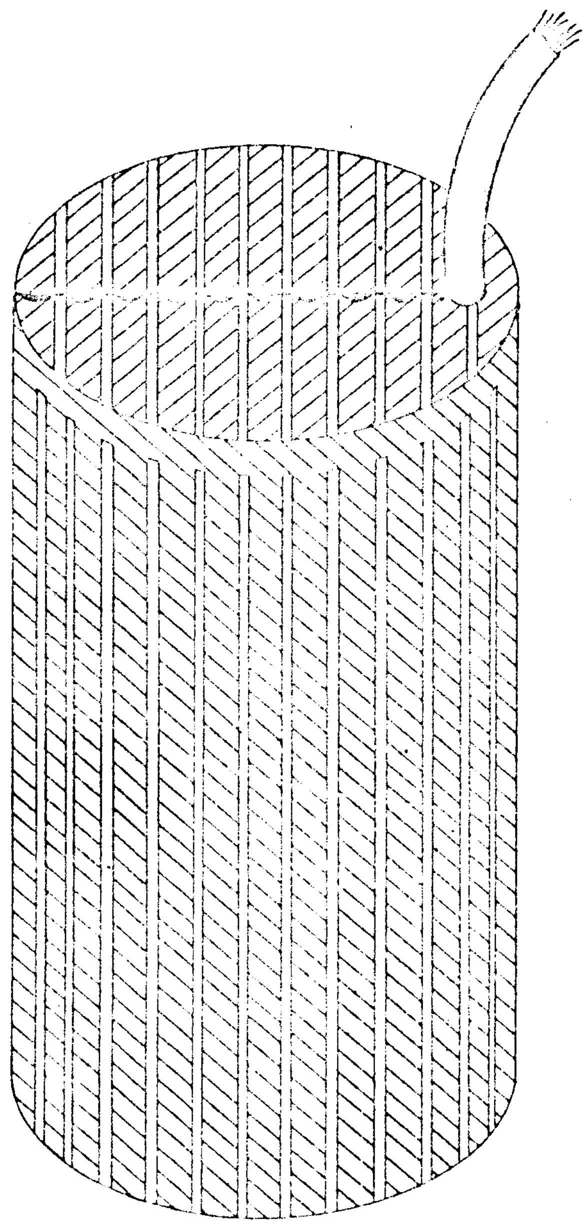
COMPONENT PARTS OF COIL ASSEMBLY

FIGURE B1



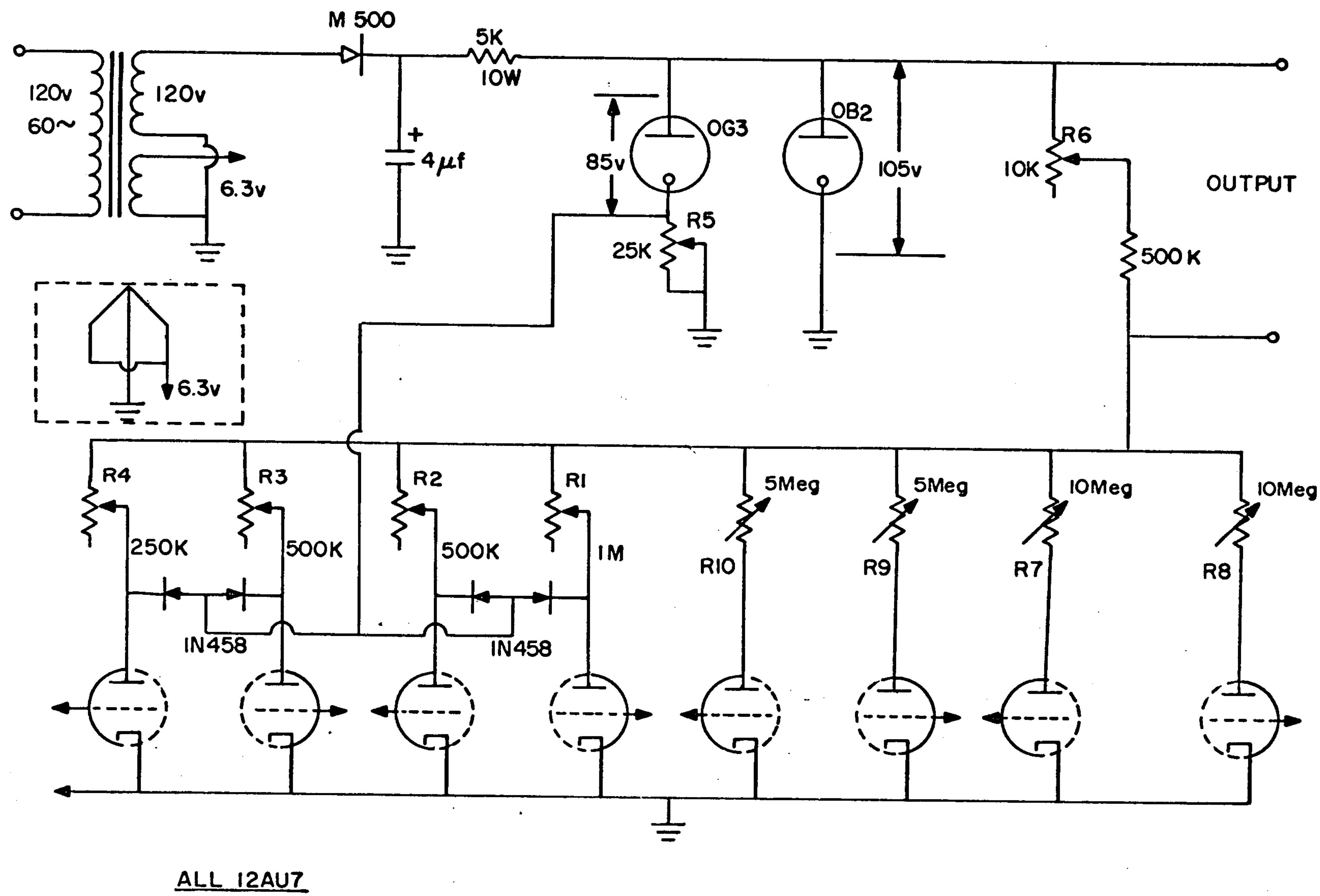
CROSS SECTION OF COIL ASSEMBLY

FIGURE B2



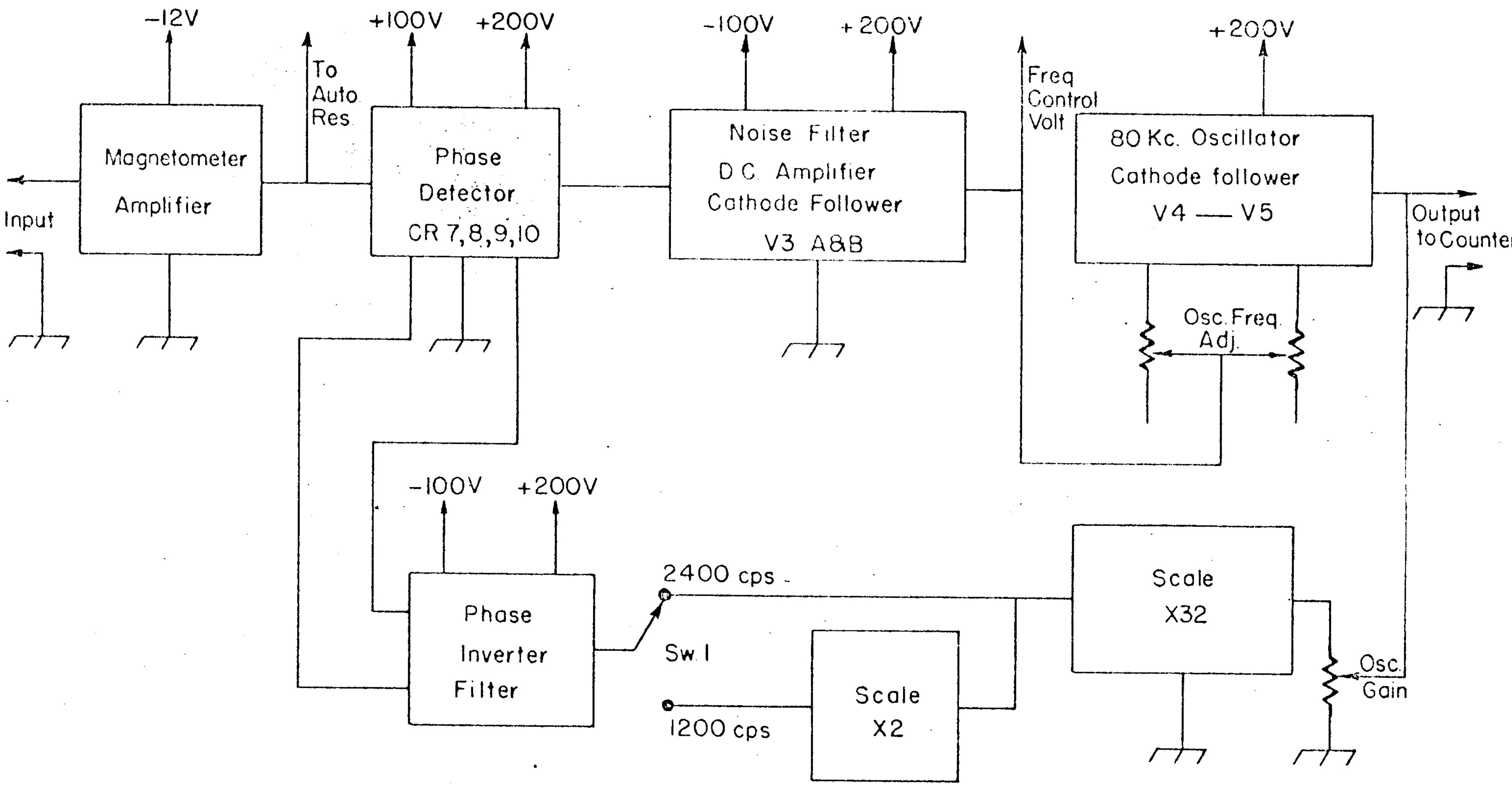
SENSOR WITH ELECTRO STATIC SHIELD.

FIGURE B3

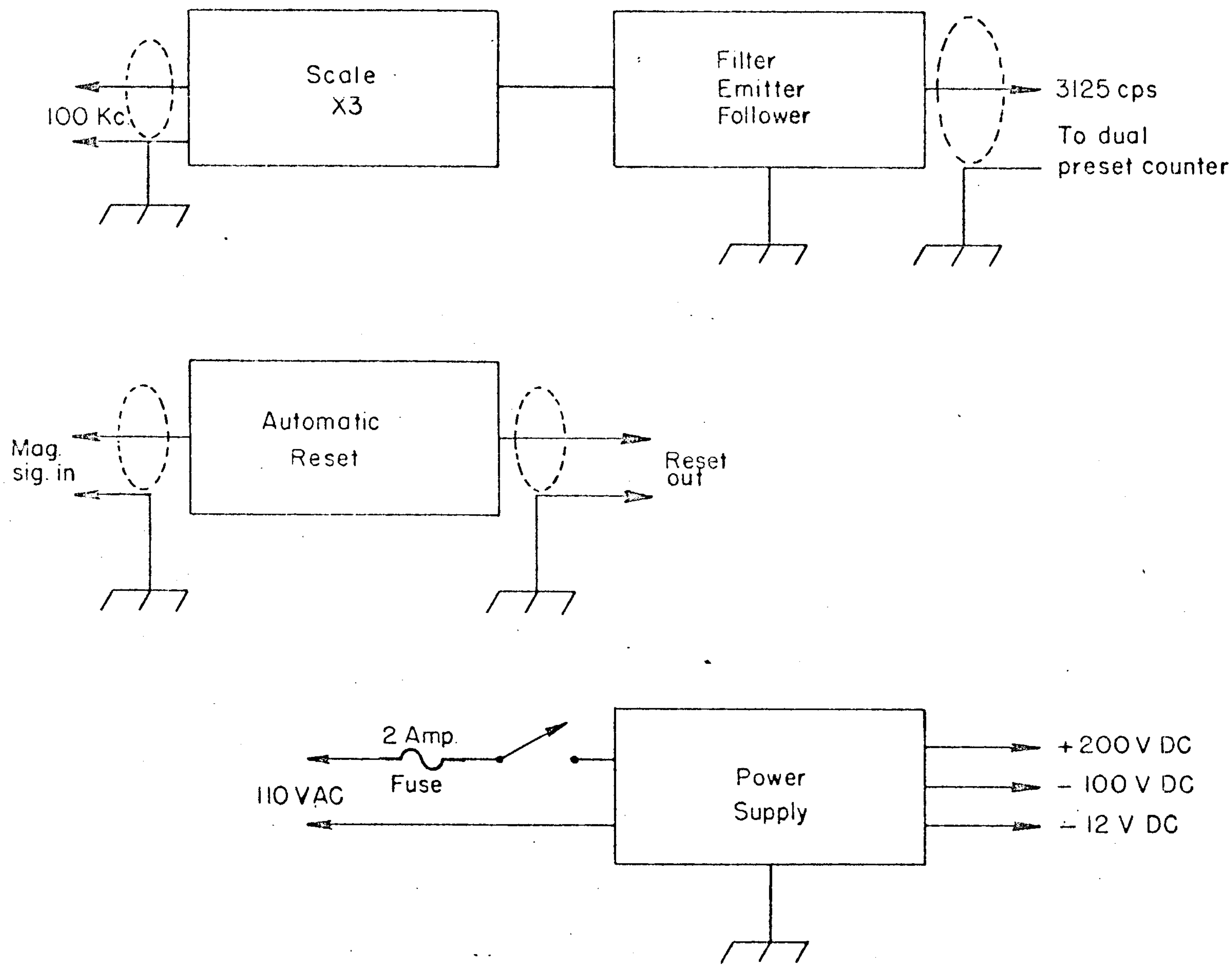


DIGITAL-ANALOG CONVERTER
FOR BERKELEY 7250R

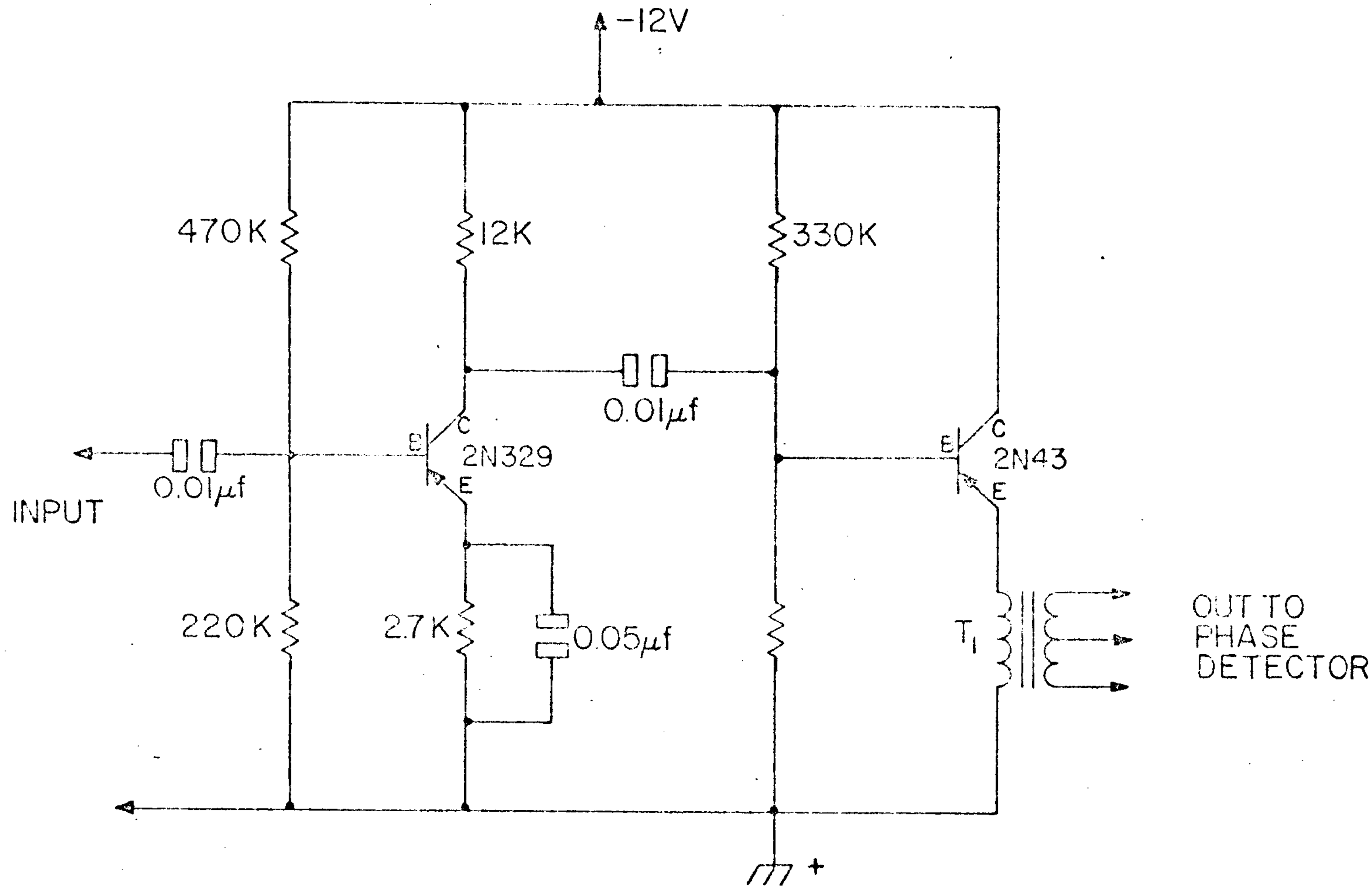
FIGURE C1



DIRECT READING PROTON MAGNETOMETER
FIGURE I

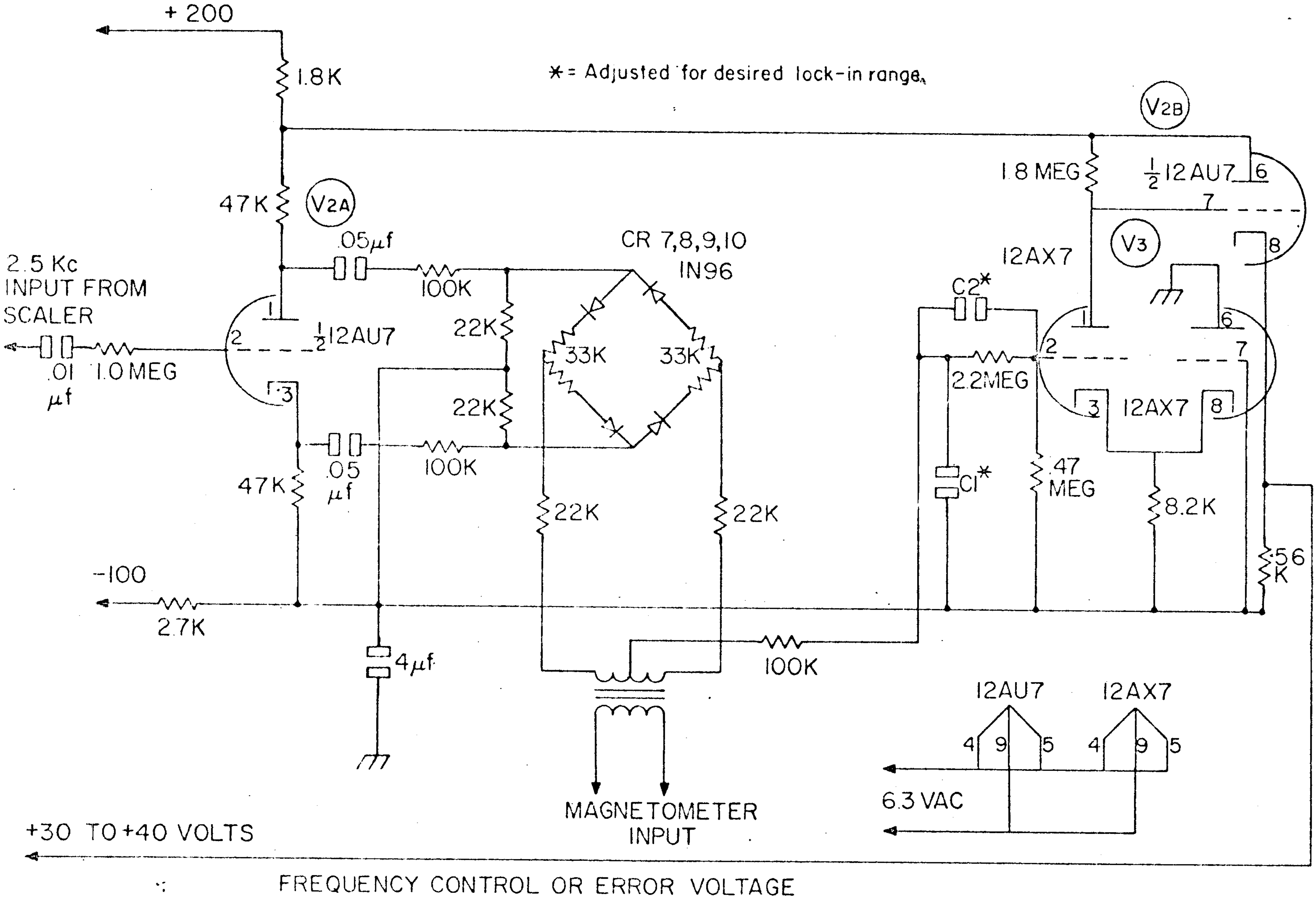


MAGNETOMETER CABLE CONNECTIONS
FIGURE 2

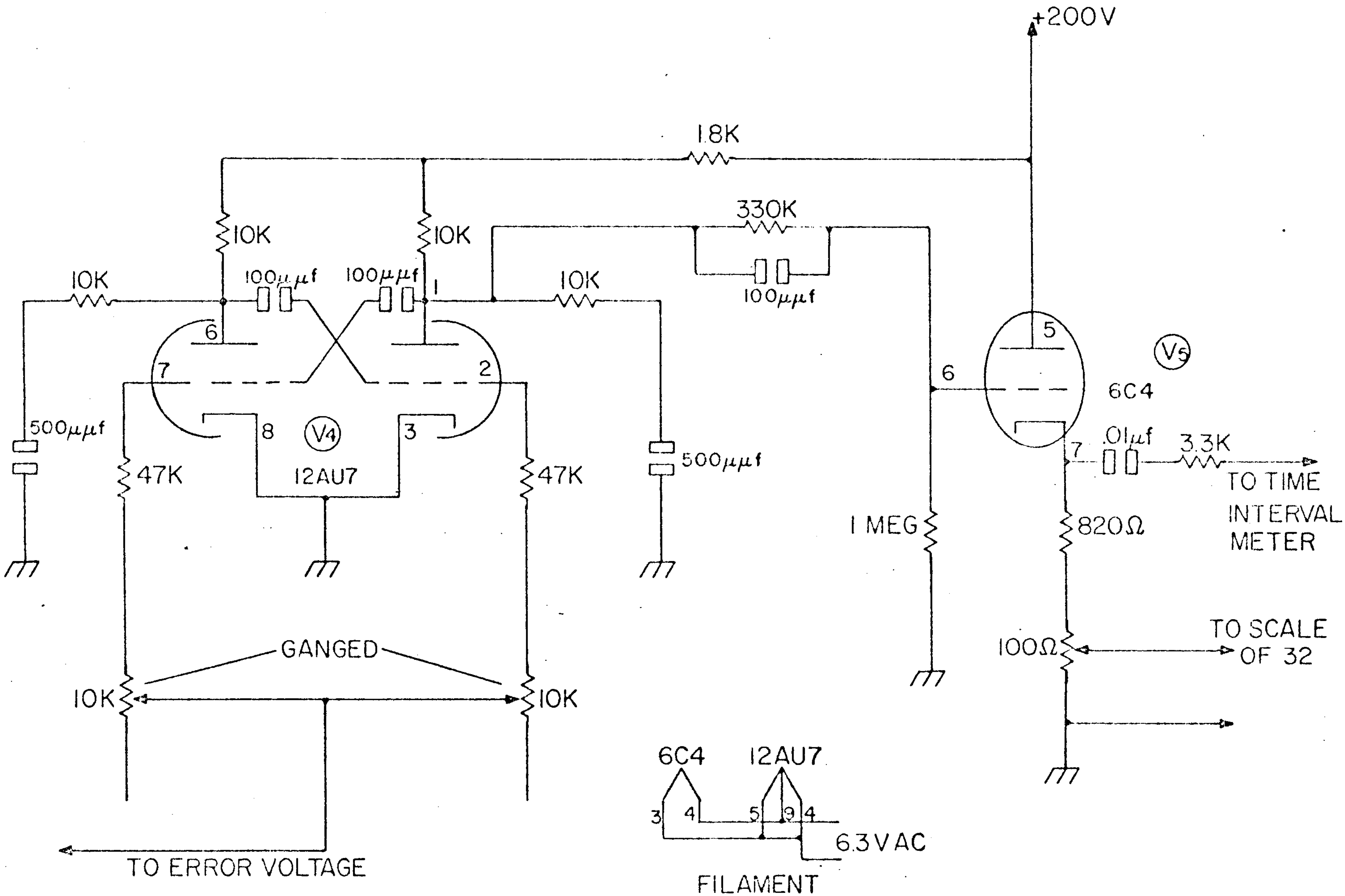


MAGNETOMETER AMPLIFIER

FIGURE 3

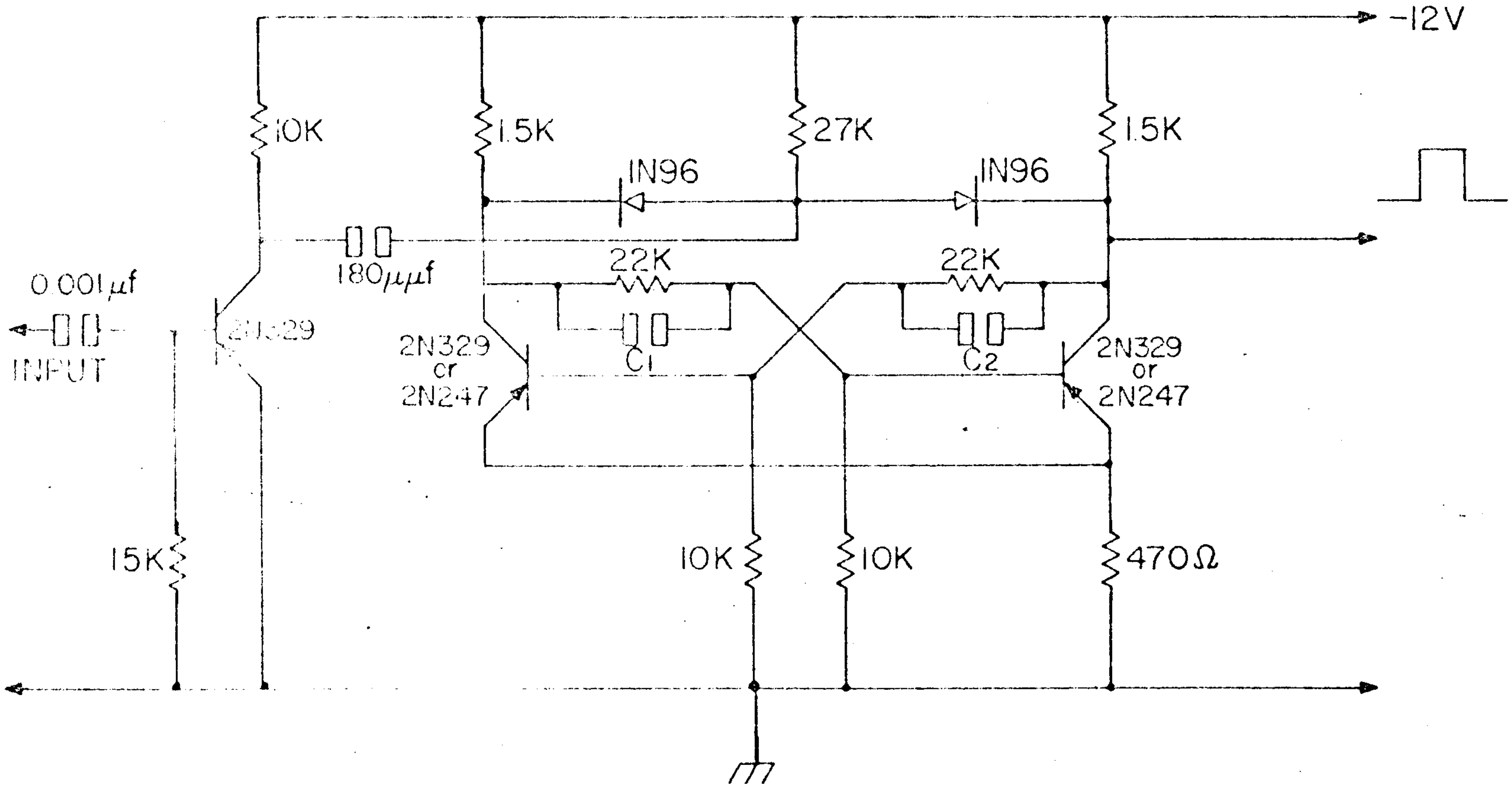


PHASE DETECTOR
FIGURE 4



80 Kc MULTIBRATOR

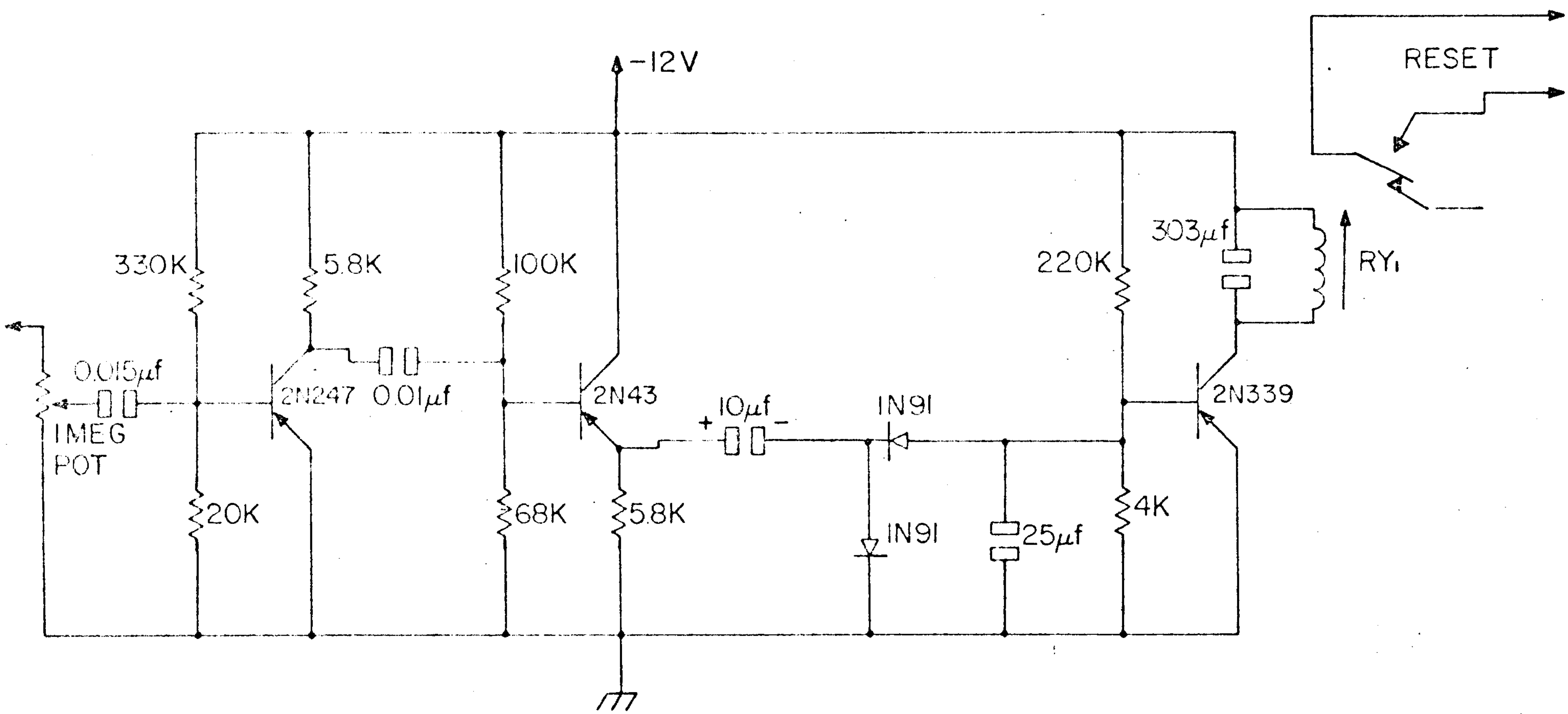
FIGURE 5



C_1, C_2 – 40Kc AND ABOVE = 100μμf, BELOW 40Kc = .001μf

BASIC SCALE OF 2

FIGURE 6



MAGNETOMETER RESET DISCRIMINATOR

FIGURE 7

NONDISSIPATIVE SOLAR ARRAY
OPTIMUM CHARGE REGULATOR

FINAL REPORT

Errata Sheet

Page 2-4:	Line following equation 2-11 should read, "The relationships derived ..."
Page 2-6:	Figure referred to in title block of Figure 2-5 should be Figure 2-4.
Page 2-10:	Equation 2-16 should read $\Delta I_B = \ldots$
Page 3-3:	In Figure 3-2, the resistor across the base-emitter of Q1 should be 100 ohms not 100 K ohms. Also, the resistor in the collector of Q5-Q6 should be 3.3 ohms not 3.3 K ohms.
Page 3-13:	In Figure 3-9, the resistor in the collector of Q4 should be 51 ohms not 51 K ohms. The capacitor in the collector of Q5 should be .022 uf, not .002 uf. The input voltage at the left of R1 should be V_{in} and not V_{10}.
Page 3-18:	The 2N2219 transistor which is designated Q1, should be designated Q4.
Page 3-19:	In Figure 3-14, the resistor in series with the 1N2929 should be 200 ohms and not 200 K ohms. The resistors in the emitters of Q1 should be 226 ohms and not 226 K ohms.
Page 3-25:	Figure 3-19c is incorrect and should be inverted.
Page 3-27:	In Figure 3-20, a tie should be placed at the junction of the 20 K resistor, the cathodes of two diodes, and the 510 pf capacitor in FF3 and FF4.
Page 3-29:	In Figure 3-21 and 3-22, the core numbers were omitted. In both cases they are Magnetics Inc. Number 50007-1D.
Page 5-3:	The title of Table 5-1 should read: Case I, Orbit A, (418 cycles per year).
Page 5-4:	The title of Table 5-2 should read: Silver-zinc cell ... The title of Table 5-3 should read: Silver-cadmium cell ...