A technical manual for the portable transistorized infrared detector

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RADIO AND ELECTRICAL ENGINEERING DIVISION

A TECHNICAL MANUAL
FOR
THE PORTABLE TRANSISTORIZED INFRARED DETECTOR

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OTTAWA

AUGUST 1961

ABSTRACT

A portable, transistorized, infrared detector is described. A method of automatic balancing is included which permits operation for longer periods without adjustment. Power consumption of only 100 mw is achieved by using transistorized circuitry and no optical or mechanical chopper. Operating and maintenance instructions are given.

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A TECHNICAL MANUAL
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THE PORTABLE TRANSISTORIZED INFRARED DETECTOR

- J. Humphries -

INTRODUCTION

The ability to detect objects whose surface temperature is effectively different from that of their surroundings is becoming increasingly important in industry, medicine, and in the field of military science and space research. A review of applications in numerous scientific and industrial fields is given in Reference 1.

Many of the instruments designed to detect and measure infrared radiation are substantial in size and are operated by a-c mains power. The field of our interest has been limited to very portable instrumentation operating with minimum power from self-contained batteries. Originally, these detectors were developed to permit rapid and accurate evaluation of the condition of compression joints on high-voltage power transmission lines, where ruggedness, light weight, and simplicity were prime considerations. In the most recent, transistorized design (Plate I) which is the subject of this report, the field of application has been extended to include remote detection of vehicle movement, with the provision of alarm circuitry.

This instrument is a d-c radiometer, in that the incident radiation is not chopped before reaching the bolometric detector element. While some sensitivity is sacrificed, the elimination of choppers results in a light and very rugged instrument that can operate for at least 350 hours on two flashlight cells. Since no temperature reference is included, the instrument registers temperature differences only. Calibration for a particular application, however, will permit its use for remote temperature measurement. Initial laboratory tests indicate that an object at 65 feet, whose image completely covers the bolometer element, can be detected if its temperature differs from that of the background by approximately 0.04°F.

NATURE OF INFRARED RADIATION

All matter, with a temperature above absolute zero, emits electromagnetic radiation, known as infrared radiation. The physical laws describing the nature of infrared radiation will be presented, together with some of the factors affecting the performance of an infrared detector.

a) Planck's Law

$$W_\lambda = \frac{C_1}{\lambda^5}\left[e^{C_2/\lambda T} - 1\right]^{-1} \qquad (1)$$

where W_λ = radiant energy emitted per unit area, per unit increment of wavelength, at a wavelength λ,

T = absolute temperature (°K),

λ = wavelength of radiation, and

C_1 and C_2 = first and second radiation constants.

Planck's Law gives the relationship between radiation intensity, spectral distribution, and the temperature for a "black" body. The family of curves for equation (1) shows how W_λ increases rapidly with temperature, and how the peak of the distribution curve moves to shorter wavelengths with increasing temperature (Fig. 1).

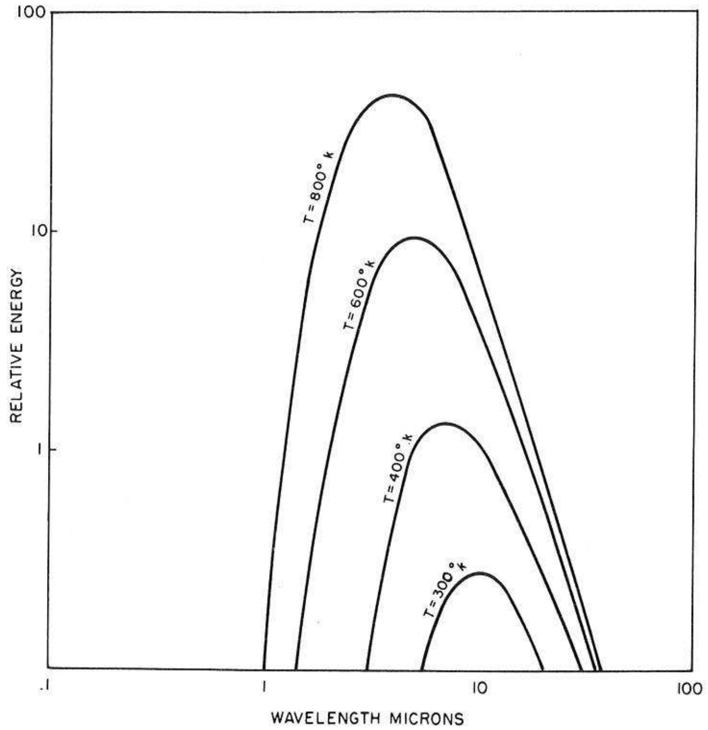

FIG. 1 INFRARED SPECTRAL DISTRIBUTION

b) <u>Wien's Law</u>

$$\lambda_m = \frac{K}{T} , \qquad (2)$$

where K = a constant = 2897 microns (°K).

This equation gives the relationship between the wavelength λ_m, where W_λ is a maximum, and the temperature of the black body. Wien's Law permits the peak of spectral distribution to be calculated readily; e.g., a man at an effective temperature of 310°K emits peak radiation at a wavelength $\lambda_m = \frac{2897}{310} = 9.3$ microns.

c) Stefan-Boltzmann Law

$$W = \sigma T^4 , \qquad (3)$$

where W = total radiant energy per unit area,
σ = a constant = 5.673×10^{-12} watts/cm^2 deg.^{4}

This law gives the relationship of the total radiant energy to the absolute temperature.

d) Lambert's Cosine Law and the Inverse Square Law

$$I_1 = \frac{WA \cos \theta}{R_1^2} . \qquad (4)$$

This expression gives the radiant intensity I_1 at a distance R_1 and at an angle θ from a plane source of area A.

EMISSIVITY

$$\epsilon = \frac{\text{radiant emittance of object}}{\text{radiant emittance of black body at same temperature}} .$$

In practice most objects radiate less energy than is predicted by the above physical laws. Such objects have emissivity factors less than that of a black body. The emissivity of a true black body radiator is, by definition, equal to unity.

ATMOSPHERIC TRANSMISSION

The atmosphere attenuates infrared radiation by absorption and scattering. Absorption is caused primarily by water vapour, carbon dioxide, and ozone. The degree of attenuation by absorption is a function of the amount of constituents present, the path length, and the spectral wavelength considered. Notable "holes" or "windows" are present in the absorption characteristics around wavelengths of 2, 4, and 10 microns.

Scattering is caused by particles in the atmosphere. These particles are present in dust, haze, smog, fog, and rain. Loss due to scattering depends on the size and concentration of particles present. Small particles cause more attenuation at shorter wavelengths than at longer wavelengths.

GENERAL DESCRIPTION OF INFRARED DETECTOR

In the instrument to be described, a 6-inch f/1 parabolic mirror is mounted in a magnesium barrel. A thermistor bolometer, located at the focus of the optical system, is sensitive to infrared radiation in the spectral region 2-20 microns. The bolometer consists of two flakes of special semiconductor material with a large negative temperature coefficient of resistance. The flakes are connected in two arms of a d-c bridge. The active flake is exposed to the received energy, while the compensating flake is used to reduce bridge unbalance caused by changes of ambient temperature.

The transistorized circuits are mounted on printed circuit boards located along the sides of the barrel under weatherproof covers. The operating controls are located on a recessed panel at the rear of the instrument (Plate II).

A 7 × 50 monocular sight, with a built-in meter movement, is mounted on top of the barrel. The sight is provided to allow accurate optical aiming and also to help identify objects as they pass through the beam.

The detector incorporates an automatic balancing system which permits the instrument to be left unattended. When operated in this mode, the system will not indicate very slow changes in background temperature but it will indicate rapid changes in radiation caused by an object passing through the beam. An audio alarm is provided to permit the instrument to be monitored at a distance.

SPECIFICATIONS

Over-all Dimensions:	Length, 12" Height, 12" Width, 16"
Weight:	16 lbs. (less tripod)
Field of View:	Standard bolometer — 0.1° × 1.5° Germanium-immersed bolometer — 0.15° × 2.25°

Ambient Temperature Range:	-20°F to 100°F
Battery Requirements:	Two "D" size mercury cells (1.35 v); life about 350 hours (100 mw) One "D" size flashlight cell for pilot light.

OPERATING INSTRUCTIONS

The instrument, mounted on a suitable tripod, should be located to provide the required coverage. Where the situation permits, the background should be carefully selected to provide maximum sensitivity. The effective temperature of the background should be stable, and differ as much from that of the target as possible. It must be remembered that the instrument has a vertical fan beam with a height-to-width ratio of 15.

The following factors should be considered:

1) Wind causes large fluctuations in surface temperature. Sheltered locations should be selected for the instrument, as well as for the background within the field of view.
2) The sun causes considerable heating of soil and foliage, the effect lasting for some time after dark. A shaded area is, therefore, preferable.

CAUTION: The instrument should never be pointed at the sun. The bolometer will be destroyed, whether or not the instrument is operating.

3) A clear sky has a low effective temperature and can be used as part of the background in certain situations; moving clouds, however, cause undesirable background fluctuations. Rainfall tends to cause a uniform background.

The monocular sight permits the instrument to be accurately aimed. When the protective covers have been removed the control panel will be accessible. The following operating procedure should be observed:

1) Set "Attenuator" to .003
2) Set "Fine Bal." near center of its range (500 on dial)
3) Turn "Selector" to "Man." position
4) Adjust "Coarse Bal." to obtain zero reading (center of scale) on panel indicator. If indicator reads to the left of center, turn clockwise; if it reads to right, turn counter-clockwise.

5) Advance "Attenuator" clockwise maintaining a zero reading with the balance controls.

Note: On those instruments using germanium-immersed bolometers, a period of five minutes may be required for the system to stop drifting.

6) A set of headphones is supplied with the instrument and should be plugged into the "Head-Phone" jack to provide an audible alarm signal. An extension may be used, if it is desirable to use the headphones at a position remote from the instrument.
7) "Selector Sw." should now be turned to "Auto Fast" or "Auto Slow" positions. If the background is sufficiently stable so that false alarms are not produced, the "Auto Slow" position should be used. For more unstable background conditions the "Auto Fast" mode is more suitable. If false alarms are still generated, "Attenuator" will have to be set to a lower gain position.
8) A meter movement is located inside the monocular sight to assist in identifying objects passing through the field of view.
9) Two "Check" positions are provided on the "Selector Sw." to measure the battery and bridge voltages. A reading of four divisions (40 μa) is normal for both.
10) The panel indicator may be illuminated by pressing the button located on the handle at the left.

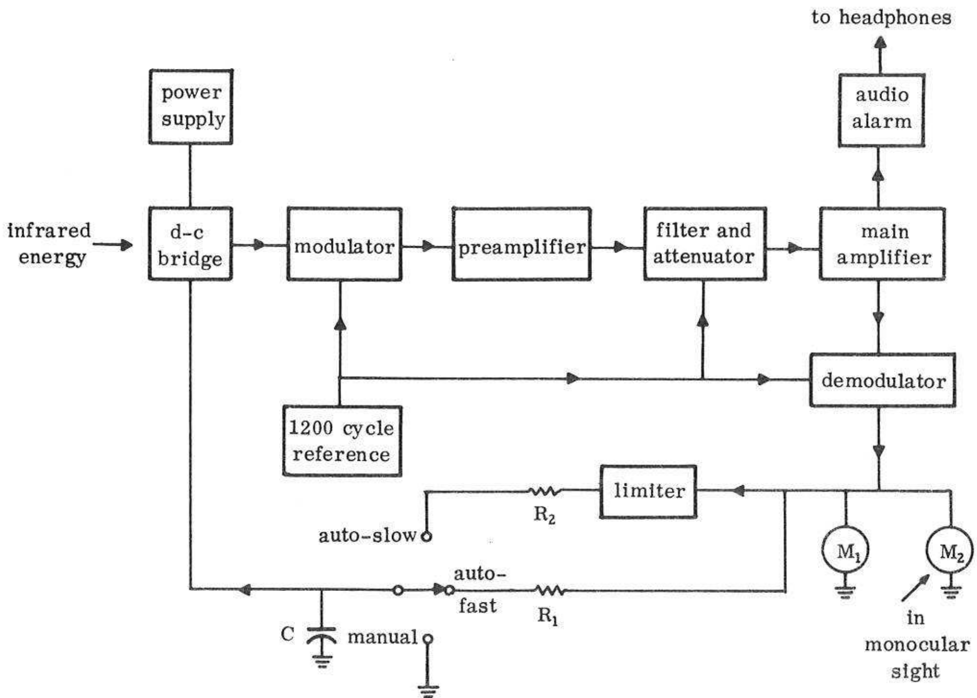

FIG. 2 BLOCK DIAGRAM OF INFRARED DETECTOR

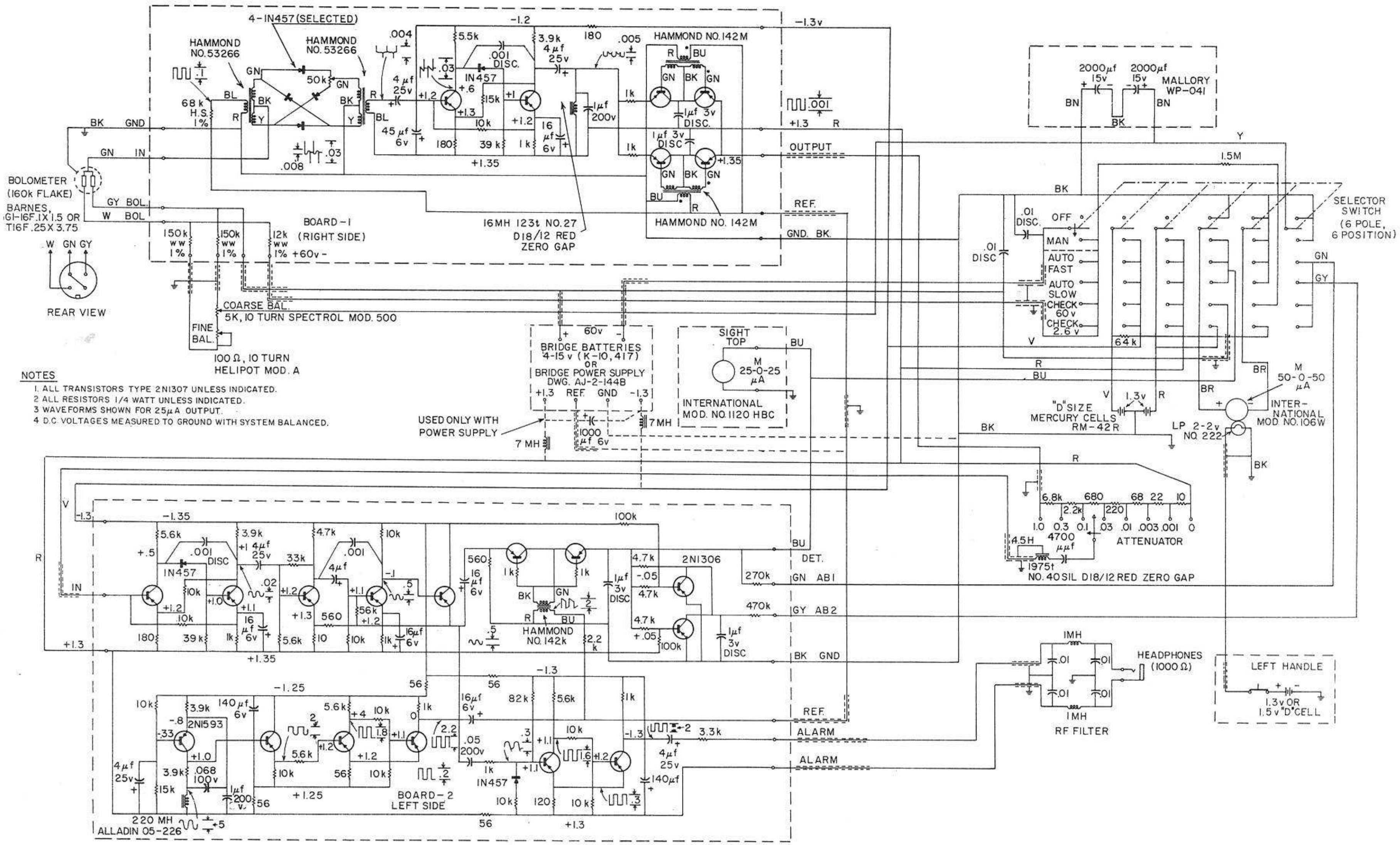

FIG. 3 CIRCUIT DIAGRAM OF INFRARED DETECTOR

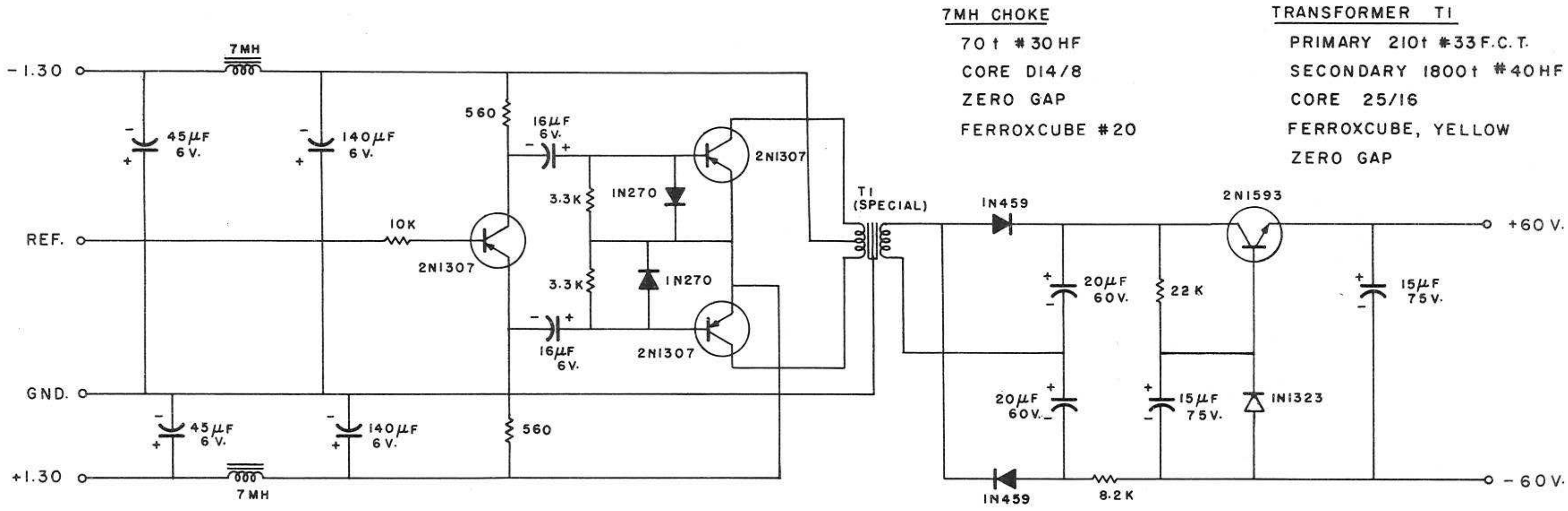

FIG. 4 BRIDGE POWER SUPPLY CIRCUIT

CIRCUIT DESCRIPTION

The block diagram, Fig. 2,shows the functional units of the electronic system. The complete circuit diagram is shown in Fig. 3; the bridge power supply in Fig. 4. In order to explain the operation of the system a brief description, together with simplified circuits, will be given.

Bolometer Bridge

The bolometer elements are connected in a d-c bridge circuit. The bridge is initially balanced with the selector in the "manual" position. The output signal will be positive if the active element is warmer than the compensator, negative if it is cooler. The infrared radiation received by the instrument is focused on the active element and can either increase or decrease its temperature. The

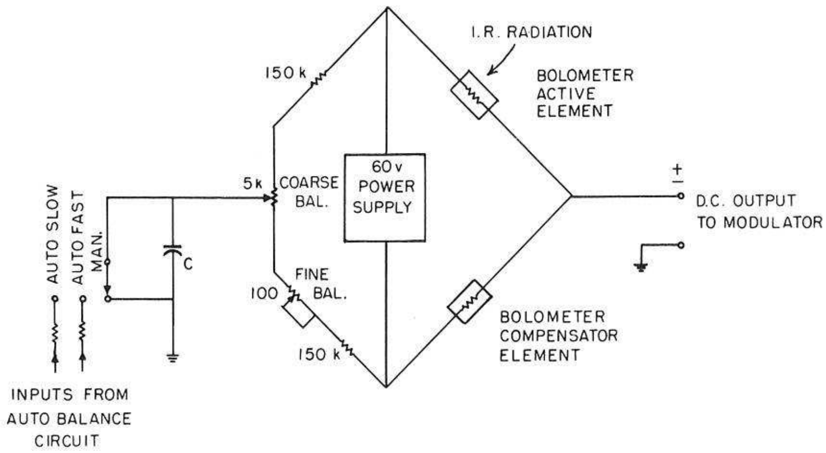

FIG. 5 BOLOMETER BRIDGE CIRCUIT

polarity of the output signal thus indicates the direction of the temperature change; the amplitude indicates the magnitude of the change.

It will be noticed that the selector switch disconnects the ground connection of the bridge in the automatic balancing positions. This permits the correction signal to be added in series with the bridge. The long time constant of the RC circuit permits only slow corrections to be made. The correction signal is obtained from the d-c output of the system, which is arranged to have the opposite polarity to the signal generated by the bolometer bridge. The correction signal is thus subtracted from the bridge signal and eventually reduces the difference almost to zero. This provides automatic balancing of the system.

Diode Ring Modulator

The well known ring modulator circuit is used to convert the d-c signal from the bridge to an a-c signal at 1200 cps. The diode pairs d_1, d_2 and d_3, d_4 are made to

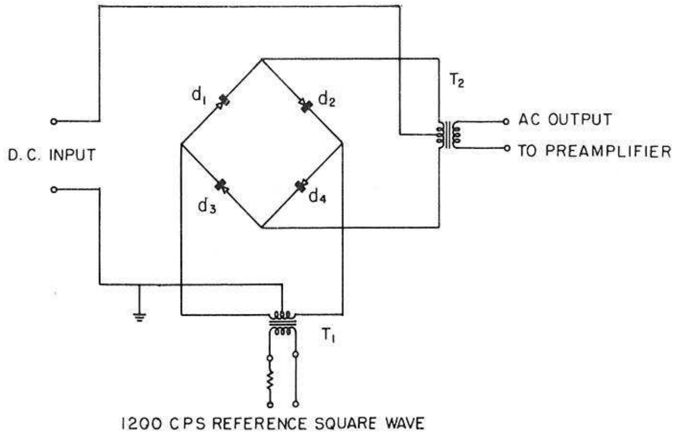

FIG. 6 RING MODULATOR CIRCUIT

conduct on alternate half-cycles by the reference signal. This causes the input current to flow alternately in opposite directions in the primary windings of T_2, producing an a-c signal in the secondary winding.

The diodes were selected for equal voltage when operated with a forward current of 4 μa.

Preamplifier

The preamplifier consists of two common emitter transistor stages. Both a-c and d-c negative feedback are employed to stabilize the gain and the operating points of the transistors. The preamplifier output is a-c coupled to the filter circuit.

Filter and Attenuator

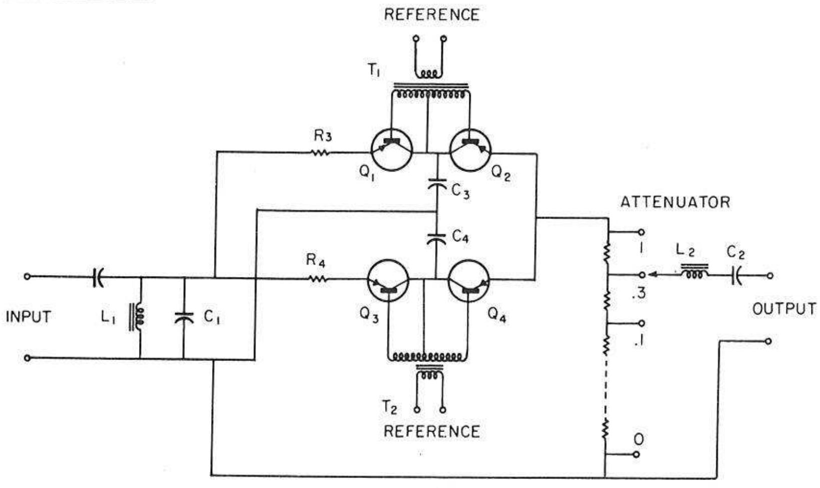

FIG. 7 FILTER CIRCUIT

The filter system is relatively complex. It consists of a parallel-tuned circuit $L_1 C_1$, followed by a synchronous quadrature rejection filter, a stepped attenuator or gain control, and a series resonant circuit $L_2 C_2$. The system has a bandwidth of 50 cps centered at 1200 cps. The synchronous filter removes any quadrature component of the input signal and allows an accurate a-c null to be obtained. The transistors are used as switches, with Q_1 and Q_4 conducting on one half-cycle and Q_2 and Q_3 conducting on the alternate half-cycle.

When Q_1 and Q_4 are conducting, the capacitor C_3 is charged through resistor R_3 to the average value of the input signal. When Q_2 and Q_3 are conducting, C_3 is connected to the output while C_4 is being charged through R_4. Any sinusoidal component of the input signal that differs in phase from the reference signal by $\pm 90°$, will have an average value of zero and will not appear in the output.

The output of the synchronous filter is a square wave having small transients at the switching times. The series resonant circuit $L_2 C_2$ produces a sinusoidal output waveform.

Main Amplifier

The main amplifier consists of four common emitter stages, and an emitter follower to provide a low output impedance. The gain and operating conditions are stabilized by a-c and d-c negative feedback.

Demodulator

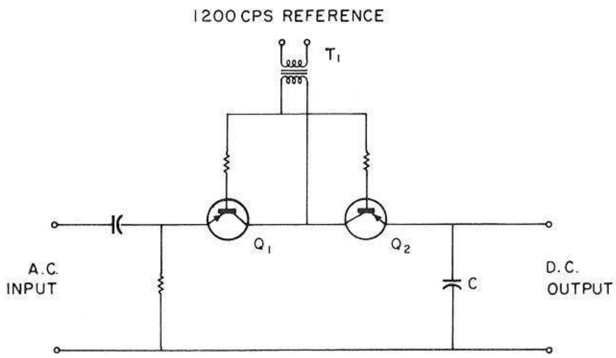

FIG. 8 DEMODULATOR CIRCUIT

The demodulator consists of a balanced transistor half-wave synchronous switch. This type of detector allows an output of either polarity depending on the phase of the input signal relative to that of the reference square wave. Filter capacitor C provides smoothing of the output voltage.

Audio Alarm

The circuit used to produce an audio alarm signal for the headphones is a two-stage regenerative amplifier known as a "Schmitt Trigger". Whenever the input signal from the main amplifier exceeds the bias threshold,the regenerative amplifier changes state, thus producing a square-wave output voltage.

On one model a 10 K potentiometer was placed in series with the input, and may be used to adjust the threshold over a wide range.

A radio-frequency filter is used at the headphone jack to prevent radio interference from a nearby transmitter.

Auto-balance System

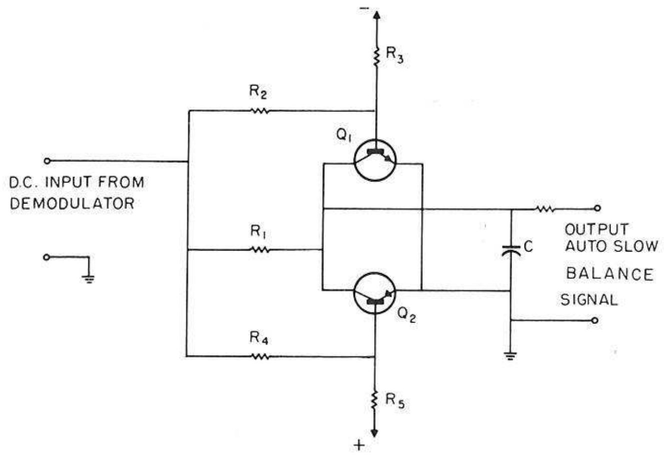

FIG. 9 AUTO-BALANCE LIMITER

The principle used to obtain automatic balancing was explained under the section on the bolometer bridge. When using the "Auto Fast" mode, the balancing signal is obtained directly from the demodulator output. The rate of correction is then proportional to the output amplitude. When a large signal is received, the correction signal increases rapidly, resulting in considerable overshoot after the target leaves the beam.

In the "Auto Slow" mode, a special limiter is inserted in the correction circuit, which limits the rate of correction on large signals. The system can, however, follow slow changes just as effectively. The limiter characteristic is shown in Fig. 10.

The limiter consists of a complementary pair of transistors with reverse bias on the base-to-emitter junctions. As the input signal increases, one of the transistors becomes forward-biased and the resulting collector current shunts the output terminal to ground.

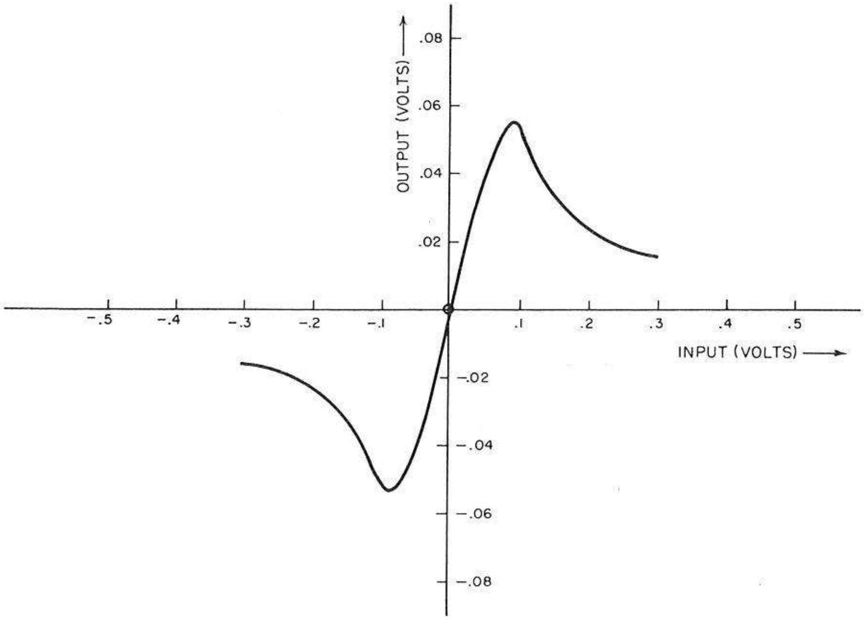

FIG. 10 LIMITER CHARACTERISTIC

Reference Generator

Four transistors are used to produce a 1200-cps square-wave reference signal which is used to operate the ring modulator, quadrature rejection filter, demodulator, and the bridge power supply. The first transistor is connected as a Colpitts oscillator, producing a 1200-cps sine wave. An emitter follower couples the oscillator to a Schmitt Trigger circuit which generates the 1200-cps square wave.

Bridge Power Supply

The reference signal operates a Class B transistor amplifier (see Fig. 4). A step-up transformer produces an 80-volt peak-to-peak signal which is rectified and filtered. A simple regulator is used to stabilize the output voltage at 60 volts d-c, and to reduce the ripple voltage. The total noise output of the supply, when operated with a 150-kilohm resistor load, should be less than 200 μv.

TEST RESULTS

Preliminary tests, conducted during daylight hours on an overcast summer day, produced the following results:

a) man detected at range of 200 yards,
b) range on automobile about 1000 yards,
c) large transport truck detected at approximately 1 mile.

It is expected that a detection range of 500 yards would be obtained on a human target under conditions of low ambient temperature and no wind. Less improvement would be obtained with vehicles which have temperatures considerably above that of the air. Bright sunshine, high air temperature, and high winds would all degrade performance.

The range equation developed in Appendix A can be used to estimate the approximate performance of the instrument.

MAINTENANCE

1) Sight Alignment

The optical axis of the sight must be aligned with the axis of the instrument. The sight mount is equipped with adjusting and locking screws to fix its vertical and horizontal angles. The alignment adjustments can be made while observing targets moving through the field of view. The sight should be located so that maximum indicator reading is obtained when the target is centered in the optical field of view.

2) Wind Screen Replacement

The front of the instrument is covered with a sheet of 0.002" polyethylene which is relatively transparent to infrared radiation. The screen may be replaced by removing the retaining ring. After the screws have been removed the ring should be tapped off with a soft hammer; then a new sheet of film should be stretched over the barrel and the retaining ring replaced. Care should be taken to align the screw holes in the ring with the holes in the barrel.

3) Circuit

Operating voltages and waveforms are included on the circuit diagram to assist when servicing the instrument.

A satisfactory sensitivity check can be made by operating in the manual mode with the attenuator set at the 1.0 position. Approximately one-tenth turn of the fine balance control should cause an indication of $\pm 25\ \mu a$.

Plate III shows the component sides of the printed circuit boards. If it is necessary to replace a component, the leads should be cut close to the defective component and the new part soldered to the remaining leads. An attempt to remove the leads should not be made, as they have been flattened at the ends to facilitate dip soldering. Care should be taken when soldering because excessive heat will damage diodes and transistors and may lift the printed wiring from the board.

External wires and transformer leads are soldered in eyelets and may be safely removed. If a break occurs in the printed wiring, it may be bridged with small-gauge copper wire.

4) Detector Removal, Cleaning, and Focus

To remove the detector, it is necessary to remove the cover from the right side of the instrument and the windscreen from the front. Remove the threaded disc from the front of the detector holder. Unsolder the three leads and pull them into the holder stem. After marking the location of the tube in the holder, the clamp screw should be loosened and the detector, mounted in its tube, may be removed. Care should be taken not to touch the lens of the detector.

Dust may be removed from the detector lens with a soft camel's-hair brush. No other cleaning should be attempted.

When replacing the bolometer, the assembly should be replaced in its original position so that a focus adjustment will not be required. The detector is normally located so that the long axis of the element is vertical.

The focus adjustment was originally set for a distance of 500 feet by the following method. A small target was set up at a distance of 23 feet and the detector holder was adjusted, with the aid of a dial gauge, for maximum output. The holder was then moved 0.115 inches toward the mirror.

5) Mirror Cleaning

The 6-inch parabolic mirror may be cleaned in place, if necessary. The reflective coating is located on the front surface and care must be taken not to touch or scratch it. Do not attempt to clean the mirror with tissue or cloth. A soft photographic sponge and a weak solution of "Wisk" detergent should be used. The sponge should be dampened with solution and wiped across the mirror surface. The sponge should then be rinsed in clean water and the mirror wiped again.

ACKNOWLEDGMENTS

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APPENDIX A

APPROXIMATE CALCULATION OF PERFORMANCE

In order to estimate the performance of the infrared detector, an approximate formula for range can be developed from the laws previously given.

Consider a target of effective temperature T_1 and area A_1 passing through the field of view of the instrument against a background of effective temperature T_2.

Emittance of target $W_1 = \epsilon_1 \sigma T_1^4$ watts/cm^2

Emittance of background $W_2 = \epsilon_2 \sigma T_2^4$ watts/cm^2

Radiant intensity at a distance R from the target is

$$I_1 = \frac{\epsilon_1 \sigma T_1^4 \, \tau a(\lambda R) \, A_1}{2\pi R^2} \text{ watts/cm}^2 ,$$

where $\tau_{a(\lambda R)}$ is the atmospheric transmission factor, which itself is a function of range and wavelength.

The power, collected by the optics of diameter d, from the target is

$$P_1 = \frac{\epsilon_1 \sigma T_1^4 \, \tau a(\lambda R) \, \tau o \, A_1}{2\pi R^2} \cdot \frac{\pi d^2}{4} \text{ watts ,}$$

where τ_o is the transmission factor of the optical system.

If the target is smaller than the field of view, all the energy is focused on the detector element. The signal results from the difference in power received from the background alone, and from the background plus target.

Power received from background alone

$$P_2 = \frac{\epsilon_2 \sigma T_2^4 \, \tau a(\lambda R) \, \tau o \, A_2 \, d^2}{8 R^2} \text{ watts,}$$

where A_2 = area of background within field of view.

Power received from target plus background,

$$P_1 = \frac{\epsilon_2 \sigma T_2^4 \tau a(\lambda R) \tau o (A_2 - A_1) d^2}{8 R^2} + \frac{\epsilon_1 \sigma T_1^4 \tau o A_1 d^2}{8 R^2}$$

$$= \frac{\epsilon_2 \sigma T_2^4 \tau a(\lambda R) \tau o A_2 d^2}{8 R^2} + \frac{A_1 \sigma (\epsilon_1 T_1^4 - \epsilon_2 T_2^4) \tau a (\lambda R) \tau o d^2}{8 R^2} .$$

The signal power $P = P_1 - P_2$.

$$\therefore P = \frac{A_1 \sigma (\epsilon_1 T_1^4 - \epsilon_2 T_2^4) \tau a (\lambda R) \tau o d^2}{8 R^2} .$$

The noise equivalent power of the detector is expressed as N.E.P. or by the detectivity D, where

$$D = \frac{1}{NEP} .$$

For most detectors a normalized detectivity D* is given for 1 cps bandwidth and an area of 1 cm^2.

The generalized detectivity

$$D = \frac{D^*}{(A_d \cdot B)^{\frac{1}{2}}} ,$$

where A_d = cell area in cm^2
B = system bandwidth;

$$\text{or} \qquad NEP = \frac{(A_d \cdot B)^{\frac{1}{2}}}{D^*} .$$

The system signal-to-noise ratio can be expressed as

$$\frac{S}{N} = \frac{A_1 \sigma (\epsilon_1 T_1^4 - \epsilon_2 T_2^4) \tau a (\lambda R) \tau o d^2 D^*}{8 R^2 (A_d \cdot B)^{\frac{1}{2}}} ,$$

for the case where the target is smaller than the field of view.

When one dimension of the target is larger than the field of view, only part of its energy is focused on the detector element.

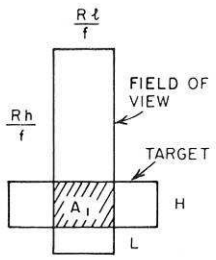

FIG. 11 RELATIONSHIP OF TARGET AND FIELD OF VIEW

In Fig. 11, if 1 and h are the dimensions of the cell,
f is the focal length of the optics,
L and H are the dimensions of the target:

the overlap area on Fig. 11 can be seen to be

$$A_1 = \frac{1RH}{f} .$$

$$\frac{S}{N} = \frac{1H(\epsilon_1 T_1^4 - \epsilon_2 T_2^4)\,\tau a(\lambda R)\,\tau o \,.\, d^2 D^*}{8fR(A_d \,.\, B)^{\frac{1}{2}}} ,$$

and it can be seen that the signal-to-noise ratio now varies in inverse proportion to R.

When the target is larger than the field of view in both dimensions, the signal-to-noise ratio is independent of range (when the atmospheric transmission is assumed constant).

$$\frac{S}{N} = \frac{1h(\epsilon_1 T_1^4 - \epsilon_2 T_2^4)\,\tau a(\lambda R)\,\tau o\, d^2 D^*}{8 f^2 (A_d \cdot B)^{\frac{1}{2}}} .$$

The expression for $\frac{S}{N}$ can be solved to give an approximate maximum range for a given target. It is necessary to make certain assumptions concerning effective temperatures, emissivities, and atmospheric transmission.

If the target is a man,

$$\text{let } T_1 = 37°C = 310°K,$$

$$A_1 = 1.5 \times 4 = 6 \text{ ft}^2.$$

Background temperature $T_2 = 27°C = 300°K$.

Also assume $\tau_a = .5$,

$$\tau_o = .5.$$

The other factors are:

$d = .5$ ft, $B = 50$ cps, $A_d = .04 \times .6 \text{ cm}^2$, $D^* = 2 \times 10^8 \frac{\text{cm}}{\text{watt}}$,

req'd $\frac{S}{N} = 5$, $\sigma = 5.67 \times 10^{-12}$ watts/cm^2 deg^4

$$\therefore R^2 = \frac{[6 \times 144 \times (2.54)^2]\ (5.67 \times 10^{-12})\ (310^4 - 300^4)\ (.5)\ (.5)\ (.25)\ (2 \times 10^8)}{8 \times 5\ [(.04 \times .6)\ (50)]^{\frac{1}{2}}}$$

$$= 100 \times 10^4 \text{ ft.}^2$$

$$\therefore R = 1000 \text{ ft.}$$

PLATE I — PORTABLE TRANSISTORIZED INFRARED DETECTOR

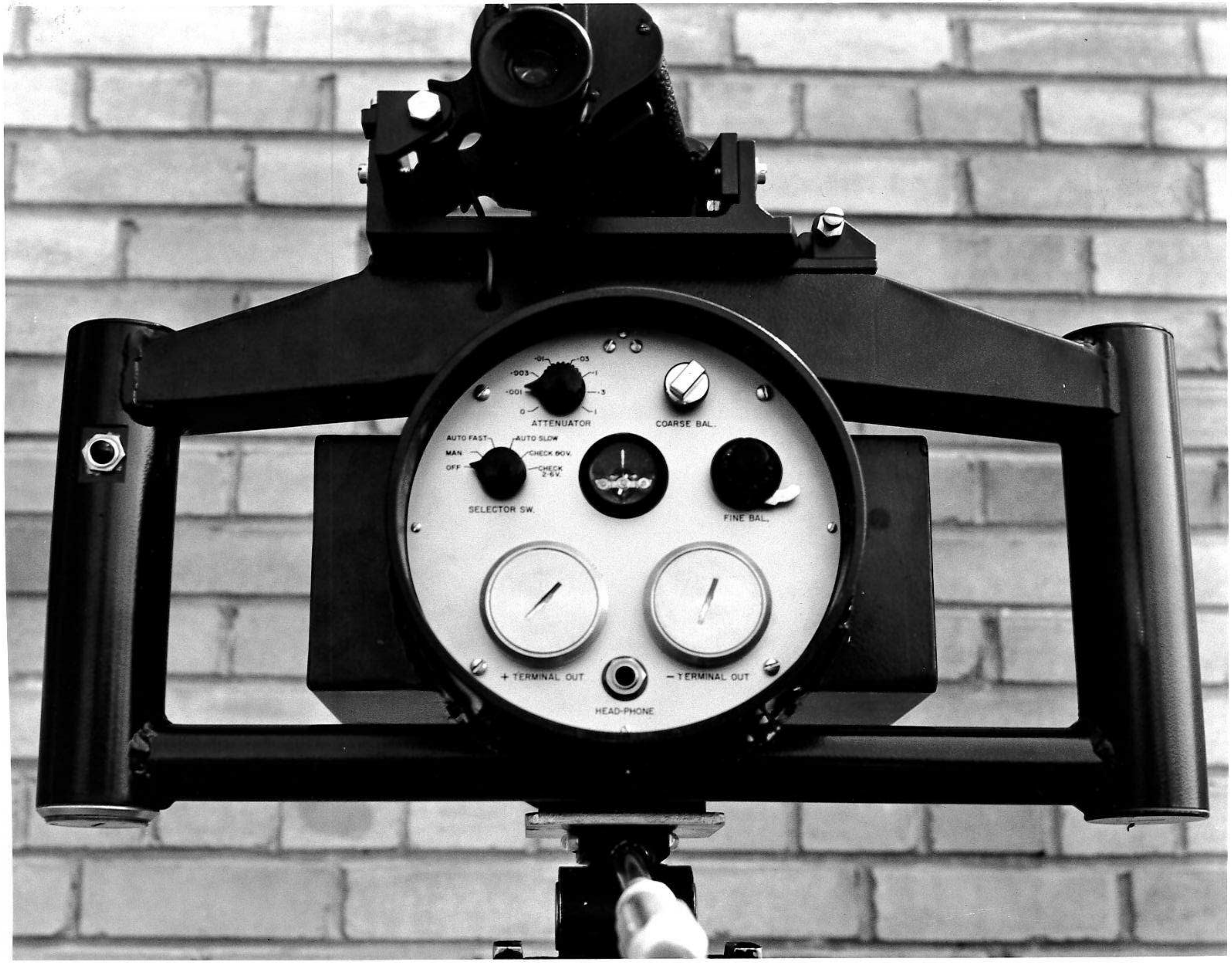

PLATE II — CONTROL PANEL OF INFRARED DETECTOR

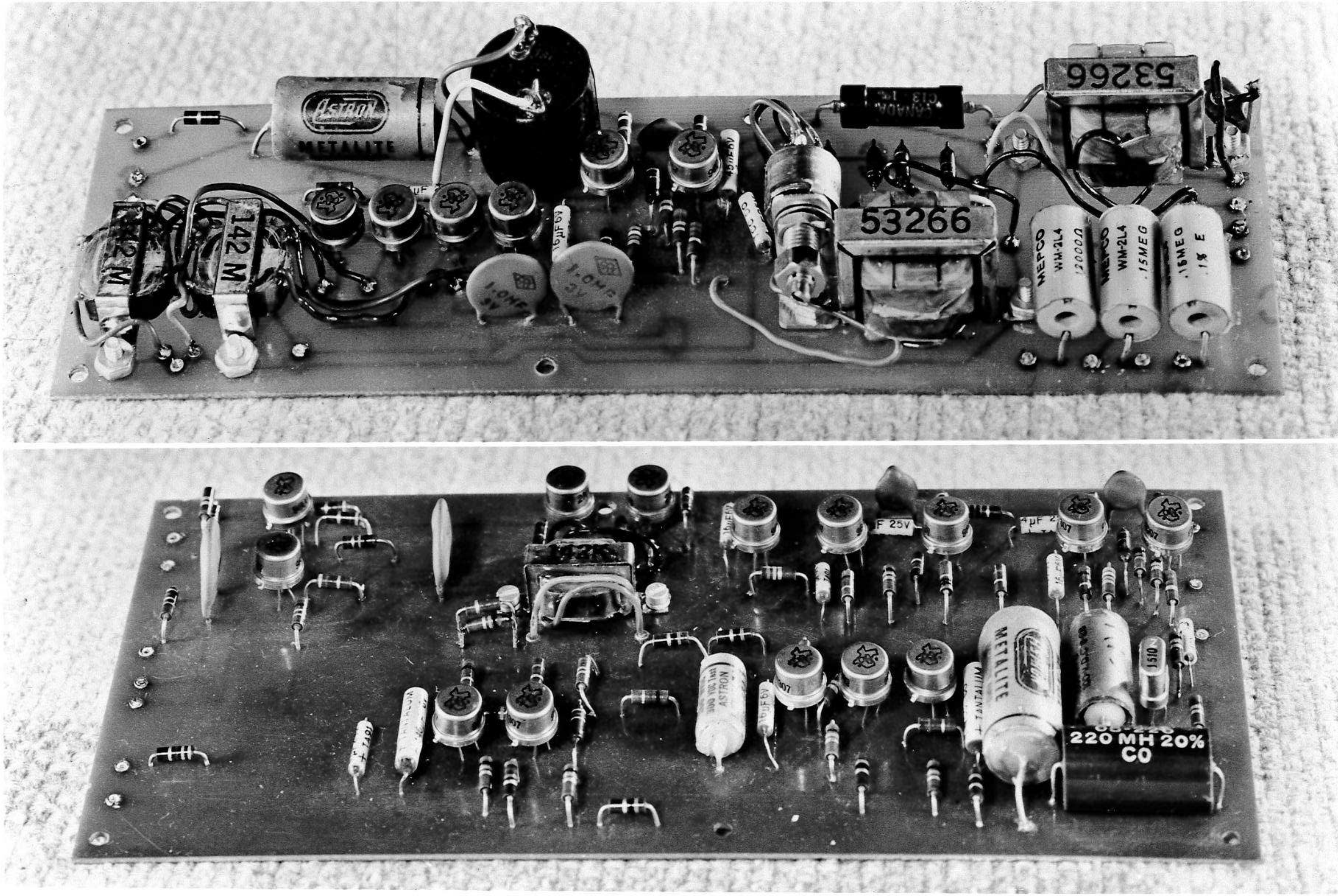

PLATE III — PRINTED CIRCUIT BOARDS NOS. 1 AND 2