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FOLDED-PATH OPTICAL C_n^2 INSTRUMENT

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ABSTRACT

This report describes an optical instrument that measures the refractive-index structure parameter (C_n^2) on a folded path to a cat's eye retroreflector. The measurement is heavily weighted toward the retroreflector. Using optimum path lengths of 150 to 250 meters, C_n^2 can be measured over a range from 1×10^{-12} to 1×10^{-16} $m^{-2/3}$.

1. INTRODUCTION

An optical technique for measuring the refractive-index structure parameter is reported in Ref. 1 and a description of an instrument that makes the measurement is contained in Ref 2. The instrument described in this report operates on the same principle. A light-emitting diode (LED) operating at 0.94 μm wavelength and amplitude modulated at 7 kHz is used as a light source. With this identified light source, it is possible to derive C_n^2 from a measurement of the log-intensity variance of the irradiance of the receiving aperture. The light source and receiver are in the same case and the measurement is made over a light path which is folded by a cat's eye reflector to return to the receiver, as shown in Fig. 1. The transmitting beam diverges slightly (about 1 mrad) but only the rays irradiating the receiver are shown.

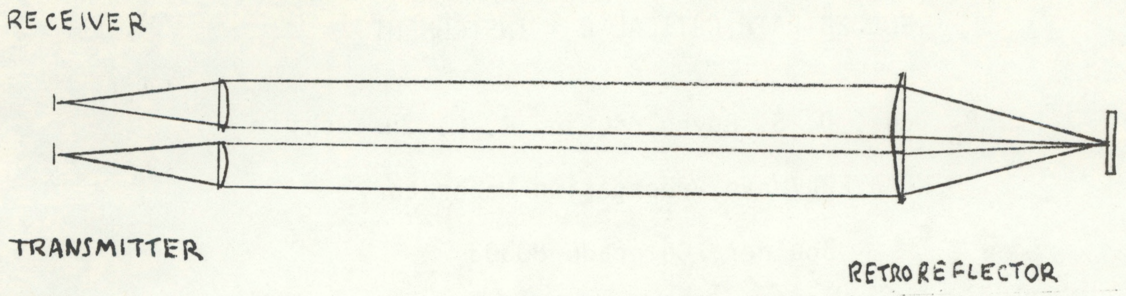


Figure 1. Folded optical path of instrument

With the plane mirror of the retroreflector at the focus of the retroreflector objective, light rays on the return path to the receiver will be parallel to and displaced from those on their way to the retroreflector, as shown in Fig. 1. There is negligible correlation between beams separated by this amount so the weighting function for measurement of C_n^2 can be obtained from the unfolded path weighting function of Fig. 3 of Ref. 1. Multiplying ordinates on this curve equidistant from the path center we obtain the folded path weighting function shown in Fig. 2.

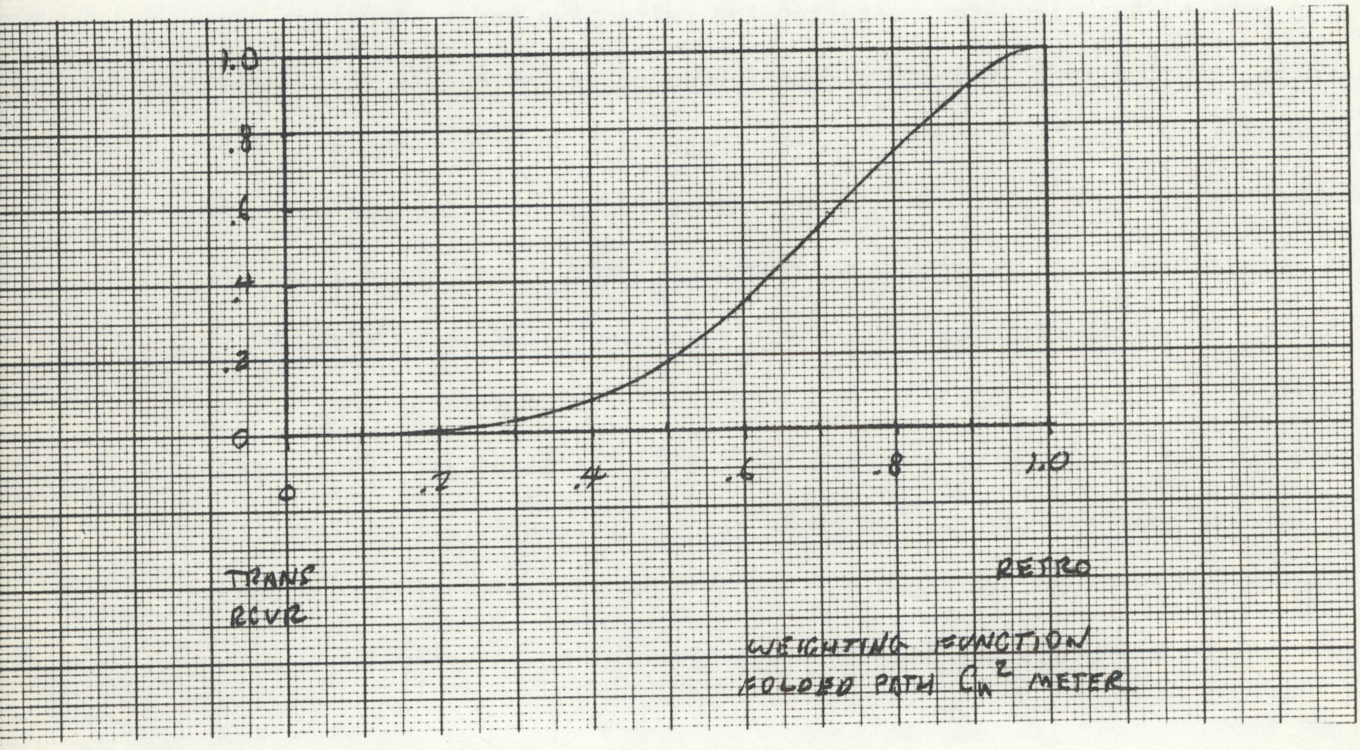


Figure 2. Weighting function of instrument

The choice of 5-cm diameter optics is somewhat of a compromise. Using this size, C_n^2 is based upon observation of spatial wavelengths around 5 cm, a region of the spectrum that is influenced by the Hill bump and the inner scale of refractive turbulence. Larger apertures were not chosen, however, because the retroreflector must be more than twice the diameter of the transmitter-receiver optics. Figure 3 shows the factor by which a C_n^2 measurement obtained with 5-cm diameter optics differs from that which would be obtained from a measurement derived from spatial wavelengths corresponding to the central portion of the inertial subrange. If desired, a value of C_n^2 more nearly representative of the central portion of the inertial subrange may be obtained by estimating the value of the inner scale and dividing the instrument reading of C_n^2 by the ordinate corresponding to this estimated inner scale from Fig. 3.

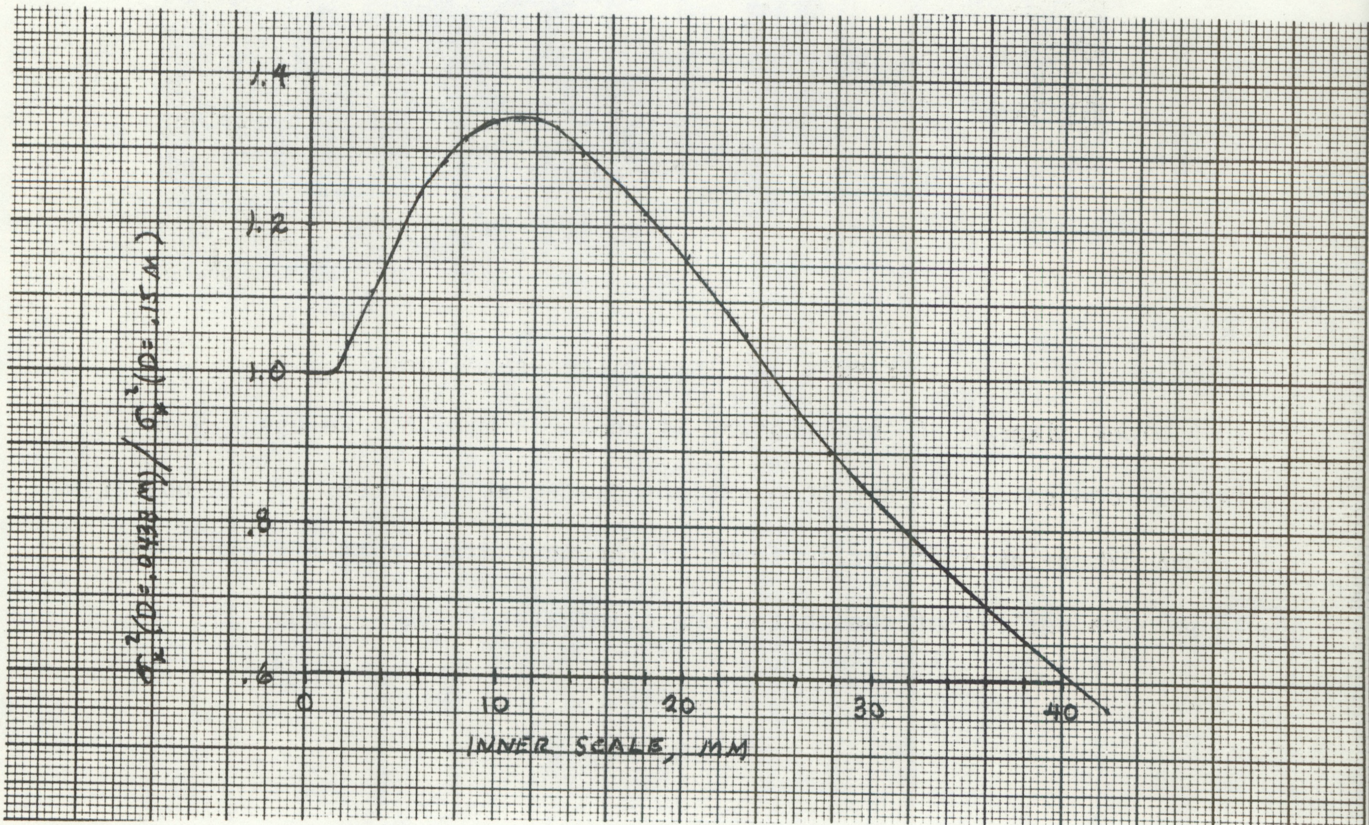


Figure 3. Inner scale effects on reading

2. DESCRIPTION OF THE SYSTEM

The transmitter-receiver is shown in Fig. 4. The transmitter (contained in the lower half of the instrument) consists of a 10 volt DC power supply driving a power oscillator which in turn amplitude modulates the TIES 27 LED at 7 kHz. The LED effective diameter is about 0.4 mm. Since the focal length of the lens system is about 20 cm, the angular cone of light is 2 mrad or about 7 minutes of arc.

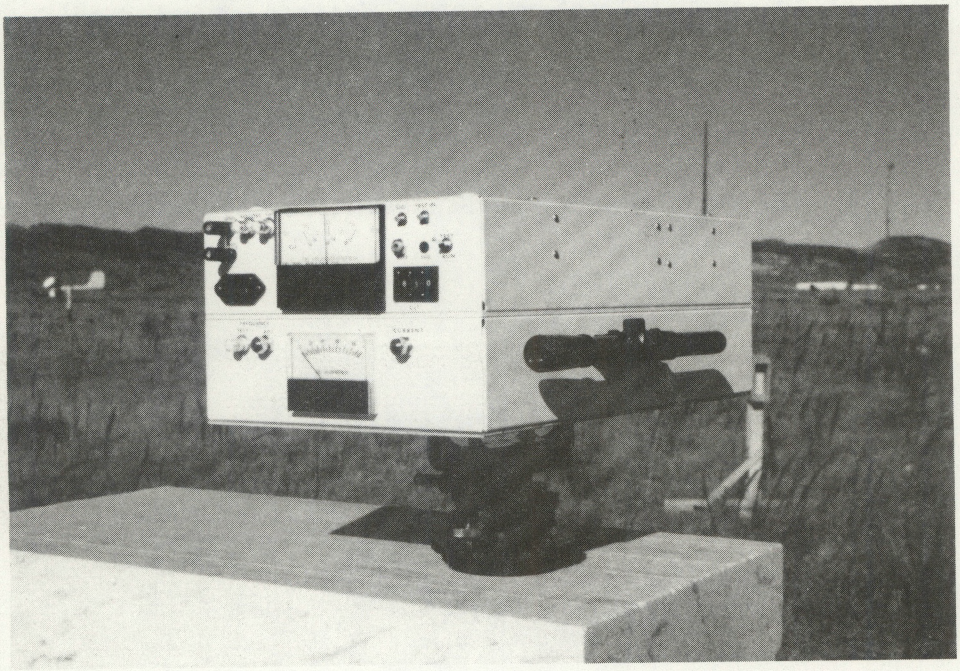


Figure 4. Transmitter-receiver

A block diagram of the receiver is shown in Fig. 5. We use 2.5 mm diameter photodiode op amp combinations placed at the focus of the objective. A Kodak 87C gelatin filter in front of the photodiode cuts off radiation below 0.8 μm; the rolloff of the photodiode eliminates response above 1.1 μm.

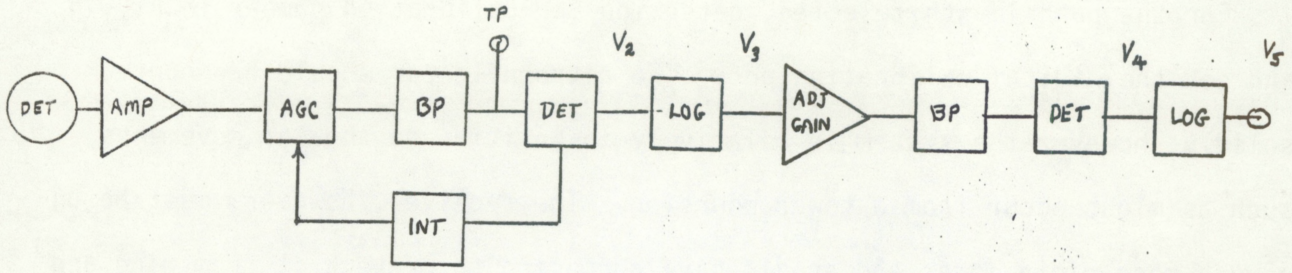


Figure 5. Block diagram of receiver

The modulated signals pass through an automatic gain control circuit which, over its operating range, maintains the output signal at a constant root mean square (RMS) value. The logarithm of the RMS of the signal is then computed. After passing through another band pass filter (1.2 - 1000 Hz) the mean square of the resulting signal is proportional to the log-amplitude variance ($\tilde{\sigma}_x^2$) of the irradiance of the binocular objective.

As $C_n{}^2$ commonly varies over orders of magnitude a signal output is provided which is proportional to the logarithm of $C_n{}^2$. This output is available on the meter and as an electrical output.

3. OPERATING PROCEDURE

In this report, the separation S is defined as the distance between the transmitter-receiver and the retroreflector to distinguish it from the optical path length L (used in the derivation in Appendix B) which is twice the separation. Separations of 150 to 250 meters are optimum although the instrument can be used outside this range. There is a further restriction on separation when the integrated turbulence is high, and the limits are discussed in Appendix B.

For the path length selected, determine the calibration number in Fig. 6 and set the digital calibration pot. The retroreflector should be mounted solidly; however the system is relatively insensitive to angular movements such as might occur from a tower mounting. The receiver, however, must be on a much more rigid mount and should have a housing to protect it from wind and weather. The transmitter LED current will initially be a little low but should increase to 250 ma, the recommended current setting, after a few minutes. The current can be adjusted at the power supply but it should not exceed 300 ma. For a path length (L) less than 100 m it may be necessary to reduce the LED current, to prevent signal saturation. This condition can be checked by observing the modulated signal at the microdot connector to make sure that no clipping occurs.

When the receiver is first turned on, the automatic gain control is at minimum gain. Allow about one minute for it to stabilize, and then check the alignment. When a signal is received, the red LED will go out. Move the receiver horizontally and vertically to find the center of the field of view. The sighting telescope crosshairs can be adjusted at this time if they do not agree. Be sure to set up on the maximum response as a diffraction pattern does exist around the central beam.

A direct readout of C_n^2 is now displayed on the panel meter and a voltage (V_5) proportional to the logarithm of C_n^2 is available at the BNC output jack. The relationship is

$$C_n^2 = 10^{(V_5-14)}$$

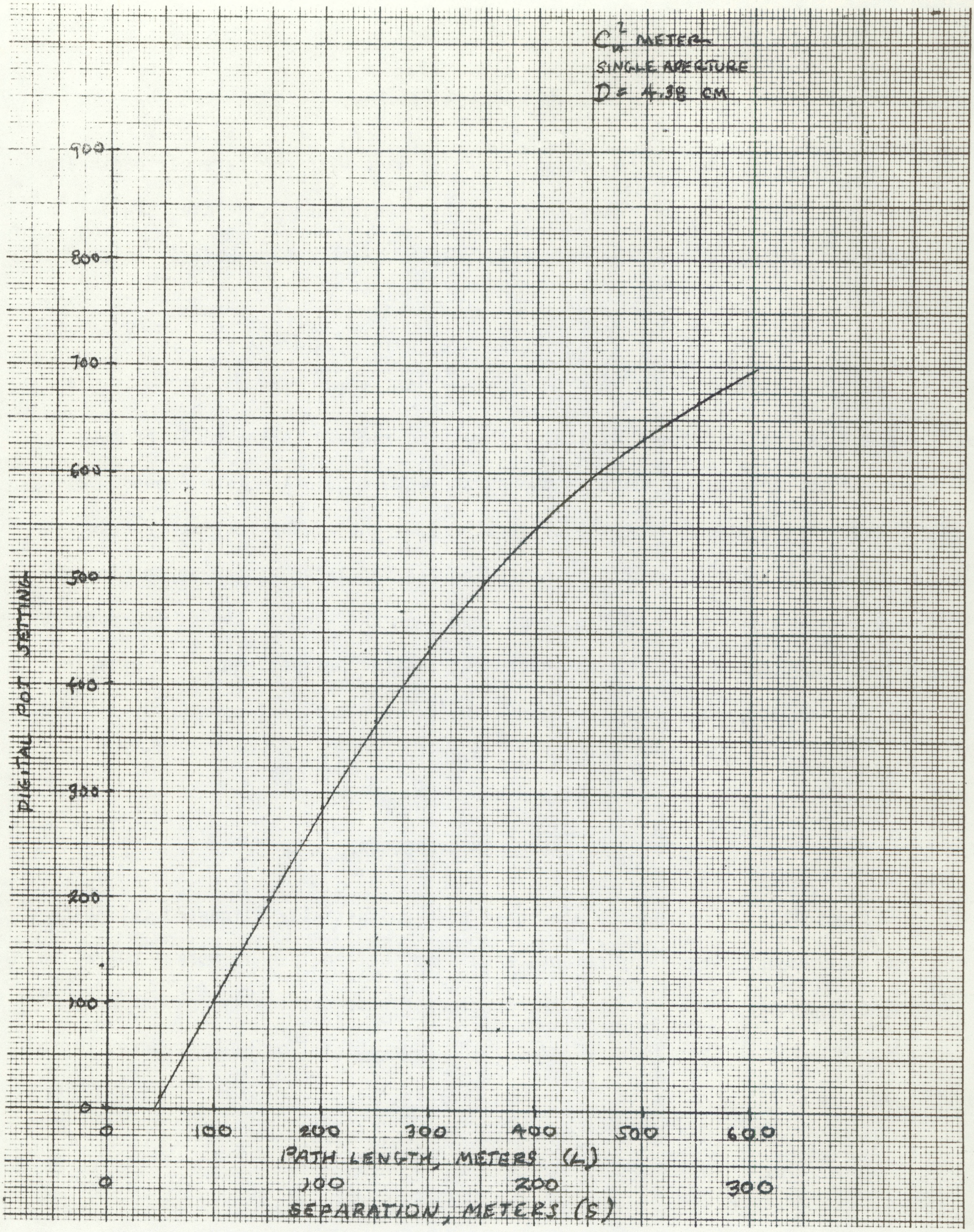


Figure 6. Calibration setting versus path length

4. USE OF CALIBRATOR

An overall check of the operation can be made with the external calibrator provided. This unit generates an adjustable square-wave modulated signal having a 7 kHz carrier. The modulation depth of the square wave is related to the output C_n^2 by

$$C_n^2 = 1.25 \times 10^{-4} \left[\frac{(5240 - 5.24P)(\log_{10}(a/b))}{3.17 \times 10^4 P + 1.49 \times 10^6}\right]^2$$

where P is the instrument digital pot setting and a/b is the ratio of the maximum to the minimum value of the square-wave modulation (see Appendix B). To check the system, place the calibrator in front of the receiver aperture, setting in a known a/b ratio by observing the modulated signal at the instrument microdot connector with a scope, and then checking to see if the correct output is obtained for a given instrument digital pot setting. For example, for $p = 500$ and $a/b = 2$, $C_n^2 = 2.59 \times 10^{-13}$. Since $V_5 = (\log_{10} C_n^2) + 14$ (eq. 8), the output voltage V_5 should be 1.4 volts.

5. ALIGNMENT PROCEDURE

The following procedures are those used to initially align and calibrate the instrument. These adjustments should not be required in normal operation. The transmitter, receiver, and retroreflector were originally focused and aligned using an infrared collimator. However the following procedures may be used.

5.1 Optical Alignment

The transmitter consists of a TIES-27 LED placed at the focus of an optical system having a focal length of about 200 mm. If the retroreflector is properly collimated (the first surface mirror exactly at the infrared infinity focus of the objective) place it 100-250 m in front of the transmitter-receiver. Observe the modulated signal at the microdot signal jack with a scope. Then reduce the transmitter current until the AGC is at full gain. Adjust the focus by loosening the 6-32 lock nuts at the rear of the transmitter and adjust for maximum received signal. Readjust the pointing as necessary. This procedure sets the focus at infinity, assuring a fully illuminated transmitting aperture.

The receiver uses a similar optical system with a photodiode placed at the infrared infinity focus. With the transmitter focused, look at the distant retroreflector. Lower the transmitter LED current until the AGC circuit is no longer active. Adjust the receiver pointing for maximum signal. Then move the receiver photodiode assembly for maximum signal. Note where the signal drops off on either side of focus and set at the midway position. Readjust the receiver pointing and repeat the focus adjustment.

5.2 Electronic Alignment

5.2.1 LED power supply

The LED power supply has a commercial regulated DC supply powering a driver that square wave modulates (on-off) the LED at approximately 7 kHz. To calibrate set the carrier frequency to 7 kHz by observing at the frequency BNC. For normal operation, the LED current should be 250 ma.

5.2.2 Receiver

Check the detector and AGC circuits as follows:

1. Illuminate the receiver aperture with the calibrator. Observe the signal at the signal test point. It may take a minute or more to build up as the AGC circuit has a long time constant. Observe the AGC action by moving the calibrator. The circuit should slowly adjust to keep the RMS level at about 2 volts.

2. Adjustment of the two AD536AKD RMS circuits is accomplished as follows. Remove the op amp that drives the AD536. Put in +0.100 volt at pin 1 of the AD536. Observe the signal at pin 6 of the op amp connecting to pin 6 of the AD536. Adjust the 50k ohm resistor for 0.00 volt. Now change the input to 1.00 volt and adjust the 200 ohm resistor b for 2.00 volts and resistors 2b and 2e for 2.00 volts.

3. Cover the receiver aperture. Turn the instrument on and wait at least 1 minute. Then adjust pot c until the red signal light on the panel goes out. Then back off 4 turns.

5.2.3 Calibrator

1. Adjust the carrier frequency to 7 kHz, and the modulation frequency to 10 Hz.

2. The bias control should be set so that the envelope of the bottom portion of the modulated carrier is a straight line.

6. REFERENCES

1. Wang, Ting-i, G. R. Ochs and S. F. Clifford (1978): A saturation-resistant optical scintillometer to measure C_n^2, J. Opt. Soc. Am., 68, 334-338.

2. Ochs, G. R., W. D. Cartwright and D. D. Russell (1979): Optical C_n^2 instrument model II. NOAA Tech. Memo. ERL WPL-51.

3. Ochs, G. R. and R. J. Hill (1982): A study of factors influencing the calibration of optical C_n^2 meters.

APPENDIX A

Circuit Diagrams

Wiring Diagram

Light-emitting Diode Driver Circuit

Photodiode Preamplifier

Automatic Gain Control Circuit

Automatic Gain Control Circuit Layout

Demodulator Circuit with Signal Detector

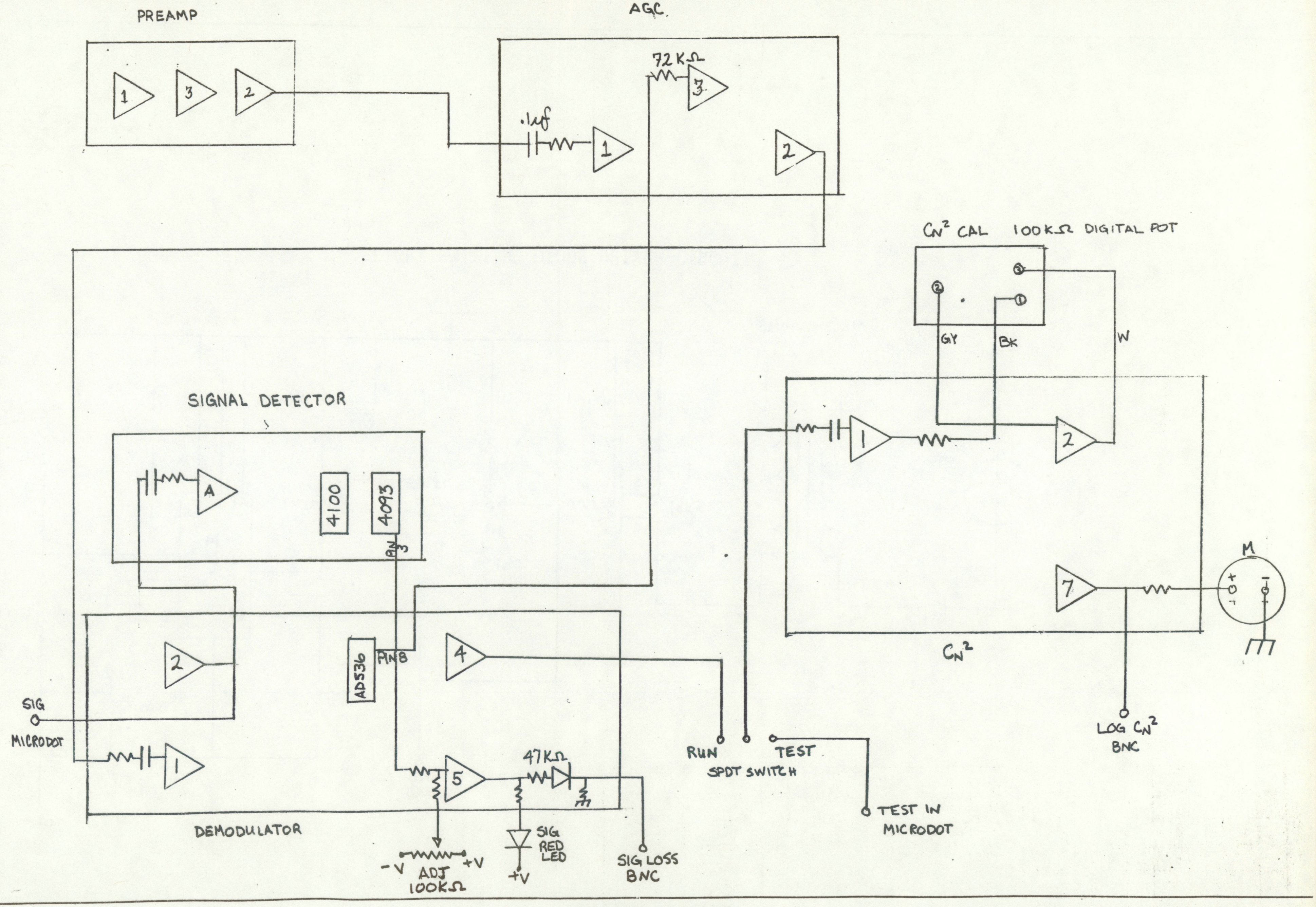
Demodulator and Signal Detector Circuit Layout

Calibration and Log Circuit

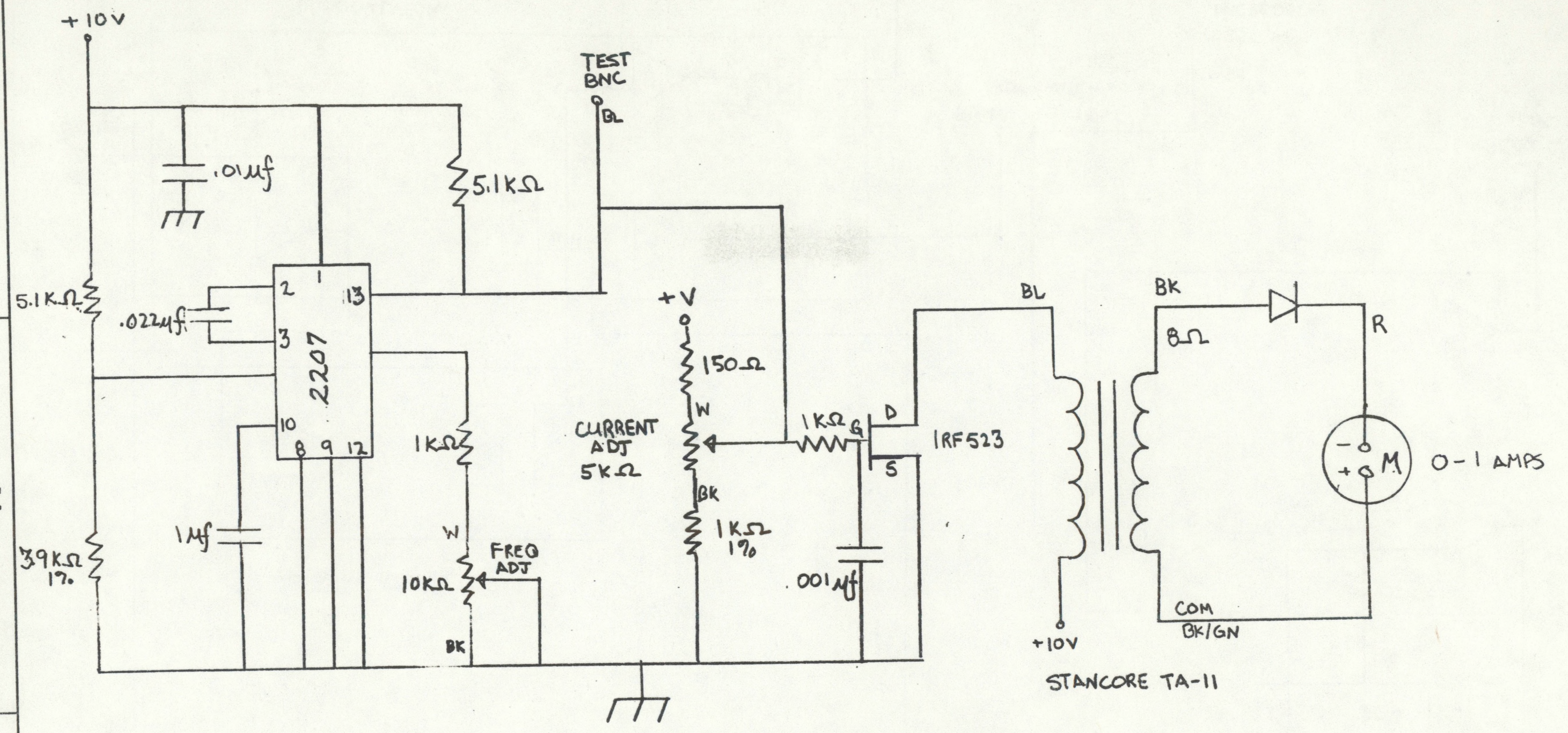
Calibration and Log Circuit Layout

Calibrator Circuit

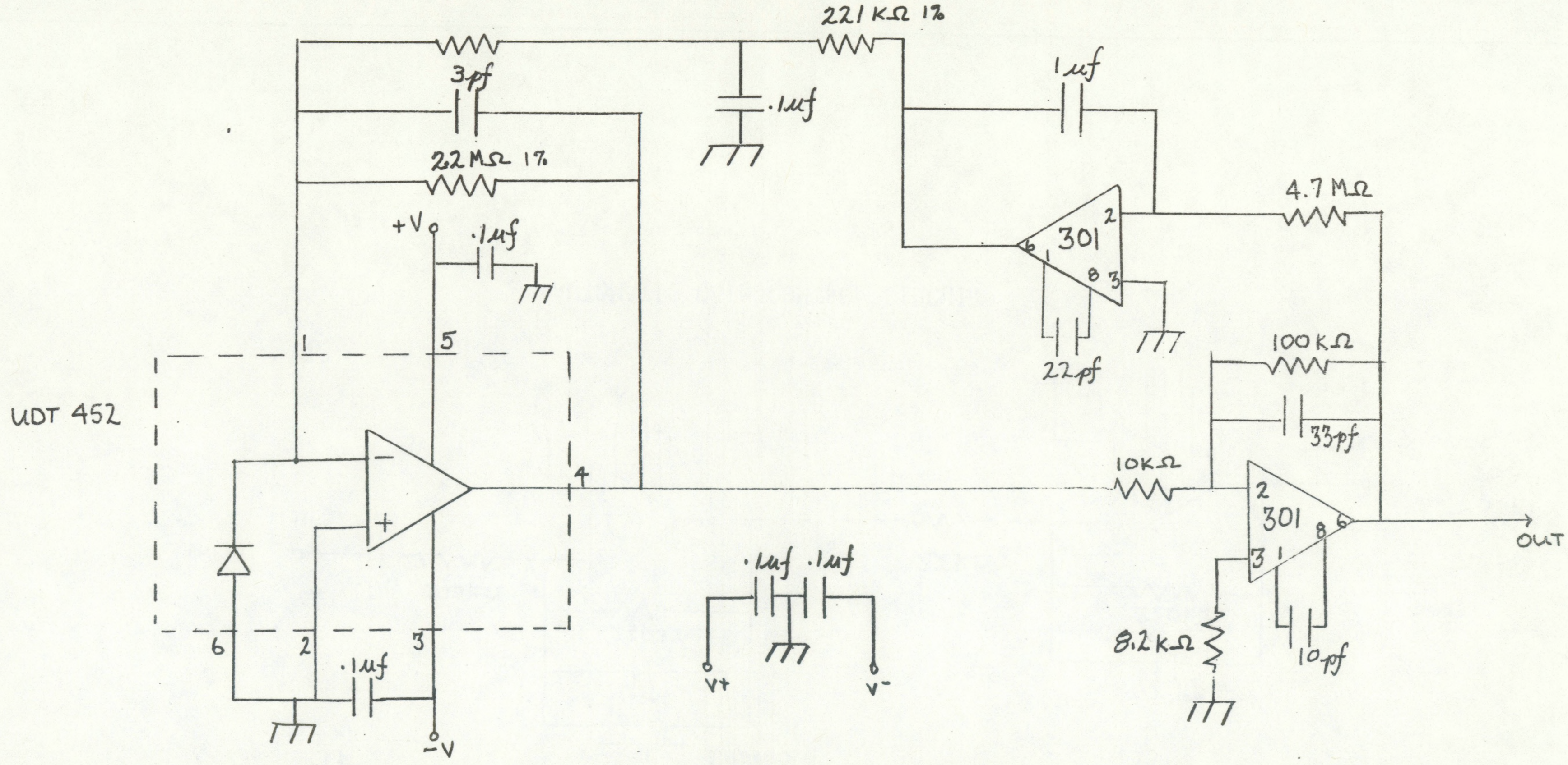
Calibrator Circuit Layout



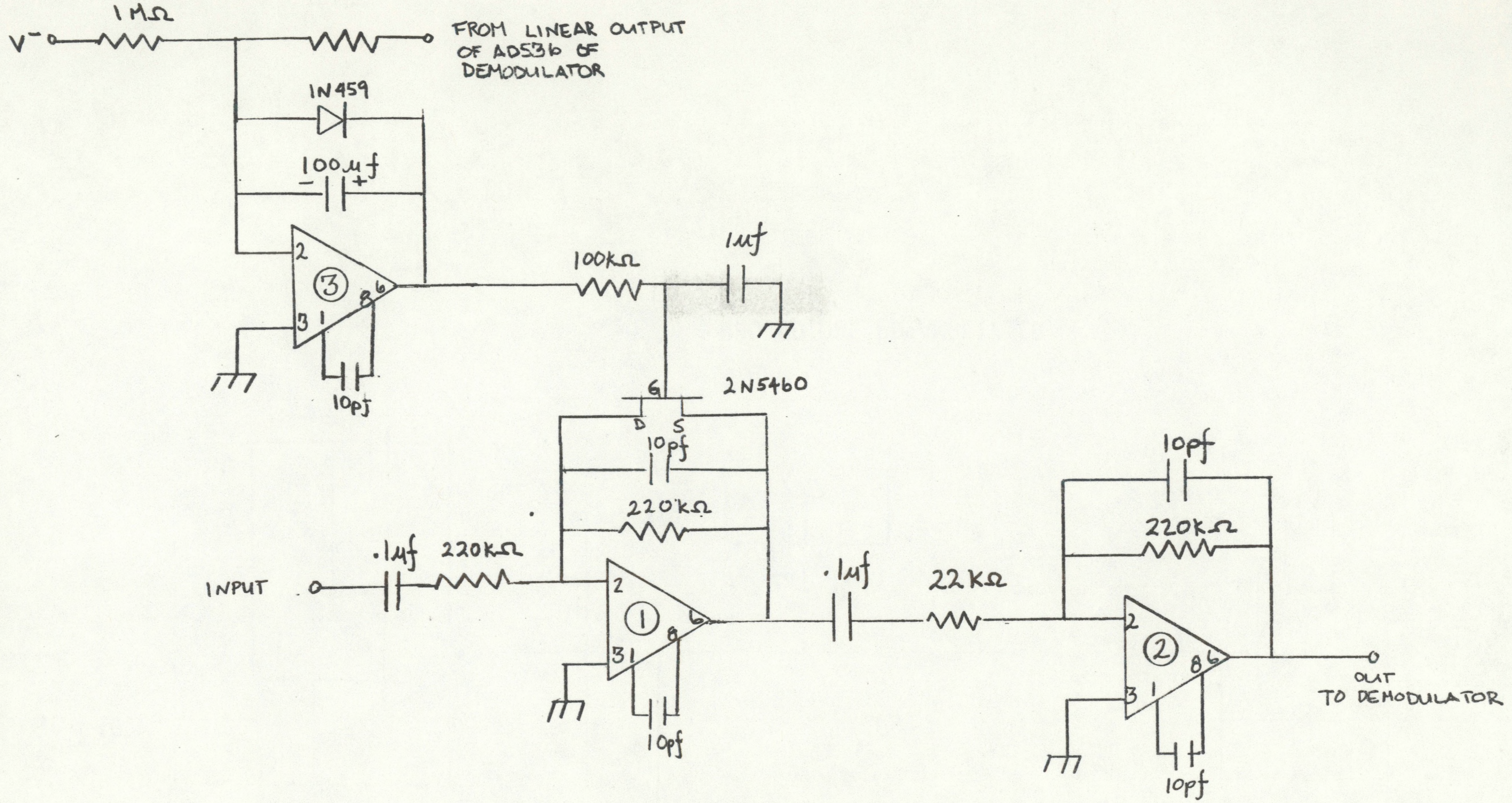
WIRING DIAGRAM



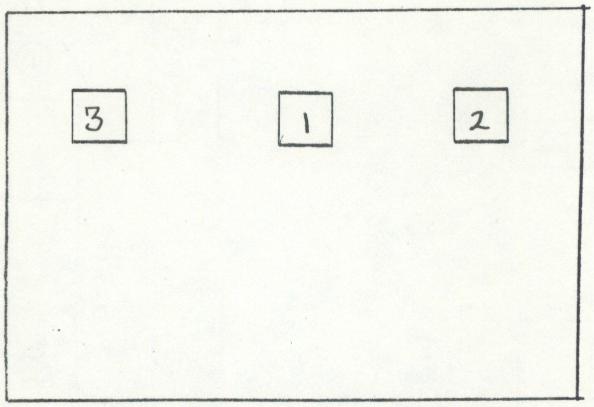
LIGHT EMITTING DIODE DRIVER CIRCUIT



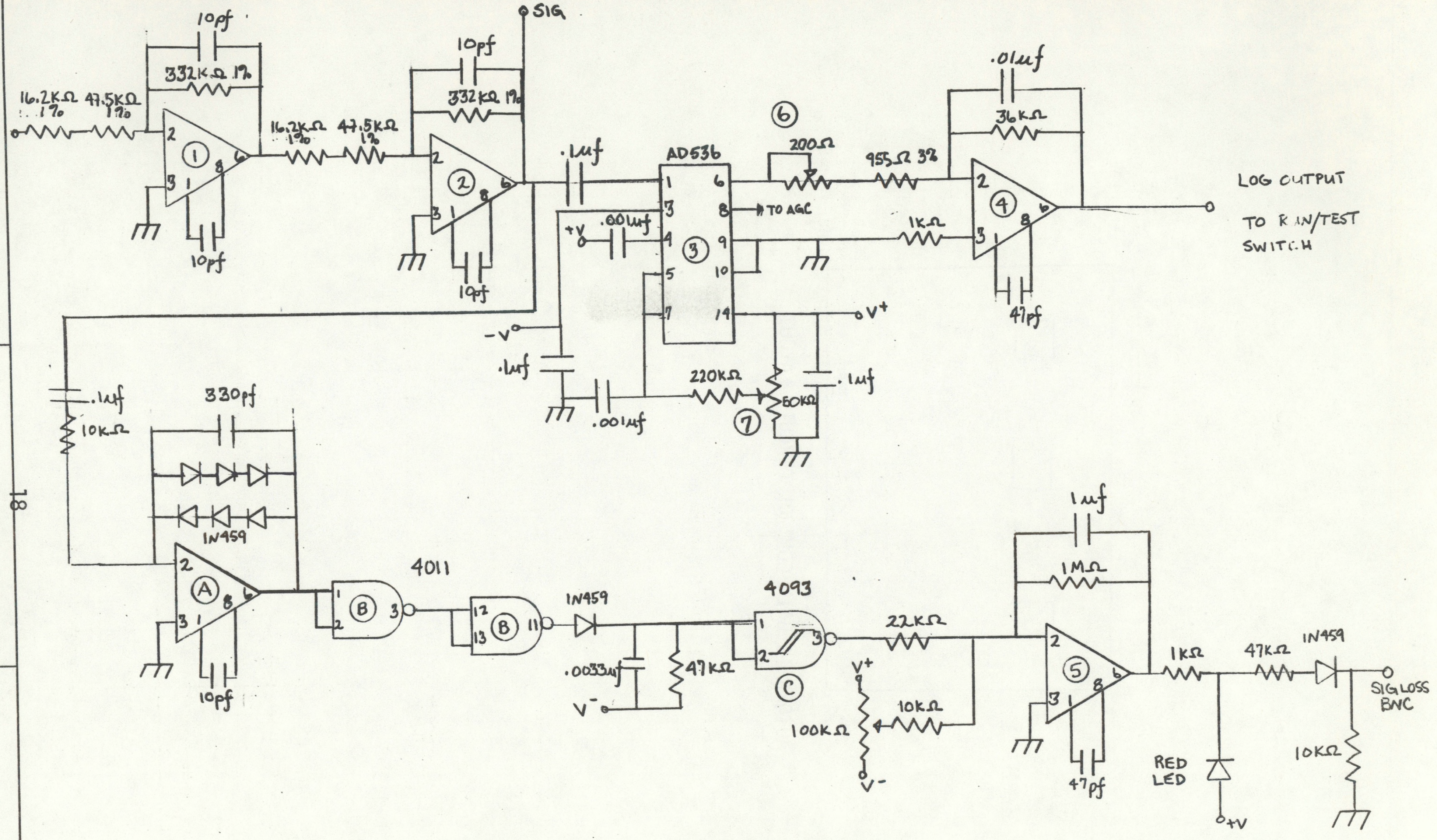
PHOTODIODE PREAMPLIFIER



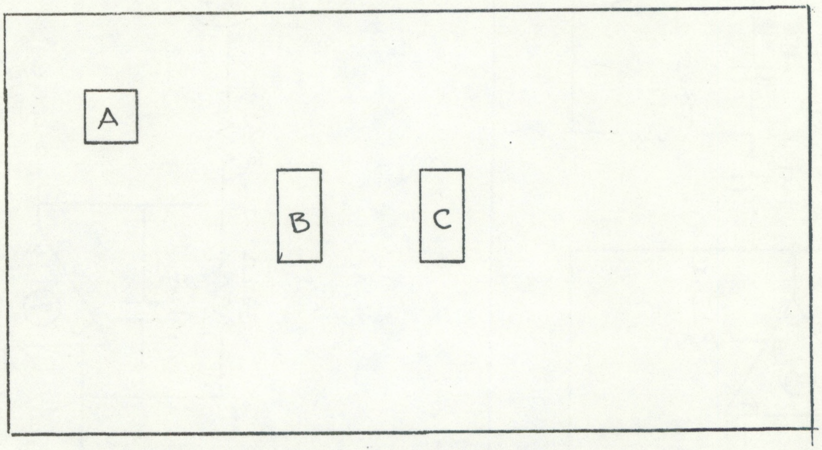
AUTOMATIC GAIN CONTROL CIRCUIT



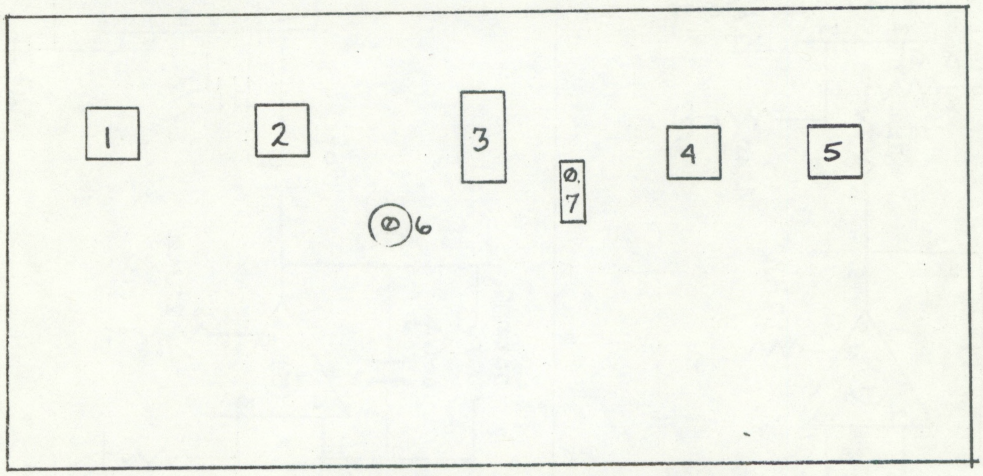
AUTOMATIC GAIN CONTROL CIRCUIT LAYOUT



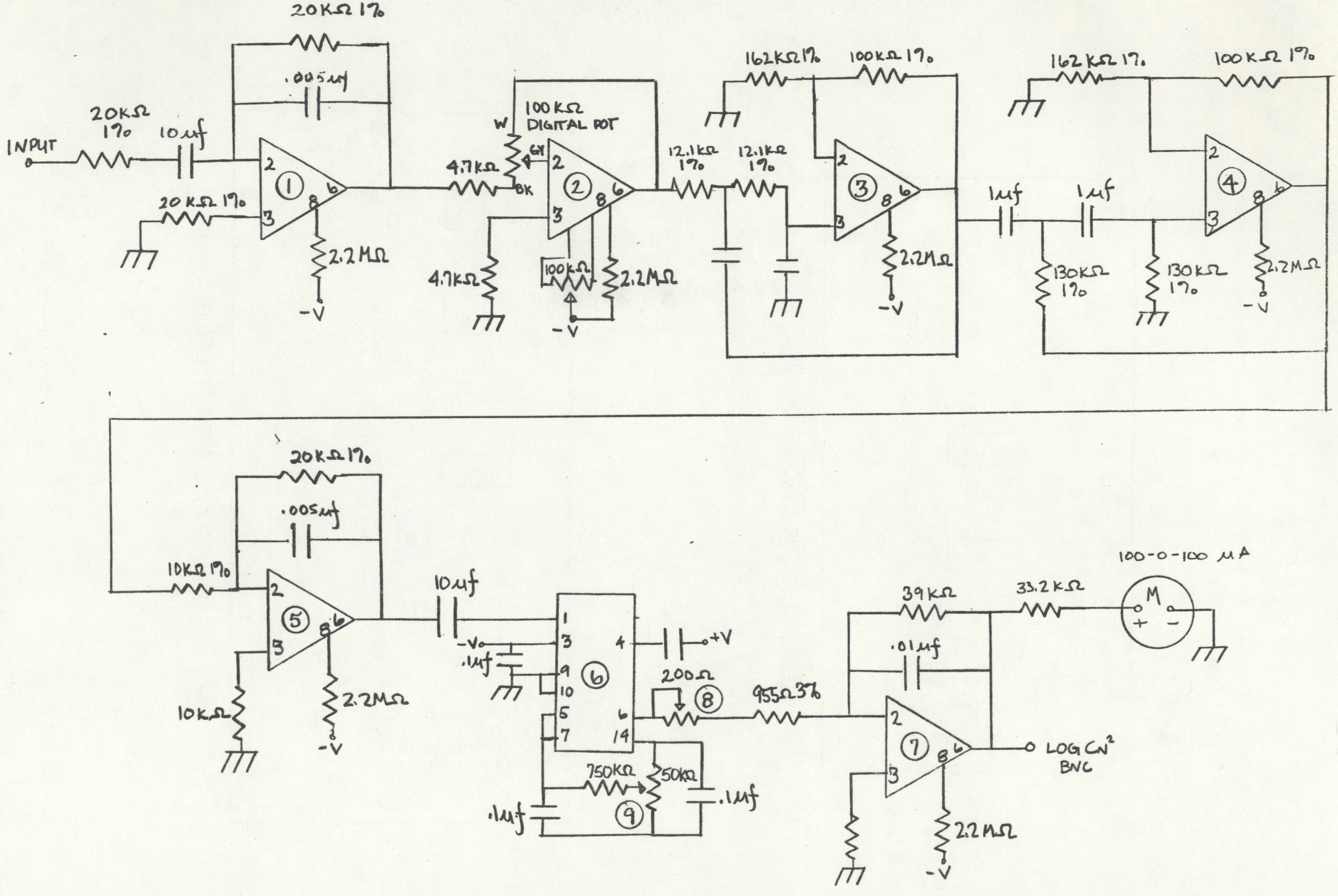
DEMODULATOR CIRCUIT W/SIGNAL DETECTOR



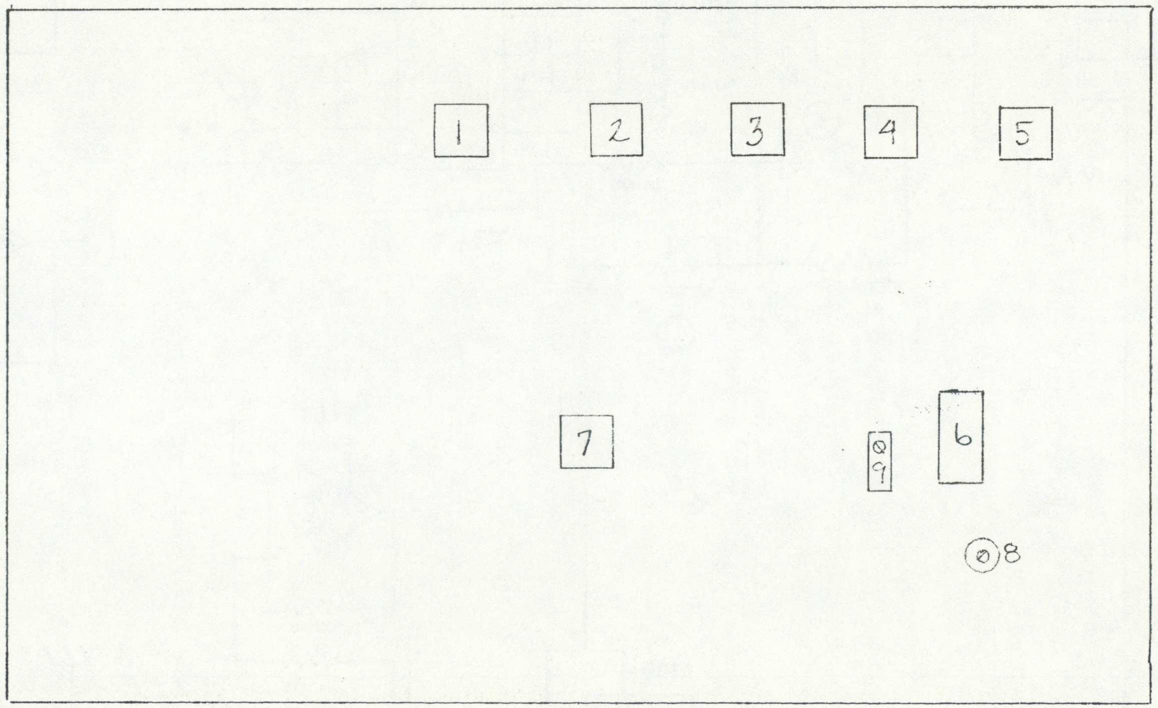
SIGNAL DETECTOR CIRCUIT LAYOUT



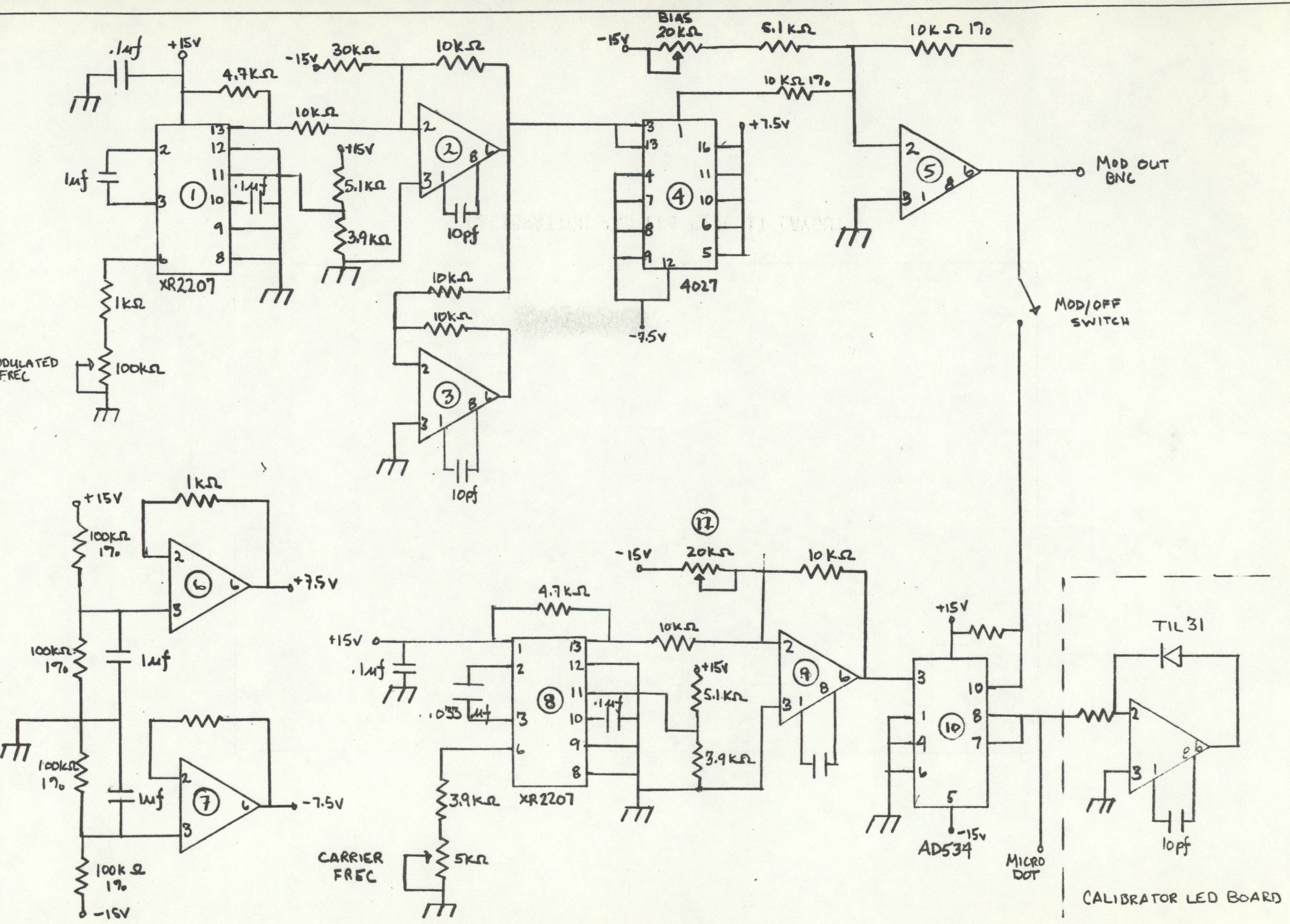
DEMODULATOR CIRCUIT LAYOUT



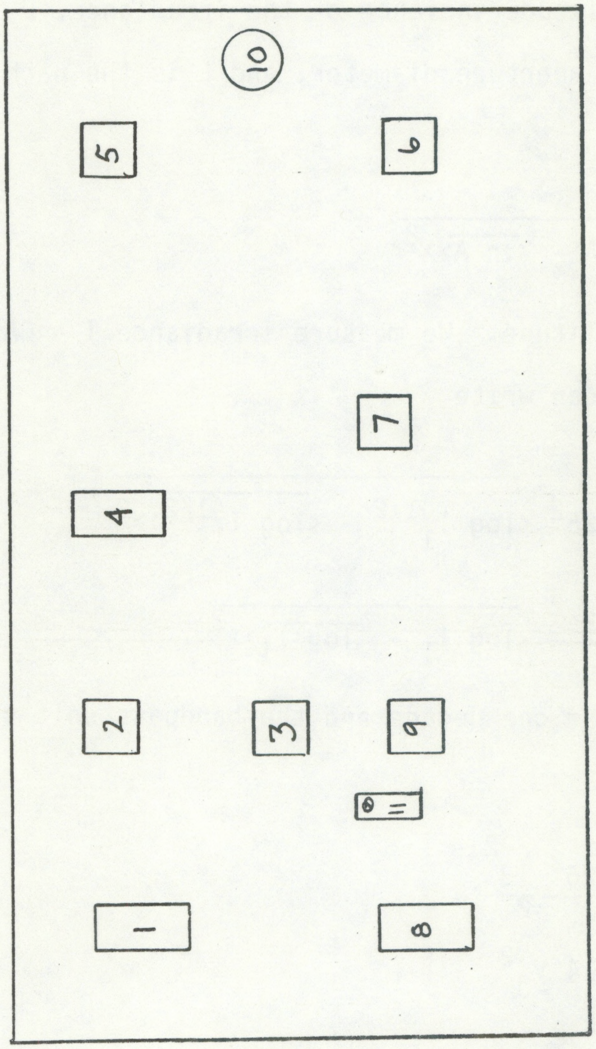
CALIBRATION AND LOG CIRCUIT



CALIBRATION AND LOG CIRCUIT LAYOUT



CALIBRATION CIRCUIT



CALIBRATOR CIRCUIT LAYOUT

APPENDIX B

Derivation of Calibration

Refer to Fig. 5.

$$C_n^2 = 4.48\ \sigma_x^2\ D^{7/3}\ L^{-3} \tag{B1}$$

where σ_x^2 is the log-amplitude variance of the irradiance, D is the transmitter and receiver aperture diameter, and L is the path length. By definition,

$$\sigma_x^2 = \overline{<\ell n\ A - \overline{<\ell n\ A>}>^2}$$

where A is the light amplitude. We measure irradiance $I = CA^2$. Also since $\ell n\ A = 2.3026 \log A$, we can write

$$\begin{aligned} \sigma_n^2 &= 2.3026^2\ \overline{<\log I_1^{1/2} - \overline{<\log I_1^{1/2}>}>^2} \\ &= \frac{2.3026^2}{4}\ \overline{<\log I_1 - \overline{<\log I_1>}>^2}\ . \end{aligned} \tag{B2}$$

In the log unit, 2 volts = one decade and the bandpass unit subtracts off $(\overline{<\log I_1>})$ so that

$$\begin{aligned} \sigma_x^2 &= \frac{2.3026^2}{4}\frac{V_3^2}{2} \\ \sigma_x^2 &= 0.3314\ V_3^2 \end{aligned} \tag{B3}$$

Combining (B1) and (B3),

$$C_n^2 = 1.48\ D^{7/3}\ L^{-3}\ V_3^2\ . \tag{B4}$$

Decide on the following instrument calibration

$$C_n^2 = 10^{-12}\ V_4^2\ . \tag{B5}$$

Determine gain K as a function of path length L. From the circuit,

$$V_4 = K\ V_3 \ . \tag{B6}$$

Combining (B4), (B5), and (B6), to eliminate C_n^2, V_3, and V_4,

$$K = 1.22 \times 10^6\ D^{7/6}\ L^{-3/2} \ . \tag{B7}$$

Decide on the following log output calibration (V_5):

$$C_n^2 = 10^{(V_5 - 14)} \tag{B8}$$

Combining (B5) and (B8)

$$\begin{aligned} 10^{-12}\ V_4^2 &= 10^{-14}\ \log^{-1} V_5 \\ V_5 &= 2\ + 2 \log V_4 \end{aligned} \tag{B9}$$

Thus the log unit should be set so that

$$V_5 = 0 \text{ when } V_4 = 0.1$$

and

$$V_5 = 2 \text{ when } V_4 = 1 \text{ (i.e., 2 volts/decade).}$$

To determine the RMS voltage to be used to check the circuit gain, set $V_4 = 1$ volt ($V_5 = 2$ volts). Then from (B7)

$$K = \frac{V_4}{V_3} = \frac{1}{V_3} = 1.22 \times 10^6\ D^{7/6}\ L^{-3/2} \ .$$

For D = .0438 m (effective diameter, see Ref. 3).

$$V_3 = 3.15 \times 10^{-5}\ L^{3/2} \ . \tag{B10}$$

Derivation of Calibrator Signal and Instrument Output Relationship

The calibrator generates an adjustable square-wave modulated signal having a 7 kHz carrier. In the instrument, modulated signals are demodulated (V_2), the logarithm is taken with 1 decade = 2 volts, and the mean is removed (V_3). Then in terms of the maximum to minimum square wave voltage ratio (a/b), the mean square output voltage (V_3^2) is then (see Fig. 7)

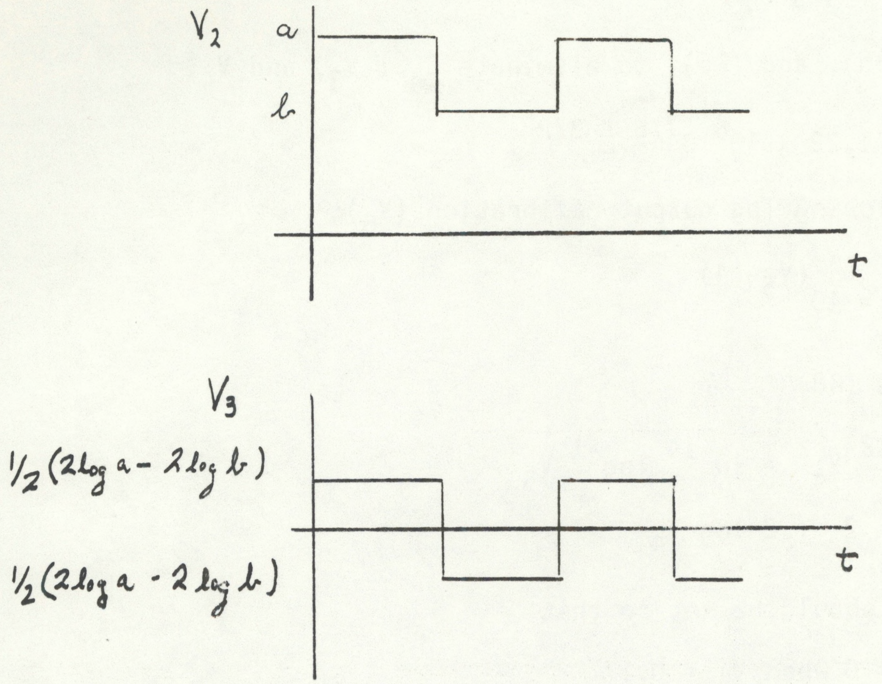


Figure 7. Derivation of calibrator signal

$\overline{V_3^{\,2}}\ [\log_{10}(a/b)]^2$.

Calculate gain (K) as a function of pot position (P). from the circuit (Fig. 8) we have

$$K = 2 \times 2.62 \left(\frac{100,000 - R}{4700 + R}\right) . \qquad \text{(B11)}$$

Since

$$R = 100\ P \qquad \text{(B12)}$$

where P is the digital pot setting, we can combine (B7), (B11), and (B12) and obtain an expression for P in terms of L as

$$P = \frac{5240 - 1.49 \times 10^6\ L^{-3/2}}{3.17 \times 10^4\ L^{-3/2} + 5.24} . \qquad \text{(B13)}$$

This function is plotted in Fig. 5.

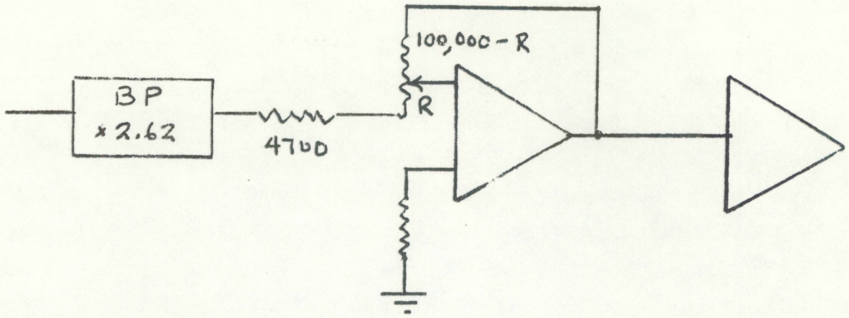


Figure 8. Adjustable gain circuit

Saturation Criteria

Assume $C_n^2 = 10^{-12}$ maximum. From Ref. 3, the transmitter and receiver diameters required to prevent saturation effects are

$$\alpha_r + \alpha_t > 5.4\ (\sigma_T^2)^{3/5} \tag{B14}$$

where α_r = receiver diameter in Fresnel zones,

α_t = transmitter diameter in Fresnel zones, and

$\sigma_T^2 = 0.124\ (\frac{2\pi}{\lambda})^{7/6}\ L^{11/6}\ C_n^2$ (λ = light wavelength).

Letting $\alpha_r = \alpha_t = D/\sqrt{\lambda L}$, (B14) becomes

$$\frac{2D}{\lambda^{1/2}\ L^{1/2}} > 5.4\ [0.124\ (\frac{2\pi}{\lambda})^{7/6}\ (2L)^{11/6}\ C_n^2]^{3/5}\ . \tag{B15}$$

In terms of aperture diameter,

$$D > 2.7\ \lambda^{-1/5}\ L^{8/5}\ (C_n^2)^{3/5}\ . \tag{B16}$$

In terms of path length,

$$L < 0.54\ D^{5/8}\ \lambda^{1/8}(C_n^2)^{-3/8}\ . \tag{B17}$$

For D = 0.0438 m, $\lambda = 0.94 \times 10^{-6}$ m, and $C_n^2 = 10^{-12}$, L < 426 m. Again note the L is the total optical path length, i.e., twice the separation.