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DEVELOPMENT OF SINGLE-COMPONENT MAGNETOMETER HeliFlux® SENSOR TYPE MODEL CRC-IX

FINAL REPORT

ERICK O. SCHONSTEDT
SCHONSTEDT ENGINEERING COMPANY
SILVER SPRING, MARYLAND
DECEMBER 15, 1961

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PROJECT NO. 7601 TASK NO. 76018

PREPARED FOR
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GEOPHYSICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
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AFCRL 1099

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Bedford, Massachusetts

ABSTRACT

The purpose of the work under Contract AF19(604)-2139 was to develop a portable, single-component magnetometer of the second-harmonic type using the HeliFlux sensor to be used for recording the time variations of the Earth's magnetic field. In the resulting transistorized Model CRC-IX Magnetometer, the major portion of the ambient field is nulled out by controls which may be used to adjust the center-scale value of the recording meter to any value between 0 and 75,000 gammas in 25-gamma steps. Time variations of the magnetic field may then be read with an accuracy of ± 1 gamma or better when the instrument is operated at its maximum sensitivity of ± 50 gammas full scale at a constant temperature between 20°F and 100°F. Temperature drift is 0.1 gamma or less per degree Fahreheit in this range. Lower sensitivities are also provided. The magnetometer is not intended to be an absolute measuring device and the accuracy with which the center-scale value of the meter is set is ± 1 per cent. However, the 25-gamma steps used for adjusting this value are sufficiently small so that the full sensitivity of the instrument can be utilized for the time variations measurements in any ambient field likely to be encountered, providing these variations do not exceed the ± 50 gammas full-scale values.

MAGNETOMETER

Figure 1 is a photograph of the magnetometer system, Shown in the central part of the photograph is the control box which houses a decade resistor network and the electronic circuits. The probe, or field sensor, is shown mounted in a stand by means of which the probe can be oriented at any angle. Variations of the Earth's magnetic field about some ambient magnetic field level are registered on the chart recorder and indicated on the panel meter of the control box.

The ambient component of the Earth's magnetic field is neutralized by means of a precisely-controlled current that is passed through a solenoid of the probe which surrounds the magnetic detection element. The intensity of the solenoid current, stated in terms of gammas of field neutralized, is indicated by the settings of the knobs of the decade resistor network.

A sensitivity switch is provided on the control unit for adjusting the scale sensity of the zero-center recorder at 50, 250, 500 and 5000 gammas.

The magnetometer operates from either a 24-volt source or a 12 and 24-volt source. A small saving in power can be realized by using the dual-voltage source. The current drain of the magnetometer when using the single 24-volt source is of the order of 30 milliamperes.

FLUX GATE

The heart of the magnetometer is the helical-core field sensing element which has been patented by E. O. Schonstedt (1), (2).

The core of the element, shown in the photograph, Figure 2, consists of two thin strips of permalloy that have been interwoven about a ceramic tube. The core is annealed in a hydrogen atmosphere to obtain the properties of a high permeability and low coercive force.

FIGURE 2

SENSOR CORE

Figure 3 is a photograph of the parts which comprise the magnetic field sensor assembly.

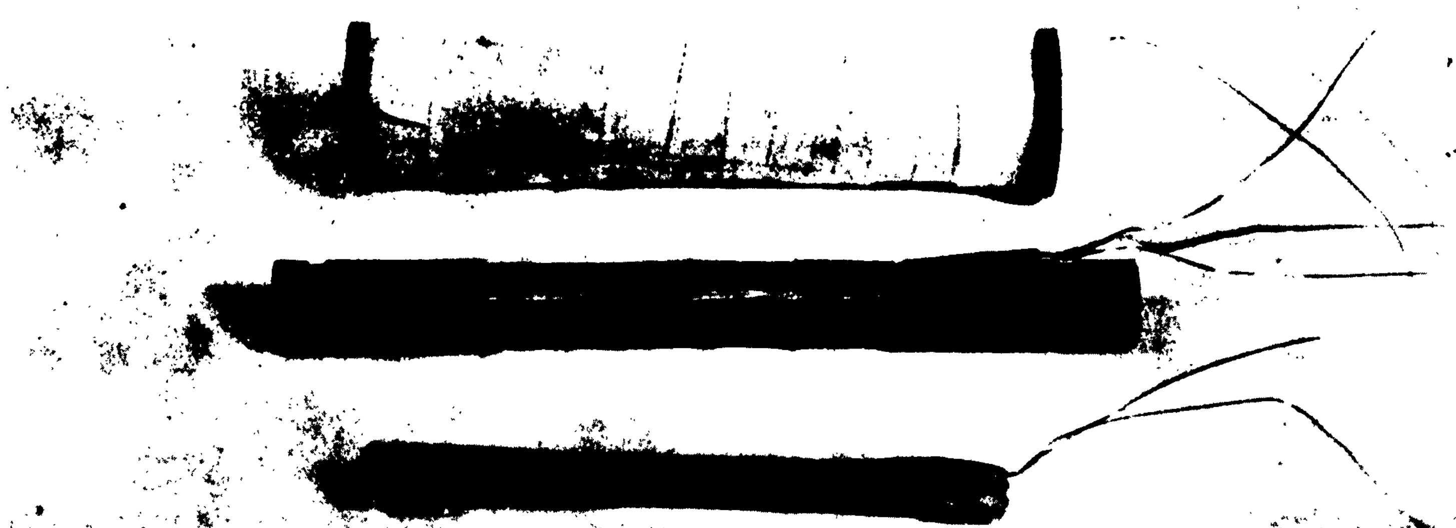
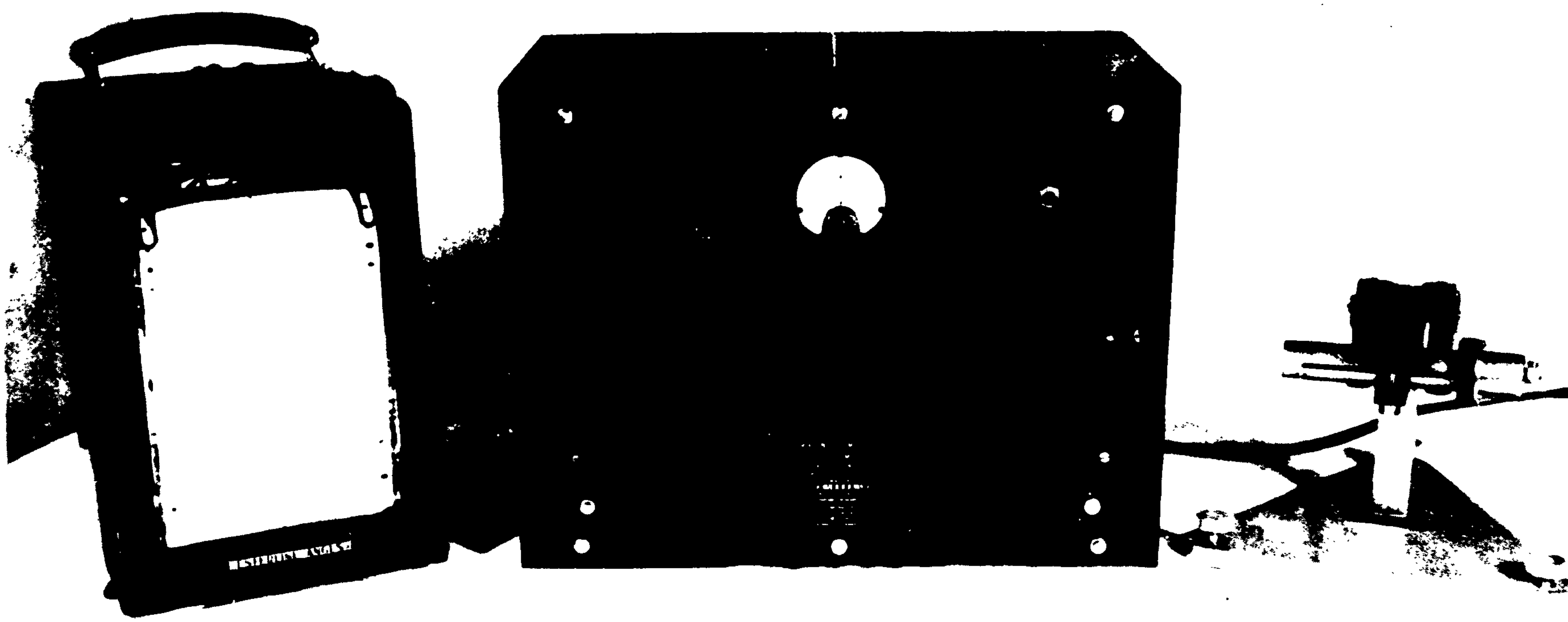


FIGURE 3

SENSOR COMPONENTS



RECORDER ELECTRONIC AND CONTROL UNIT SENSOR UNIT

FIGURE I

CRC-IX MAGNETOMETER SYSTEM

In the lower part of Figure 3, the core of Figure 2 is shown with a toroidal winding added to it. This winding is referred to as the excitation winding. The ends of the core are fitted with slotted nylon ferrules to keep the excitation winding from contacting the permalloy and to provide a supporting means for the core.

The nylon ferrules of the core assembly closely fit the bore of a phenolic tube which carries the signal pickup winding. This tube is shown in the center of Figure 3.

The phenolic tube in turn is fitted into the neutralization solenoid. This solenoid, shown at the top of the photograph, has its winding supported by a glass tube that has a low thermal coefficient of expansion. The coil constant of the neutralizing solenoid is a function of the length of the solenoid; hence, its dimensional stability is critical.

In the operation of the sensor, a 5,000 cps current is passed through the toroidal excitation winding that surrounds the core. The current is of sufficient amplitude that the alternating magnetic field associated with the current cyclically drives the core into magnetic saturation. Owing to the unique design of the core, the flux generated in the core of the fundamental (5kc) frequency is, to a large extent, decoupled from the signal pickup winding. The existence of a magnetic field magnetizing the core along its length results in the generation of second-harmonic (10kc) fluxes which cut the turns of the pickup winding so as to generate second-harmonic voltages therein. For weak fields such as that of the Earth, the second-harmonic voltage generated in the pickup winding is proportional in amplitude to the intensity of the component of field magnetizing the core.

The physical process of second-harmonic field detection involved is generally of the type described by Felch and others (3) and Rumbaugh and Alldredge (4). The specific and unique details of the operation of the helical core sensor can be obtained from the Schonstedt patents (1),(2).

MAGNETOMETER SYSTEM

Figure 4 is a block and circuit diagram of the magnetometer. The signal-generation portion of the circuit starts with a 5 kc tuned-collector oscillator. The output of the oscillator is power amplified before being fed to the excitation winding of the magnetic field sensor.

The two outer ends of the center-tapped signal pickup winding are connected to the push-pull input stage of a three-stage amplifier. The centertap of the signal winding is grounded through a large capacitor.

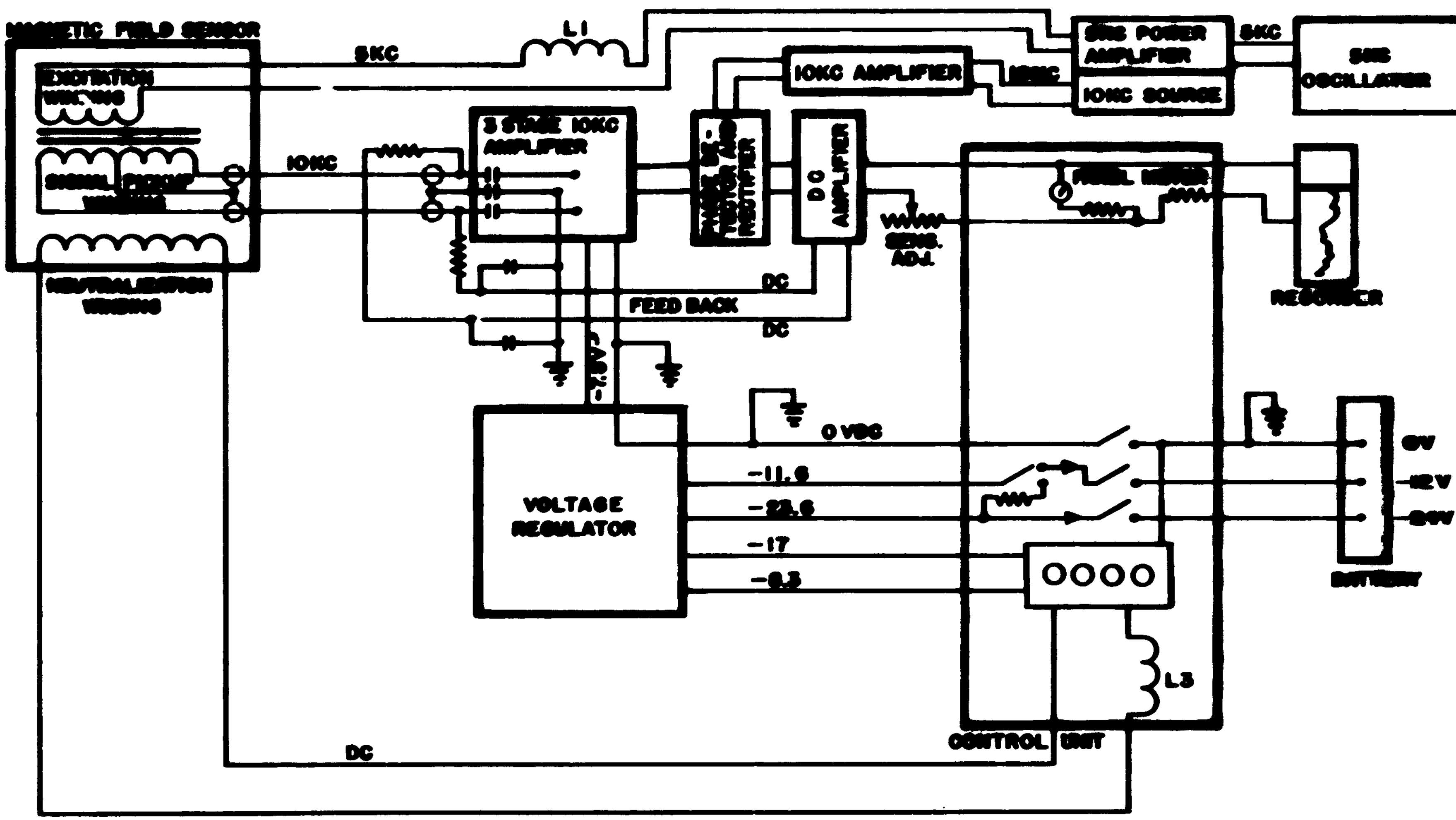


DIAGRAM OF MAGNETOMETER CIRCUIT

FIG. 4

The three stages of the 10kc signal amplifier are transformer coupled and tuned to the second-harmonic frequency.

The output of the third amplifier stage is connected to a phase-sensitive rectifier where the ac signal is converted into a dc current.

A second-harmonic reference voltage, required for the operation of the phase-sensitive rectifier, is generated across a common emitter resistor in the push-pull 5kc power amplifier of the excitation circuit. These second-harmonic pulses are amplified in a single-transistor amplifier having in its collector circuit a transformer that is tuned to the 10 kc frequency.

The dc output of the phase-sensitive rectifier is power amplified in a push-pull emitter-follower circuit to drive the indicating meter and recorder. A part of the dc current produced in the emitter-follower circuit is fed through the signal-pickup winding of the field sensor to provide negative feedback for stabilizing the signal circuit.

The ambient value of the Earth's magnetic field is neutralized around the core of the field sensor by means of a calibrated dc current maintained in a neutralizing solenoid surrounding the field sensor. The current is fed to the neutralizing coil by way of a precision decade resistance box. The decade box is calibrated in terms of the field neutralized.

OSCILLATOR AND POWER AMPLIFIER

The oscillator and power amplifier are diagrammed in Figure 5. The oscillator is of a tuned-collector type and is comprised of the circuitry involving transformer T1 and transistor TR4.

The primary of transformer T1 is tuned to a frequency of 5,000 cps by means of capacitor C4. Temperature compensation of the circuit is achieved in part by means of resistor R16 and thermistor TR2 in series across the primary of T1. Additional compensation is provided by thermistor TR1 in parallel with R13 in the base circuit of TR4. This compensation arrangement is designed to keep the output of the power amplifier at a constant level.

The opposite ends of the split secondary of transformer T1 are connected to the bases of TR5 and TR6. The level of drive of the power amplifier is adjusted initially in the selection of the value of R18.

Emitter resistor R19 serves two purposes. One purpose is to provide a means by which the operation of TR5 and TR6 can be observed. TR5 and TR6 should be fairly closely matched

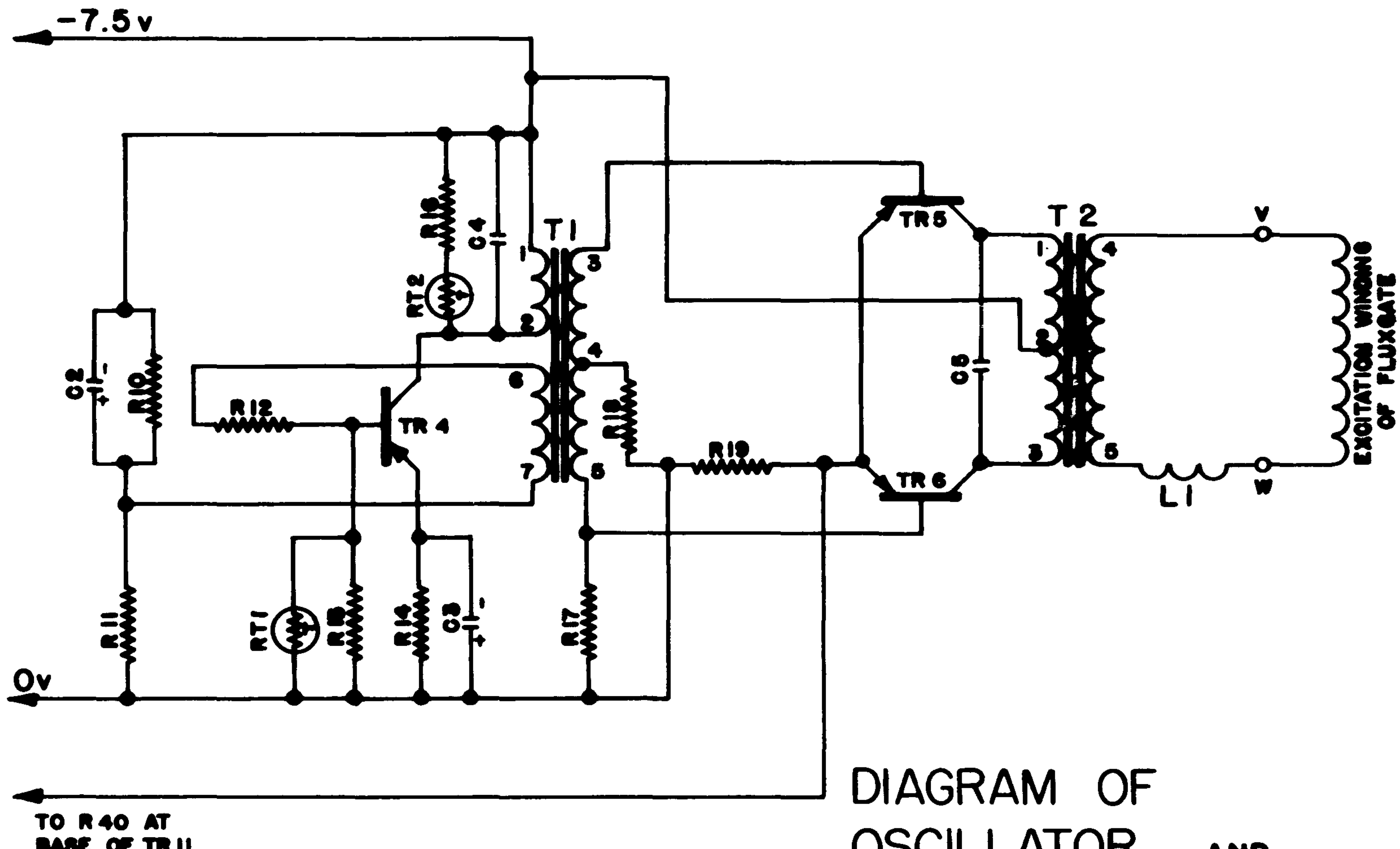


DIAGRAM OF
OSCILLATOR AND
POWER AMPLIFIER

FIG. 5

72461

pair. Since TR5 and TR6 conduct alternately, the emitter currents can be ascertained by placing the leads of an oscillator across R19.

In view of the alternate conduction of TR5 and TR6, R19 serves a second purpose, mentioned previously, in providing a source of second-harmonic voltage for use in developing the second-harmonic reference voltage required for operation of the phase-sensitive rectifier.

Capacitor C5 provides for tuning the primary of the power amplifier transformer T2 to the second-harmonic frequency. When C5 is at the proper value for parallel resonance of T2 at the 5kc frequency, the phase of the voltage generated across R19 is not the most suitable for operation of the phase-sensitive rectifier. In order to obtain the proper phase angle of the second-harmonic reference frequency, capacitor C5 must be adjusted to detune the circuit somewhat.

The flux gate excitation current is furnished from the secondary of T2. The inductor L1 in series with the flux gate provides additional inductance to the circuit. Without inductor L1, the power amplifier could assume one of two modes. In one mode, the flux gate would appear to the circuit as a largely resistive load, the state which exists when the flux gate is saturated. In the other mode, the flux gate would appear in the circuit as a largely inductive load, the state which exists when the flux gate is unsaturated. The two modes are vastly different in so far as power output from the amplifier is concerned.

SIGNAL AMPLIFIER

Figure 6 is a diagram of the signal amplifier. The pickup winding of the flux gate is tuned to parallel resonance at the second-harmonic frequency by means of capacitor C8. Resistor R20 loads the flux gate to prevent the combination of the flux gate inductance and capacitor C8 from becoming a self-oscillating circuit. Without this resistor, self oscillation can occur under certain conditions which depend upon the circuit constants and the amplitude of the excitation current.

The push-pull input represented by TR7 and TR8 eliminates the necessity for an input filter to clean up the wave form obtained from the flux gate. Some fundamental-frequency signals are generated in the flux gate pickup winding that are not completely eliminated by tuning the flux gate. The effect of this fundamental-frequency input, is to make the magnetometer circuit slightly less sensitive to input signals of one phase as contrasted to input signals of the reverse phase.

DIAGRAM OF SIGNAL AMPLIFIER CIRCUIT

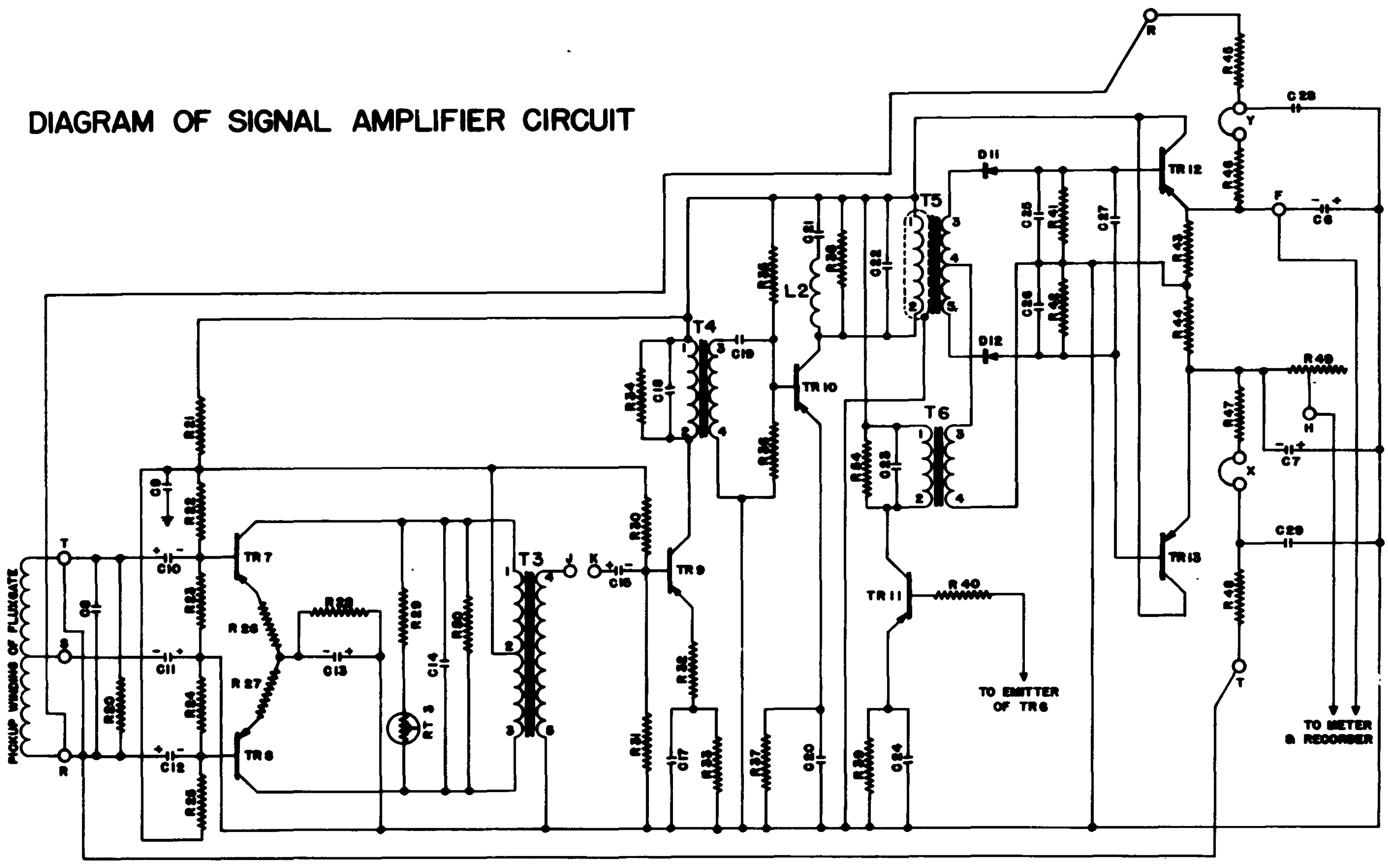


FIG. 6

Compensation of the circuit to minimize variations of sensitivity with temperature is accomplished by means of the resistor and thermistor in series across the primary of transformer T3. Interstage coupling transformers T3, T4, and T5 are designed to have a Q of approximately 10 as a compromise between filtering ability and gain stability for slight changes in oscillator frequency. For purpose of impedance match, T3 has a stepdown ratio from primary to secondary of five to one.

Adjustment of the sensitivity of the circuit is achieved between the secondary of T3 and the base of TR9. Points J and K are directly connected for the 50-gamma range of the magnetometer. For the 250, 500 and 5000-gamma ranges, the appropriate voltage divider is switched into the circuit.

The primary of T4 is tuned to parallel resonance at the second-harmonic frequency by capacitor C18. Resistor R34 is employed to reduce the gain of the stage so as to prevent self-oscillation. The step-down ratio from primary to secondary is four to one.

Across the primary of T5 there is an L-C filter that is series resonant to the third harmonic (15kc). A relatively large third-harmonic component exists in the signal output of the flux gate. A sufficient portion of this third harmonic persists up to the third amplifier stage to make the use of this filter necessary. Capacitor C22 tunes the primary to the second-harmonic frequency. Resistor R38 serves the same function as resistor R34.

The phase-sensitive rectifier has diodes D11 and D12 in series with the output terminals of the secondary of T5. The ends of the diodes are connected together through parallel resistor and capacitor combinations consisting of C25, R41, and C26, R42. The second-harmonic reference frequency is introduced by connecting one terminal of the secondary of transformer T6 to the centertap of T5 and the other terminal of T6 to the common junction of the parallel resistor and capacitor combination. This circuit is quite conventional.

Capacity coupling between the secondary and primary of T5 is undesirable as the second-harmonic reference frequency will then appear in the primary of T5. To reduce this coupling, an electrostatic shield is placed between the two windings.

Ripple in the dc signal output of the phase-sensitive rectifier is reduced by capacitor C27. One leg of the rectifier is connected to the base of transistor TR12 and the other leg is connected to the base of transistor TR13. Transistors TR12 and TR13 comprise an emitter-follower, push-pull power amplifier that supplies the power necessary to drive the chart recorder.

A part of the dc current generated in the power amplifier is fed back through the pickup windings of the flux gate to provide negative feedback for further stabilization of the magnetometer sensitivity. The values of feedback resistors R45, R46, R47 and R48 are selected when the magnetometer is set for its highest sensitivity to give a 0.5 milliampere current through the chart recorder for a field of 50 gammas on the flux gate.

Capacitors C28, C29, C6 and C7 are filter capacitors that prevent any second-harmonic content in the output of the power amplifier from being fed back through the flux gate windings.

Variable resistor R49 provides for making the final adjustment on the magnetometer sensitivity.

VOLTAGE REGULATOR

Figure 7 is a diagram of the voltage regulator. The -17 volt output is developed from a reference voltage across zener diodes D3 and D4 in series with temperature compensating diodes D5 and D6. This reference voltage is applied to the base of TR-2 and the output voltage is obtained at the emitter of TR-2 which is operated essentially as an emitter follower.

The circuitry associated with TR-1 is used to maintain substantially a constant current through diodes D3, D4, D5 and D6. The voltage change with load across R4 is coupled through zener diode D-2 to the base of the TR-1. This changes the collector current in TR-1 providing for the variation of base drive required at TR-2 as the load on the emitter of TR-2 varies.

The -17 volts developed at the emitter of TR-2 is applied to zener diode D7 through R5 to develop the -8.4 volt output. Diode D7 is a IN430A which is very accurately compensated for variations in operating temperature. For instance, the manufacturer's specification states that the maximum variation from the voltage at 25°C is ± 7 millivolts at temperature extremes of -55°C and +100°C.

The -17 volts is also applied to zener diode D8 and temperature compensating diode D9 thru resistor R6. This reference voltage is applied to the base of the emitter follower TR3. The collector of this transistor is connected to the -12 volt supply and the -7.5 volt output is obtained at the emitter of this transistor. Capacitor C1 is connected between the emitter and ground to lower the ac source impedance of the -7.5 volt supply.

DIAGRAM OF VOLTAGE REGULATOR

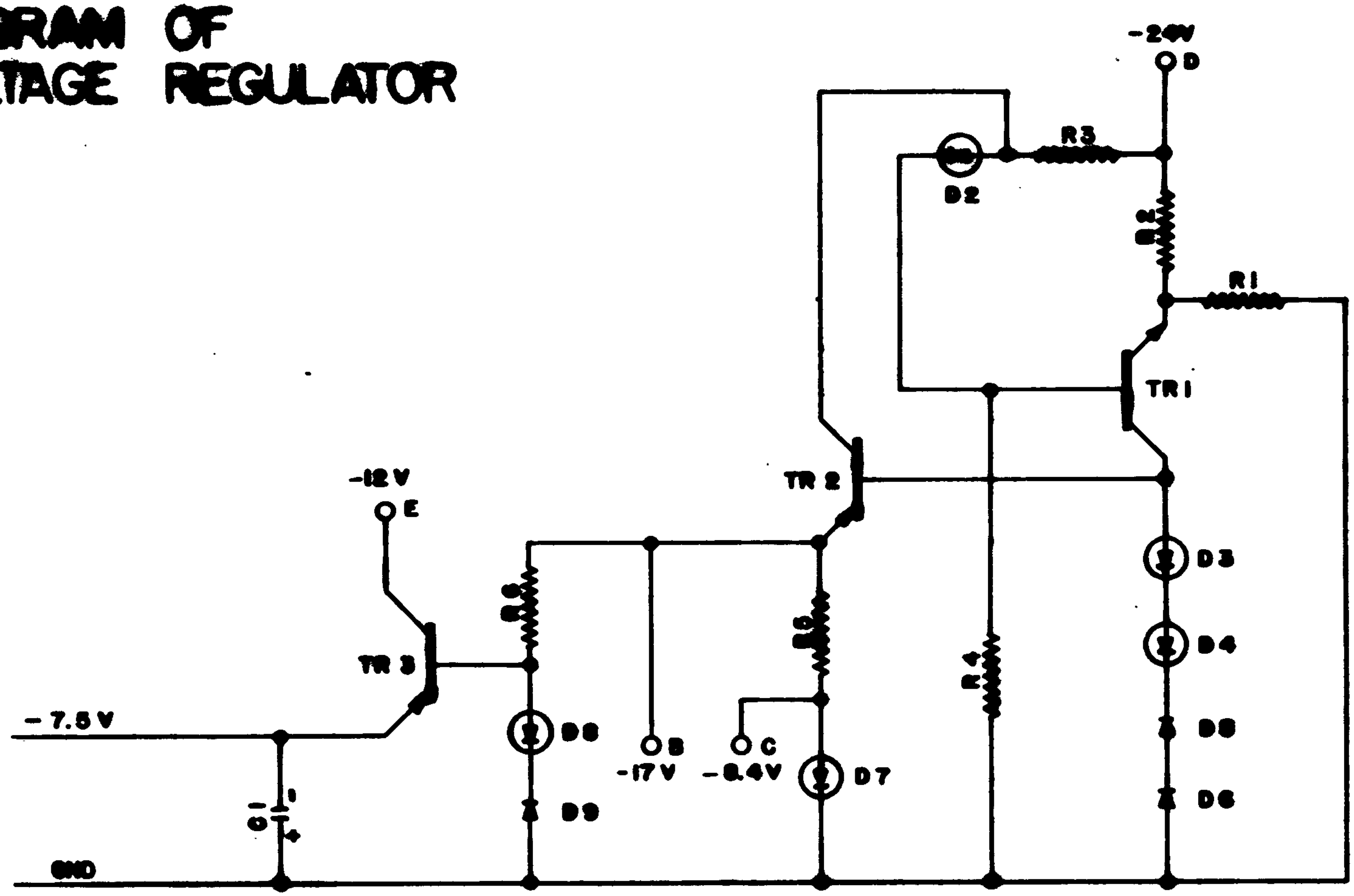


FIG. 7

CONTROL UNIT

The purpose of the control unit is to provide a precise and stable current to the neutralizing coil so as to balance the major part of the component of the Earth's field along the axis of the detector.

Figure 8 is a diagram of the control circuit. Diode D7 is the zener diode (1N430A) which has an exceptionally low temperature coefficient to provide a stable voltage source. This voltage source is connected to the flux gate neutralization winding through a network of precision resistors controlled by four switches.

Switch S5 provides five increments of current each equivalent to 25 gammas of field. Switch S6 provides ten increments equal to 100 gammas each. S7 provides ten increments of 1000 gammas each and S8 provides seven increments of 10,000 gammas each.

Because of the internal resistance of the zener diode, the current through the diode must be maintained constant at all times. This is accomplished by employing a well-regulated -17 volt source for the diode circuit and by imposing a constant current drain through the diode irrespective of the intensity of neutralizing current passed through the neutralizing winding of the flux gate.

Switches S7 and S8, which supply current in increments of 1000 and 10,000 gammas, respectively, are wired such that the current drain is essentially constant irrespective of switch position.

The current increments of S5 and S6 are so small that no compensation of current drain with switch position is required. The resistors R108, R109 and R110 in the S6 switch circuit compensate for the difference in the equivalent source resistance of the divider at the different positions of S6. These resistors permit equal values of resistance to be used in the divider. The resistor R111 is chosen to give a voltage at the bottom of the divider, point D equal to the voltage at point B.

Switches S7" and S8" and their associated resistors serve two purposes; the first of which is to maintain the voltage from point B to ground at an essentially constant value for all settings of S7 and S8. This is important if the current increments produced by a particular switch are to be independent of the settings of switches S7 and S8. The change in the voltage at B produced by changes in S5 and S6 are not large enough to require compensation.

The second purpose of switches S7" and S8" and their associated resistors is to compensate for changes in the voltage from A to ground due to changes in the -17 volt

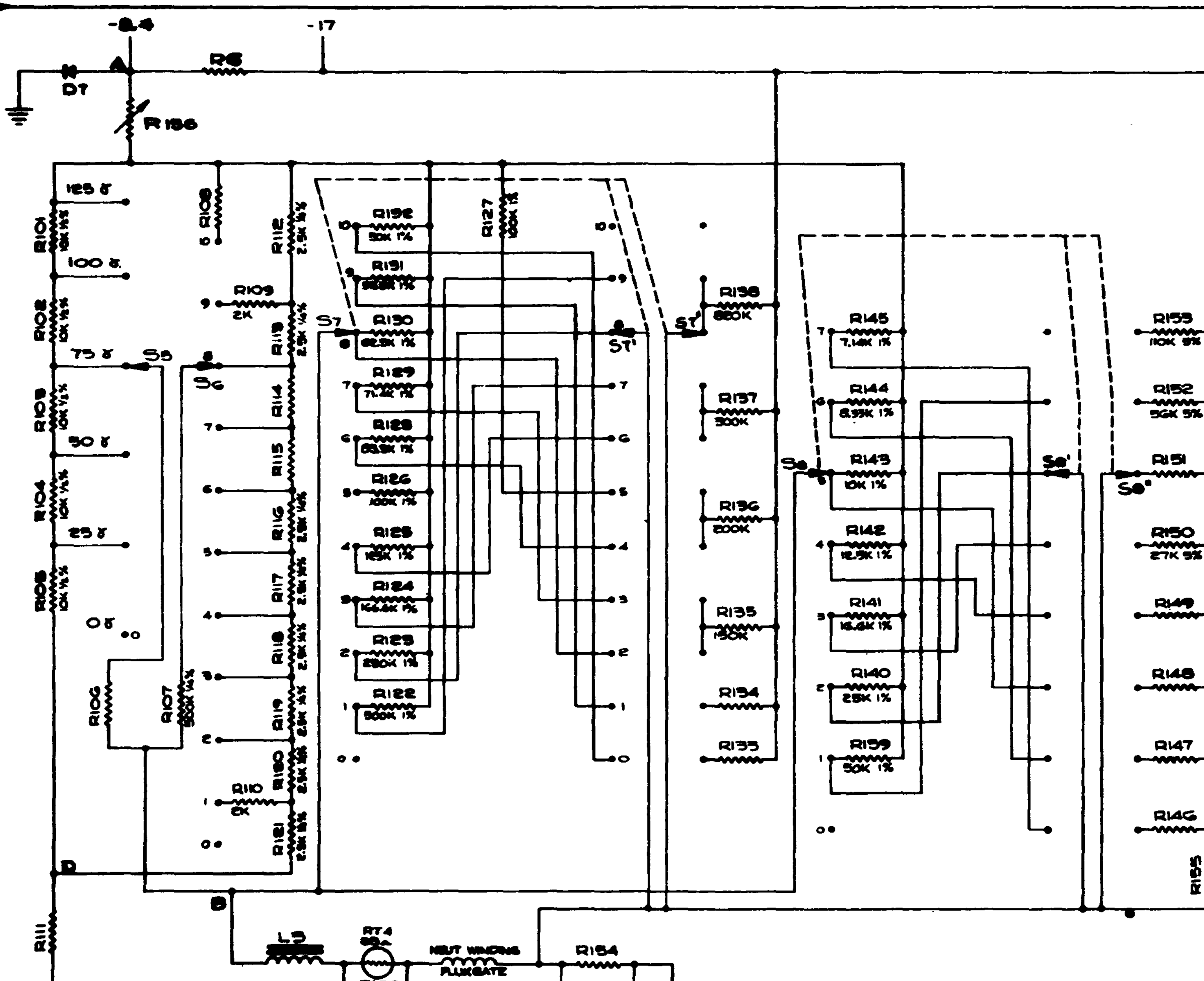


DIAGRAM OF THE CONTROL CIRCUIT

FIG. 8

supply. By proper selection of R154, the resulting bridge structure can be balanced at any desired setting of the control unit (i.e. at 50,000 γ) and the current through the neutralizing coil is then independent of variations in the -17 volt supply. At other settings of the control unit, the bridge is no longer balanced, but produces a considerable reduction in neutralization current changes caused by changes in the -17 volt supply.

Resistor R156 is selected so that the field produced by the neutralizing coil agrees with the values indicated by the control dials of the control unit. The nominal value of the coil constant is 1.5×10^{-6} ampere per gamma.

Thermister RT4 and its parallel resistor compensate for changes in resistance of the neutralizing coil and inductor L3 with temperature. The inductor is needed to provide a high impedance for the ac voltages induced in the neutralizing coil.

GENERAL DISCUSSION

For proper operation of the magnetometer it is essential that the flux gate operate properly. Besides any general design considerations, it is important that the permalloy core have no stresses due to mishandling. Evidence of such mishandling consists of an excess of out-of-phase (quadratue) second-harmonic voltage appearing across the primary winding of T5 of the third stage of the signal amplifier. This voltage will appear as a null voltage and should not exceed 0.5 volts before the feedback is introduced into the system.

The problem of stray pickup of second-harmonic frequency by various parts of the signal amplifier was a problem. This stray pickup was minimized by the use of very heavy bus bars for the ac ground circuits (0 volts and -7.5 volts). A screen wire electrostatic shielding in the control unit case provides an important low resistance ground circuit that significantly reduces the ground resistance that would normally be provided only by the ground wire of a cable which connects the electronic unit to the control unit.

Without the elaborate grounding system, a small zero shift would occur when changing from one sensitivity range to another. This is due in part to the pickup which occurs in the sensitivity-changing circuit. Owing to the requirement for the 5000-gamma range, the signal sensitivity circuit had to be placed between the first and second stages of the signal amplifier. Had this range been eliminated, the sensitivity adjusting circuit could have been placed between the second and third amplier stages where stray pickup would be less serious. A 5000-gamma sensitivity could not be achieved by an adjustment between the second and third stages as the second stage of the amplifier would saturate before a full-scale reading could be obtained.

The method for generating the second harmonic reference frequency, though simple in circuitry, was not completely ideal. In order to achieve the proper phase relationship between the signal frequency and the reference frequency, it was necessary to detune the power amplifier to some extent. Though not ideal, the system was satisfactory.

The contract specified the following critical requirements:

1. Noise level and drift not to exceed 0.5 gamma for a period of one minute while operating at any constant temperature between the range of 20°F to 100°F.

2. Drift rate while operating at a constant temperature between 20°F to 100°F not to exceed 5 gammas per hour and 20 gammas per 24 hours.

3. Drift due to change in temperature not to exceed one gamma per degree F.

With regard to items A and B, test indicated the drift to be less than one gamma during any part of a 24-hour period. The noise level as observed by the indication meter or chart recorder was less than 0.5 gamma.

With regard to item C, drift with temperature was 0.1 gamma or less per degree Fahrenheit.

All other technical specifications were achieved.

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