NOAA Technical Memorandum ERL WPL-52
Revised

OPTICAL SYSTEM MODEL IV FOR SPACE-AVERAGED WIND AND C_n^2 MEASUREMENTS

G. R. Ochs
W. D. Cartwright

Wave Propagation Laboratory
Boulder, Colorado
March 1980
(Revised October 1985)

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ABSTRACT

This report describes an optical instrument that measures the path-averaged values of the refractive-index structure parameter (C_n^2) and the crosswind over optical paths from 200 to 1500 m. On optimum path lengths of 900 to 1200 m, C_n^2 can be measured over a range from 1×10^{-12} to 1×10^{-16} $m^{-2/3}$.

1. INTRODUCTION

In reference (1) a new optical technique for measuring the refractive index structure parameter (C_n^2) is described. The paper derives expressions for obtaining a path-averaged measurement of C_n^2 by observing the scintillation of an extended incoherent light source, as seen with an extended receiving aperture. An instrument designed to make this measurement is described in reference (2). Reference (3) discusses various techniques for measuring the component of wind at right angles to a line-of-sight path, by analyzing the motion of the scintillation patterns from a light source, seen by a suitable receiver. The so-called covariance technique discussed in this reference is employed in the model III optical crosswind instrument described in reference (4). The model IV described in this report is essentially the model III with C_n^2 measurement capability added.

The new configuration requires some component changes, however. A larger photodiode (5 mm^2 area rather than 0.8 mm^2) is used so that the pointing is easier and more likely to be correct for the C_n^2 measurement. The increased noise background reduces the wind measurement range from that of the model III, however. The C_n^2 measurement circuit also contains changes from that employed in reference (2) to accommodate the lower scintillation frequencies resulting from the use of larger apertures.

2. OPERATING PROCEDURE

The receiver and light source are shown in Figures 1 and 2. The light source consists of a light emitting diode (LED) at the focus of a 15-cm dimaeter concave mirror of 28 cm focal length. Since the LED emitting surface is less than 0.4 mm in diameter a ground glass diffuser is included, which can be positioned in front of the LED to make a larger beam that is easier to point. The ground glass can be inserted or taken out after removing the back plate holding the concave mirror. It is better to operate from a solid support and not use the ground glass, however.

The power supply modulates the LED at 25 kHz. There is a modulation switch but it should be on at all times when using this system. Also there is provision for frequency modulation for data transmission at a future time. There is an adjustment for LED current on the front panel. For paths from 0.5 to 1.5 km, set the current to 300 ma. DO NOT EXCEED 300 MA AT ANY TIME. The automatic gain control (AGC) circuit in the receiver will adjust for proper signal level. For paths less than 500 m, the current must be reduced approximately in proportion to the square of the path length to prevent receiver saturation. For example, at 100 meters, set the current at $300(1/5)^2 =$ 12 ma.

Both the light source and the receiver should be mounted on firm vibrationless mounts. The receiver should have some protection from the weather in a permanent installation. This might consist of an open-ended box, or if desired, the instrument can operate satisfactorily through an ordinary glass window. To set up the system point the light source at the receiver using

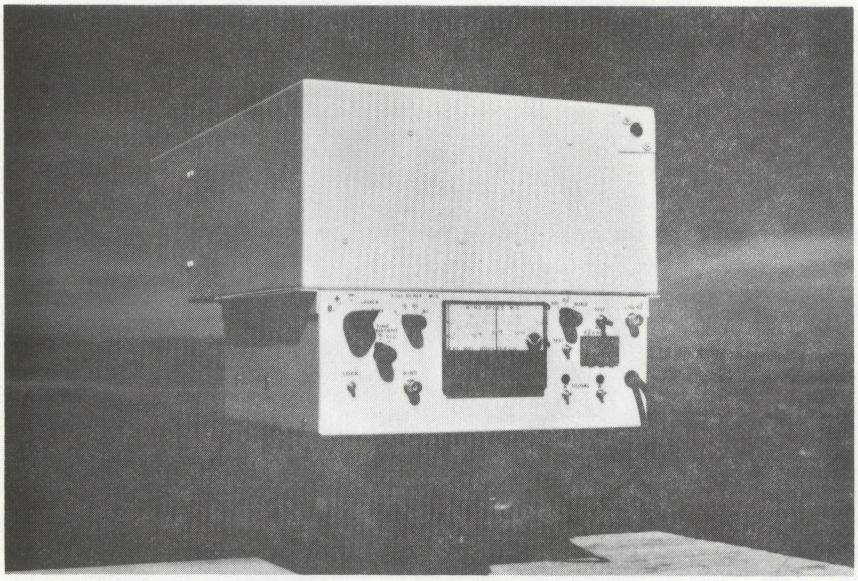

Figure 1. Model IV receiver.

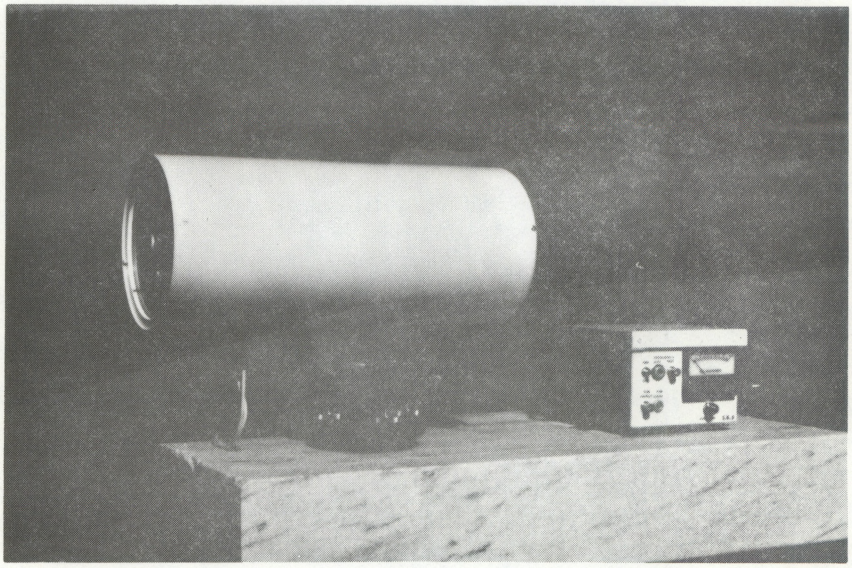

Figure 2. Model IV transmitter.

the sighting telescope. Set the meter switch to SIGNAL. Then align the receiver by looking through its sight. When a signal is received, the green LEDs will light up and a meter deflection will be seen. Now move the receiver up and down and sideways fairly rapidly, watching when the LEDs go out, and set at the midpoint for the best alignment. The AGC will affect this procedure somewhat. When the receiver is first turned on the AGC is at lowest gain. When not receiving a signal it will go to maximum gain in about one minute. When receiving a signal the AGC time constant is about 5-10 seconds.

For maximum signal-to-noise on long paths we recommend connecting an oscilloscope to the panel signal jacks and lowering the LED current to the point where the signal is just barely detectable at the receiver. Then adjust the transmitter for maximum signal at the receiver both by transmitter pointing and by adjustment of the carrier frequency at the LED power supply. The AGC will be at its maximum gain and will not interfere with the pointing adjustment. When this adjustment is completed, raise the LED to its normal value. When the system is properly aligned, and the function switch turned to LOCK, the meter should read in the region from 10 to 50 (+ or - depending on wind direction across the path). If the wind is almost directly down the path, this test may fail and the reading will be zero even with proper alignment.

2.1 Wind Measurement

The front panel controls function as follows:

METER SWITCH - Connects the front panel meter to SIGNAL, C_n^2, or WIND. In the wind position, the FUNCTION SWITCH controls what is presented on the meter.

FUNCTION SWITCH - This switch displays various functions on the front panel meter and also controls other operation as indicated.

0,+,- - These positions (zero, +full scale, -full scale) serve as calibration points for circuit alignment and for wind signal recording convenience. At the WIND BNC the output for ± full scale is ± 3.0 volts.

LOCK - In this position, the meter reads a relative indication (0 to full scale) of the signal available for wind measurement. The polarity of the signal indicates the wind crossing direction. If the reading is zero or fluctuates + and - around zero, the wind is directly down the optical path, the servo system has not yet locked on, or there is insufficient signal-to-noise to operate.

RUN - The normal operating position with the panel meter indicating crosswind speed. When the meter is to the right of zero (or + output at the WIND BNC), the wind is crossing from left to right.

FULL SCALE M/S - This control sets the full scale reading for both the front panel meter and the WIND BNC output.

SIG - The modulated optical signals may be seen at these two test points.

LOCK - The lock voltage is available on the panel for test purposes.

TIME CONSTANT - The wind measurement can be averaged over 1, 10, or 100 second periods. Generally, the 1 second position is used for testing, with 10 or 100 second averaging used in operation.

2.2 C_n^2 Measurement

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.

To calibrate the system, determine the path length to be used. Paths of 900 to 1200 meters are optimum although the instrument can be used over a range from 200 to 1500 meters with restricted dynamic range. For the path length selected, determine the calibration number in Fig. 3 and set the digital calibration pot.*

A direct readout of C_n^2 is now displayed on the panel meter when the function switch is set to C_n^2. Regardless of the function switch setting, a voltage (V_5) proportional to the logarithm of C_n^2 is available at the BNC output jack. The relationship is

$$C_n^2 = 10^{-14} \log^{-1} V_5.$$

3. ALIGNMENT PROCEDURE

The following procedures are those used to initially align and calibrate the instrument. These adjustments should not be required in normal operation.

3.1 Optical Alignment

The transmitter consists of a TIES-27 LED placed at the focus of a concave 15-cm diameter mirror of 27.9-cm focal length. To set the focus, point the transmitter at a bright light at least 200 m away. Loosen the knurled nuts supporting the LED mount and adjust them until the light is precisely focused on the LED surface. Since the LED is reversible and will perform as a photodiode, the pointing and focus can be checked by observing the current with an oscilloscope. After roughly aligning the transmitter with the riflescope sight using the knurled nuts, the final alignment can be accomplished with the click stops on the riflescope.

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* The setting may also be calculated from equation (13). This equation is derived from the calculated gain of the circuit. It may be checked by inserting a sine wave test signal of about 100 Hz into the calibration test jack, of RMS value determined by equation (10). Adjust the digital pot until $V_4 = 1.00$ volt (log output $V_5 = 2.00$ volts). This setting should check with the value calculated from equation (13).

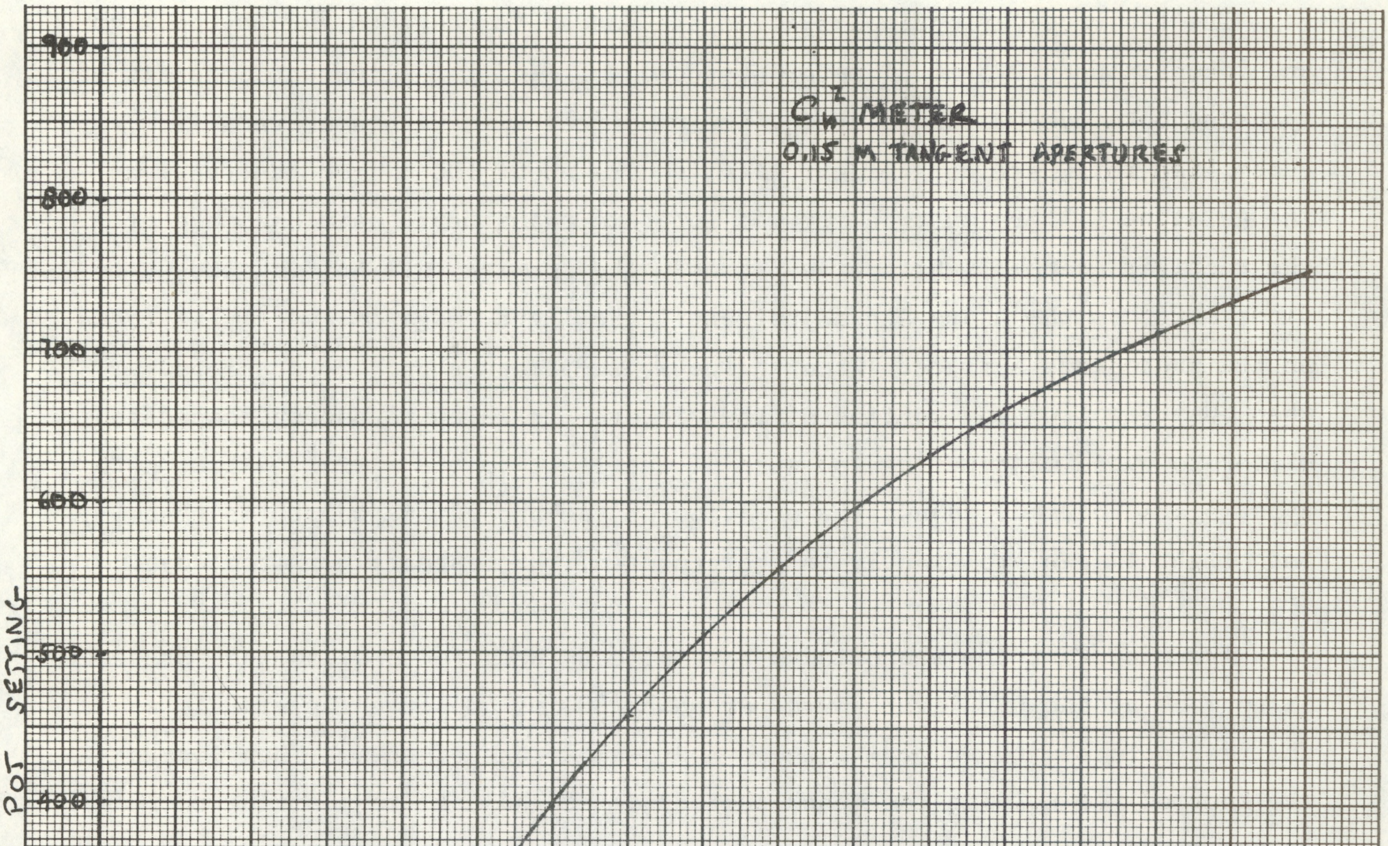

Figure 3. Calibration setting versus path length.

The two receiver optical systems use concave mirrors to gather the light and focus it upon 2.5-mm diameter photodiodes. Initial alignment consists of focusing both systems and aligning their optical axes within 1 mrad. To accomplish this, set up a bright light source about 500 m from the receiver. The gelatine filters must be removed for this adjustment. Aim one edge of the receiver at the light source. Loosen the knurled nuts holding the photodiode mount to the glass and adjust until the light image is exactly in focus on the photodiode surface. When in focus, the image should be stationary when observed from any portion of the mirror. It helps to use an inspection mirror to avoid obstructing too much of the light to the mirror. After both systems are focused, adjust the position of the photodiode mounts so that both light images are exactly in the center of the respective photodiodes.

Assuming that the photodiodes have already been focused, another procedure is to look at the LED light source at about 500 m. Observe the signals at the test points with an oscilloscope and peak up one of them. Then loosen the knurled nut holding the other photodiode and adjust its position to peak up the other signal.

3.2 Electronic Alignment

Refer to Appendix A for circuit diagrams and layout.

3.2.1 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 30 kHz. To calibrate, set the DC power supply to +10 volts with the internal adjustment on the power supply board. Then point the LED at the receiver, reducing the driver current as necessary, and peak up the signal response by adjusting the frequency control on the power supply front panel.

3.2.2 Receiver

Check and calibrate the preamplifier, AGC, detector, and C_n^2 circuits as follows:

1. Connect a 0.94 µm LED to a signal generator and modulate at about 30 kHz. Illuminate each objective in turn with the LED. A piece of ground glass placed a few cm in front of the LED is helpful. Observe the signal at the signal test points. It may take a minute or more to build up as the AGC circuit has a long time constant. Peak up the signal by adjusting the signal generator frequency. Observe the AGC action by moving the LED. The circuit should slowly adjust to keep the RMS level at about 2 volts.

2. Adjustment of the three AD 536AKD RMS circuits, which determine the C_n^2 calibration, is accomplished as follows. Remove the op amp (2B, 2G, or E) 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 for 2.00 volts.

3. Cover the optics. Turn the instrument on and wait at least 1 minute. Then adjust pot c until the green signal light on the panel comes on. Then back off 4 turns.

4. Adjust pot e in the same way as pot c.

Check and calibrate the covariance analyzer (wind measurement), as follows:

5. Remove op amps A and G.

6. Set panel controls as follows:
    Meter Switch- WIND
    Function- RUN.
    Time Constant- 1 second.
    Full Scale- 20 m/s.

7. Set pot L approximately to midscale. This step is necessary for the initial calibration only.

8. Adjust gain pot h and offset pot g for + and -3.00 volts at the wind output, with the function switch in CAL + and -, respectively. This can be done by adjusting gain pot h for a 6 volt difference between the CAL + and - positions, and then adjusting offset pot g to obtain +3.00 and -3.00 volts in the respective CAL + and - positions.

9. With the function switch in CAL + or -, adjust pot i for meter full scale.

10. With the function switch in CAL + or -, and the full scale switch set to each pot in turn, adjust pots j, k, l, and m for 2.27, 4.53, 9.06, and 18.13 kHz, respectively, at the clock TP (jumper near pin 7 of IC S).

11. Apply a sine wave signal of about 2 kHz to pin 6 of op amp sockets A and G. This frequency will not get through the low pass digital filters so that nonchanging DC signal levels are applied to the following digital circuitry. Adjust pot e for full scale in the appropriate direction to keep the meter deflected right or left of zero duing these adjustments. Set the full scale switch to 20 m/s. Turn the function switch momentarily to CAL and back to RUN so that the meter is neither zero nor full scale (right of center). Adjust pot d so that the meter drifts slowly toward zero (takes approximately 10 seconds to go from 50 to 40). It is very important that the drift tendency is toward zero, rather than full scale. Now adjust pot c in the same way for the left hand portion of the meter scale. Then repeat both adjustments as they may be slightly interactive.

12. Continue the 2 kHz sine wave to the inputs. With the function switch set to the 0 position, check for zero wind output and adjust pot g for zero if necessary.

13. Using the same inputs as used in 7, set the function switch to the zero position and adjust pot e for zero volts average at pin 6 of op amp EE (jumper above op amp BB).

14. Apply about 10 Hz sine wave signals, 90¼ out of phase, to the circuits. With the function switch set to LOCK, adjust pot f for full scale on the meter.

15. Replace op amps A and G.

4. REFERENCES

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2. Ochs, G. R., W. D. Cartwright, and D. D. Russell (1980): Optical C_n^2 instrument model II, NOAA Tech. Memo. ERL WPL-51.

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4. Ochs, G. R., W. D. Cartwright, and P. S. Endow (1979): Optical system model III for space-averaged wind measurements, NOAA Tech. Memo ERL WPL-46.

5. Ochs, G. R., R. F. Quintana, and G. F. Miller, (1977): An optical device for measuring refractive-index fluctuation in the atmosphere, NOAA Tech. Memo. ERL WPL-30.

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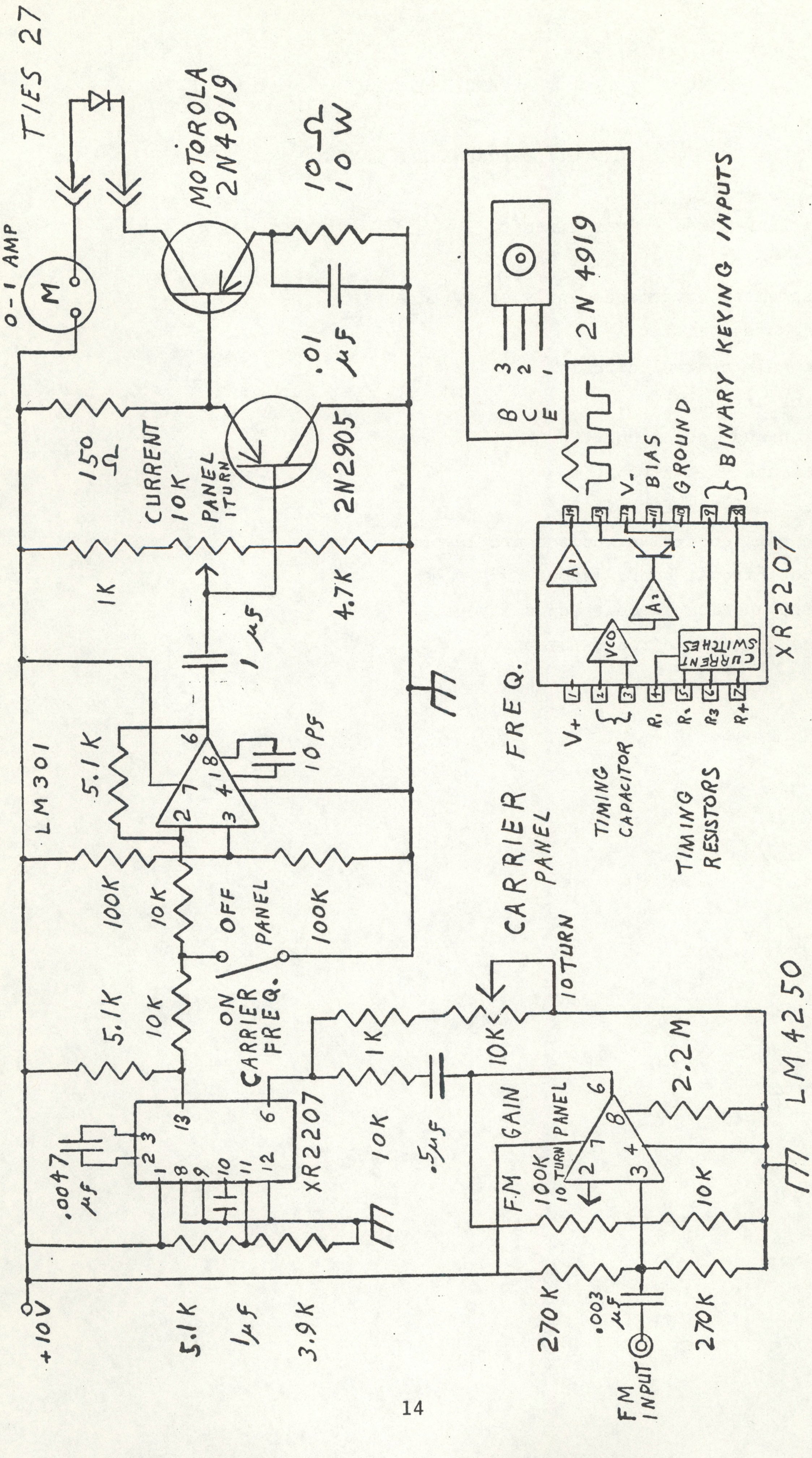
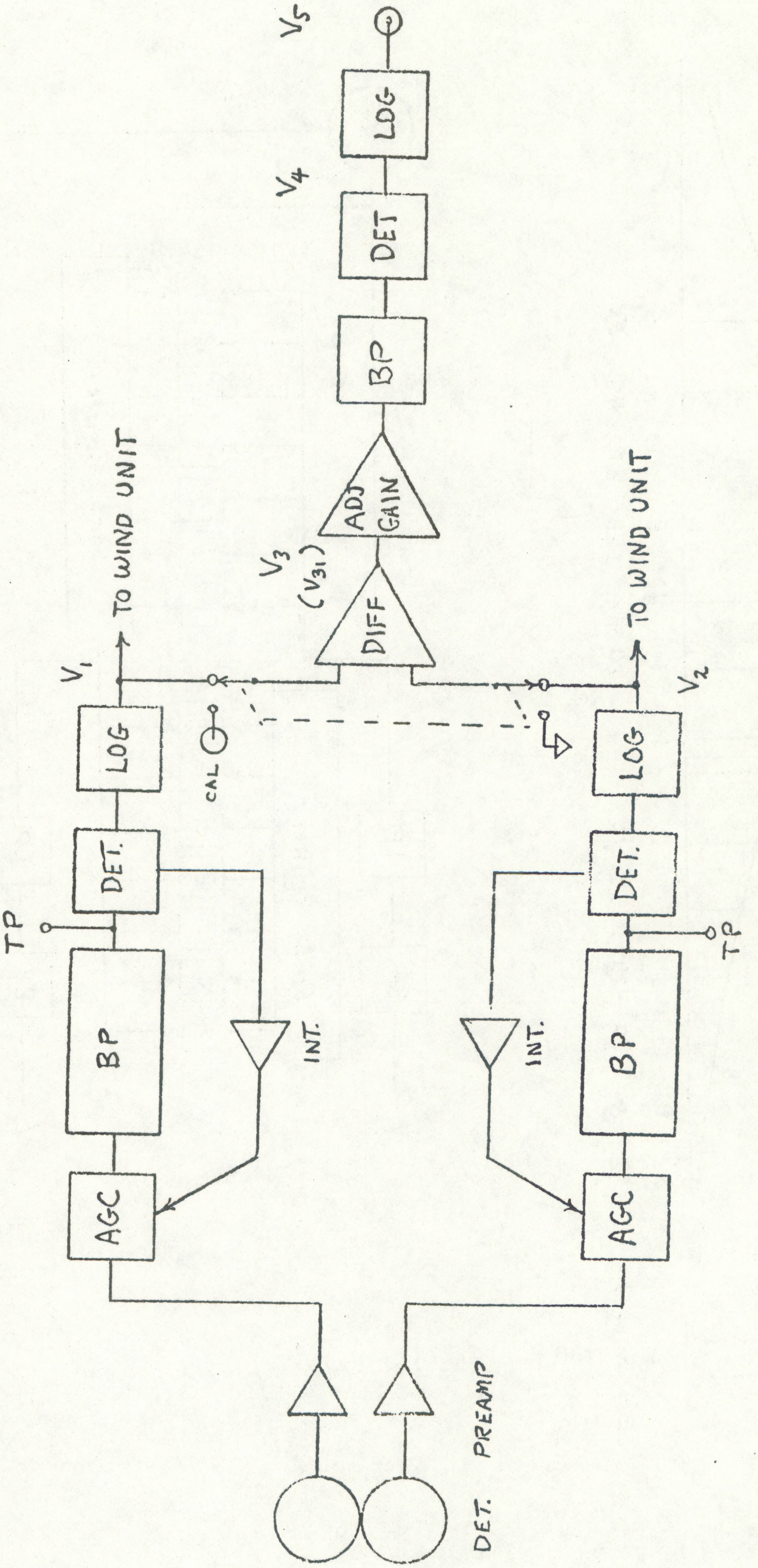
APPENDIX A

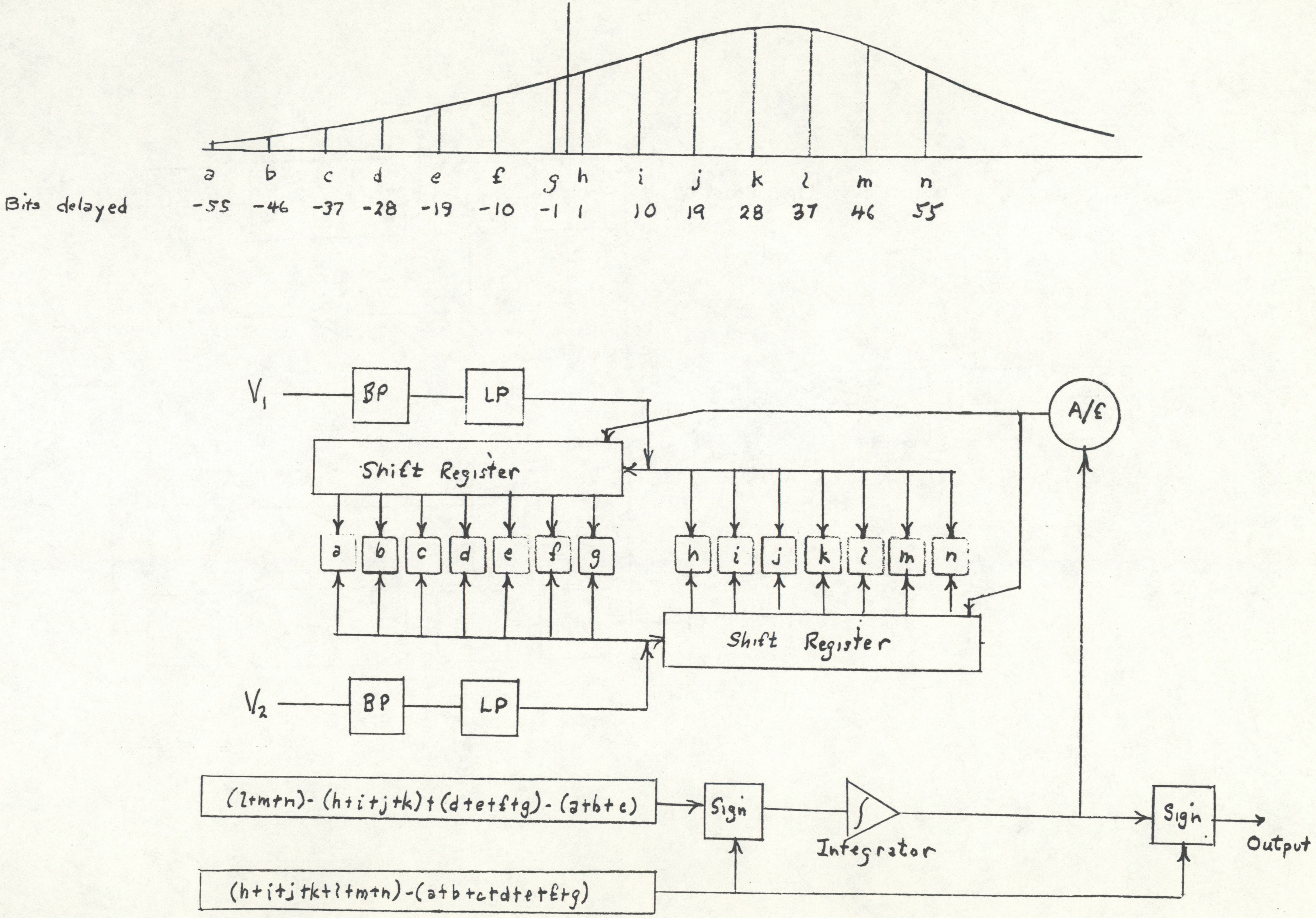
CIRCUIT DIAGRAMS AND LAYOUT



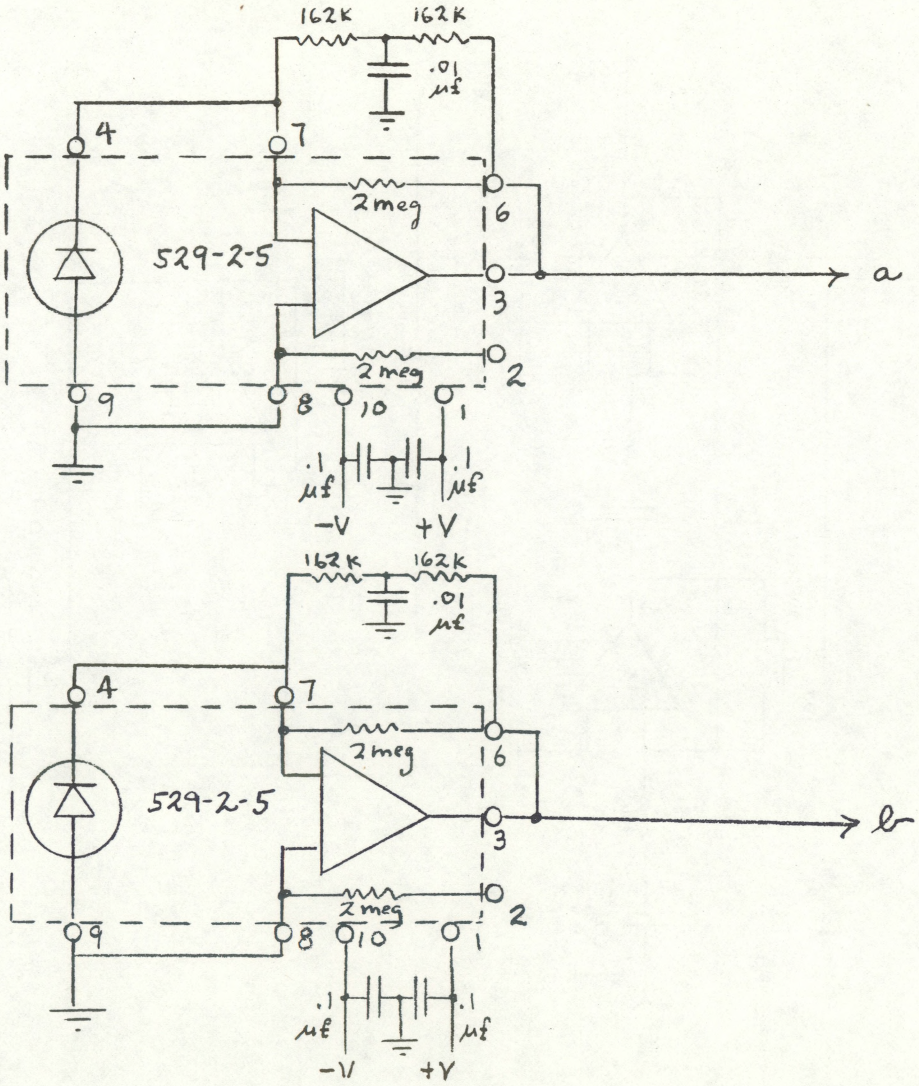
Light emitting diode driver circuit.



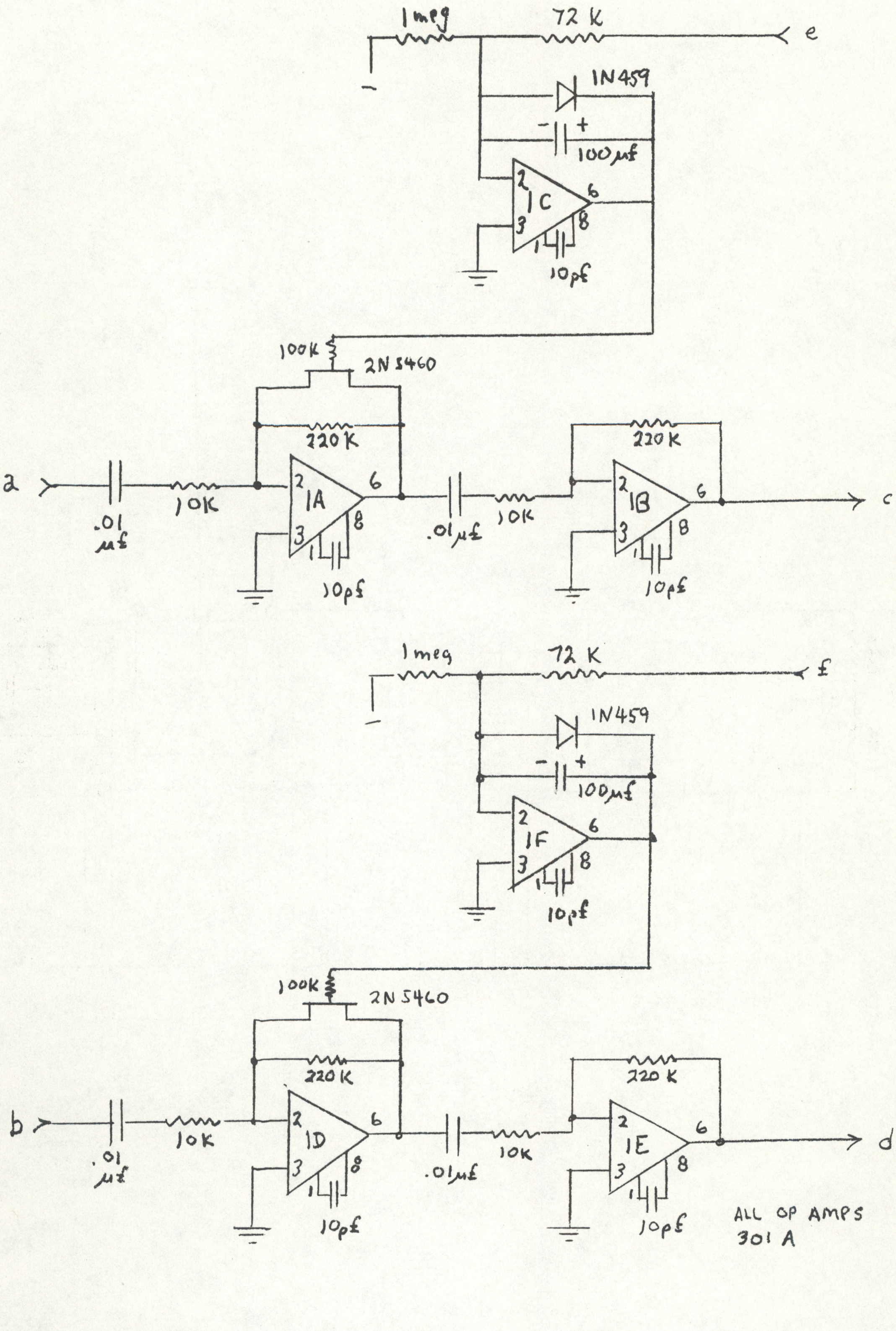
Block diagram of C_n^2 system.



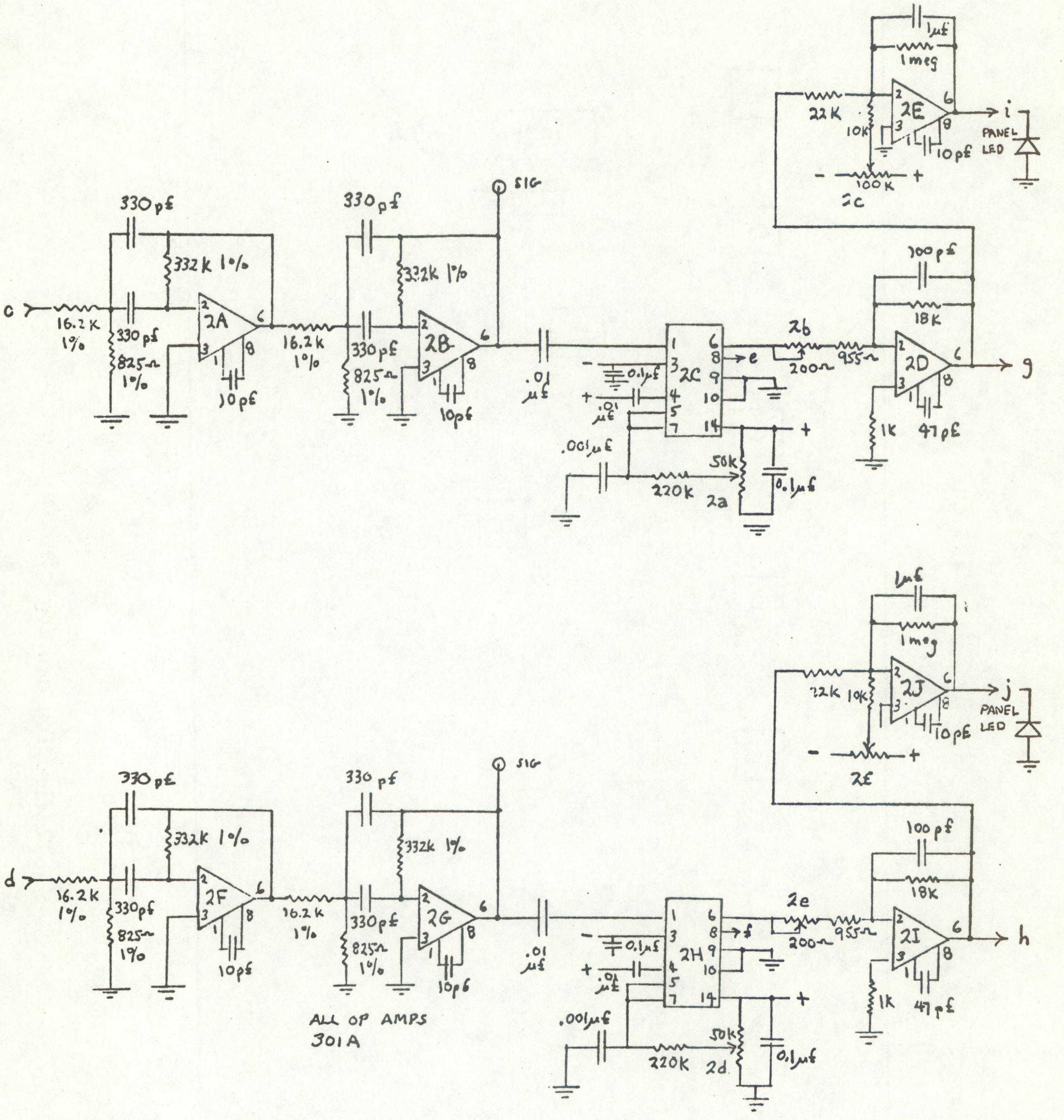
Block diagram of covariance analyzer (wind system).



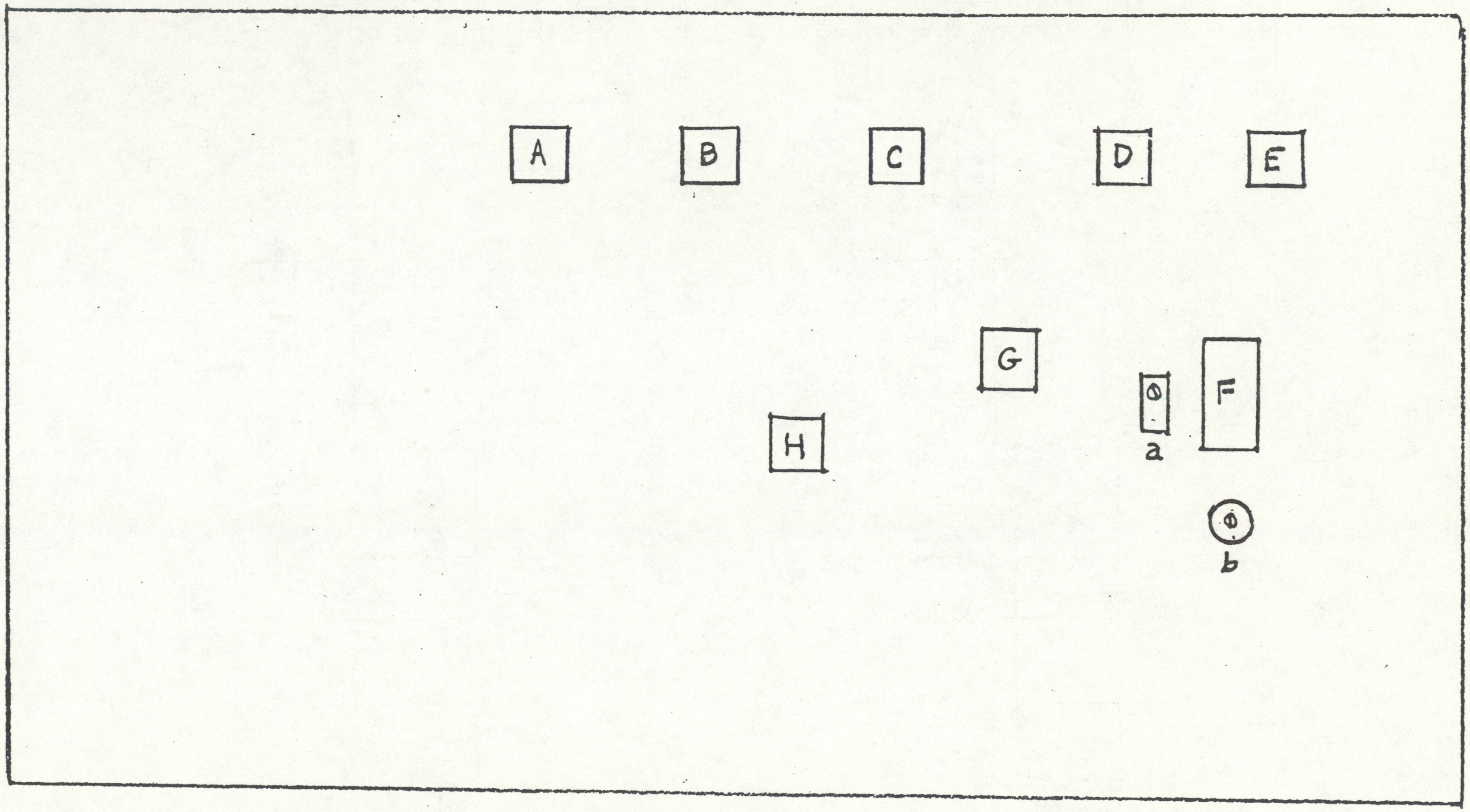
Photodiode preamplifier.



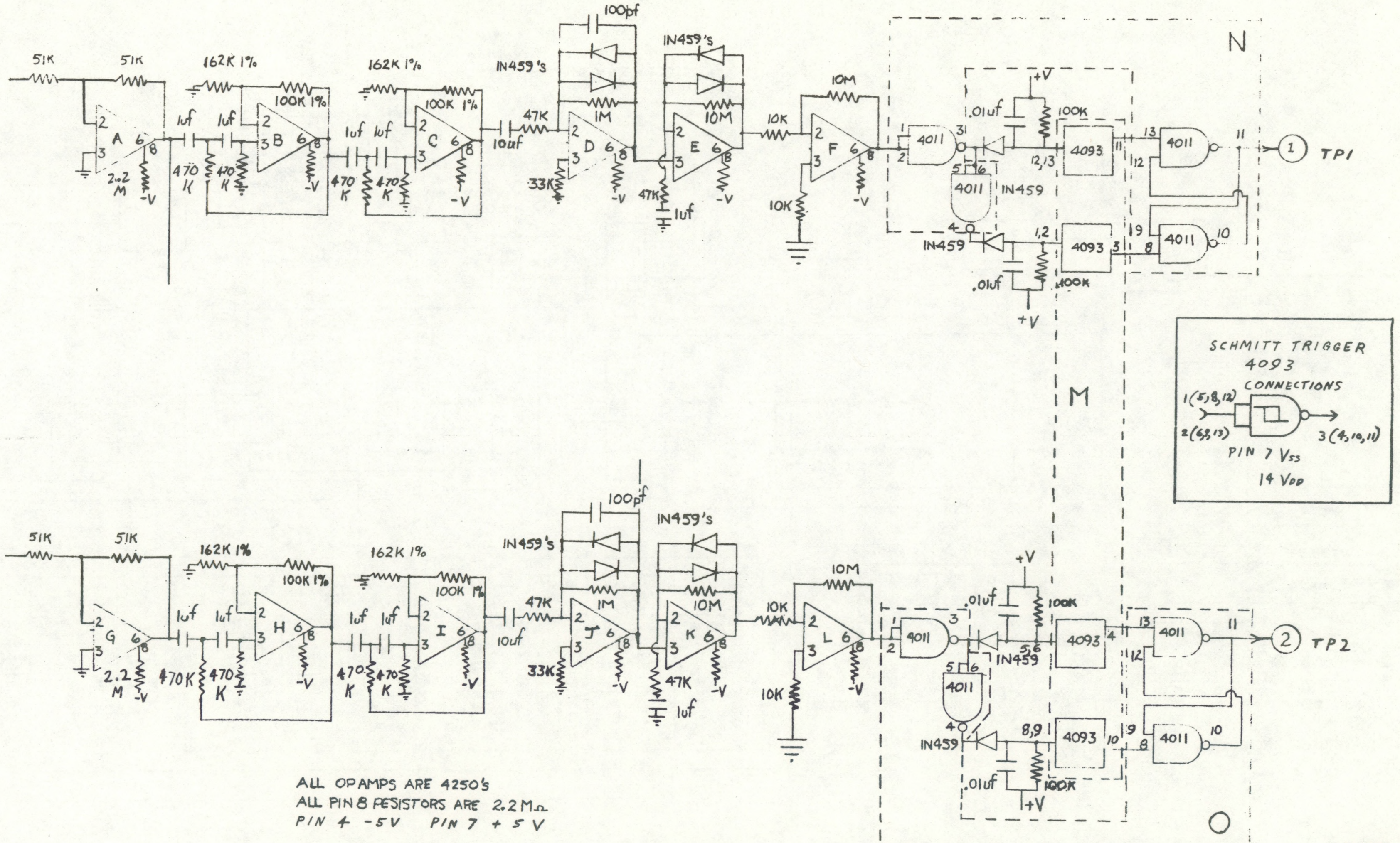
Automatic gain control circuit board layout.



Demodulator circuit board layout.



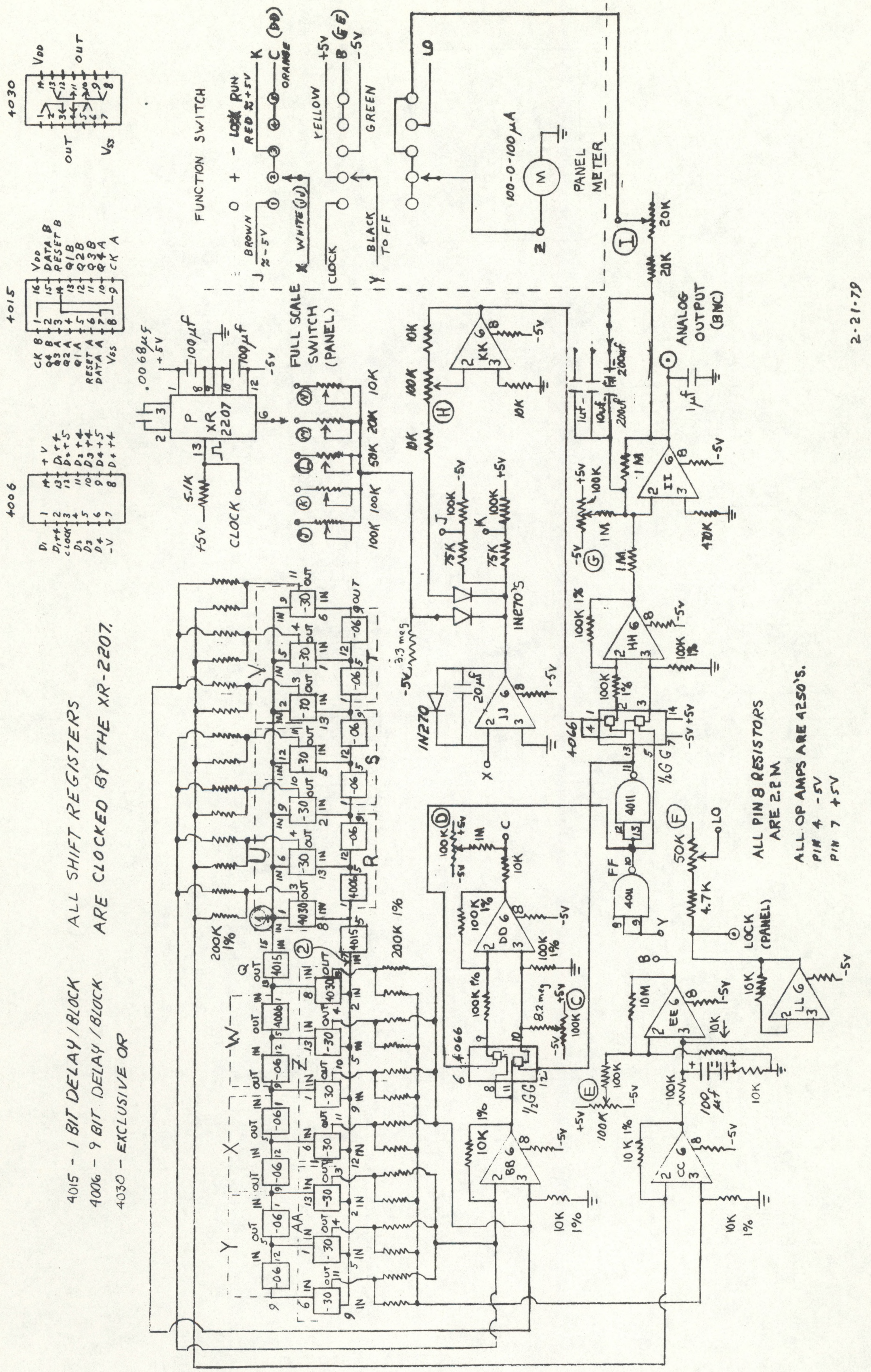
Calibration and log circuit board layout.



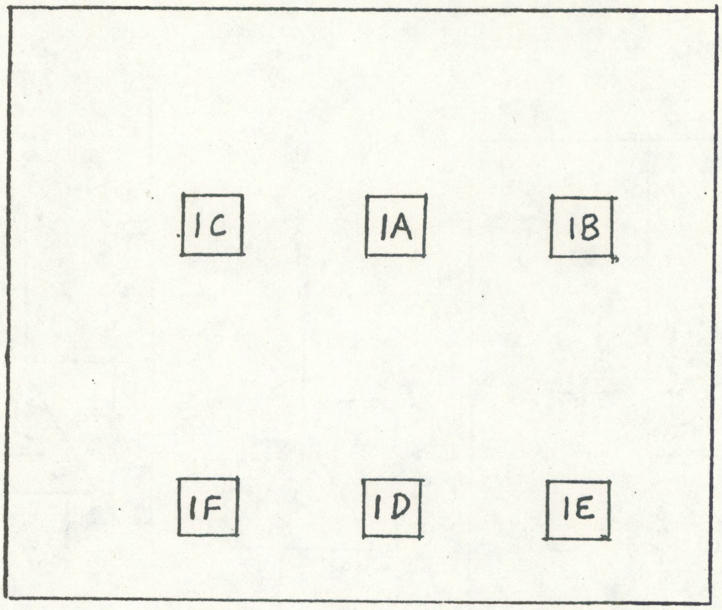
ALL OPAMPS ARE 4250's
ALL PIN 8 RESISTORS ARE 2.2 MΩ
PIN 4 -5V PIN 7 +5V

2-21-79

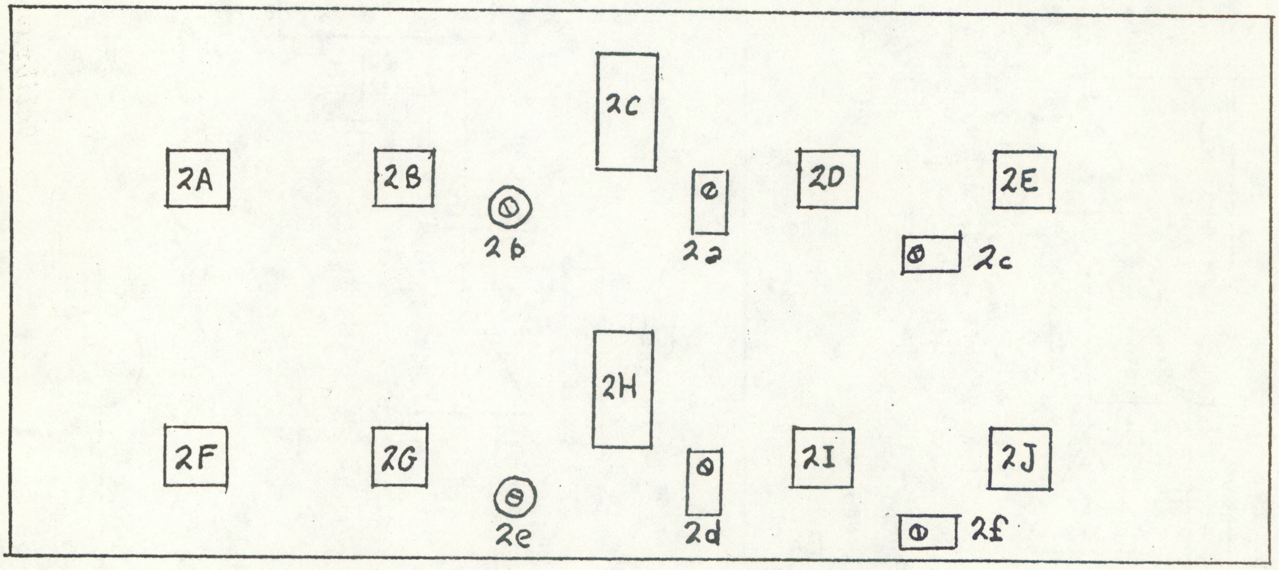
Covariance analyzer circuit 1.



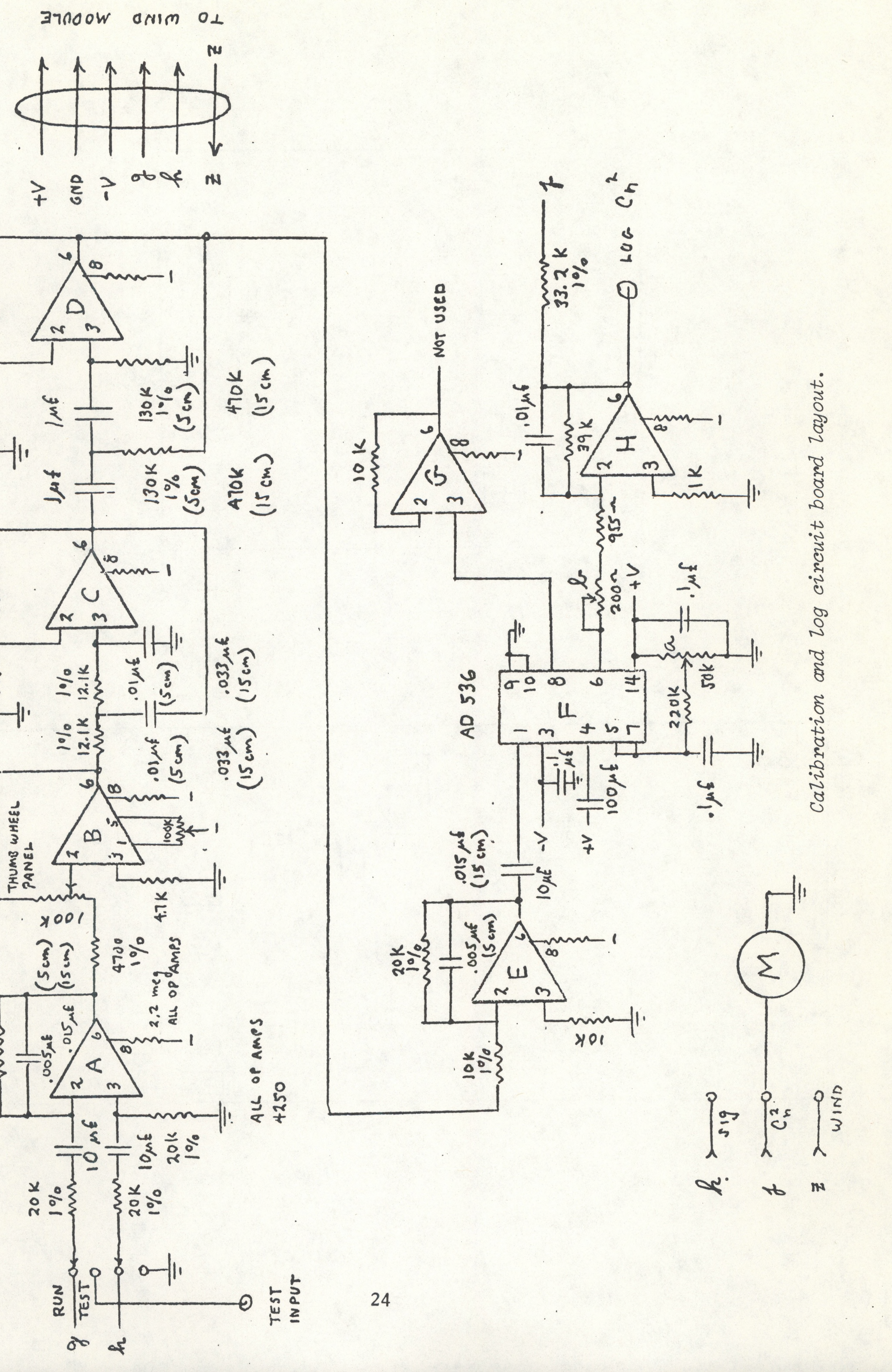
Covariance analyzer circuit 2.



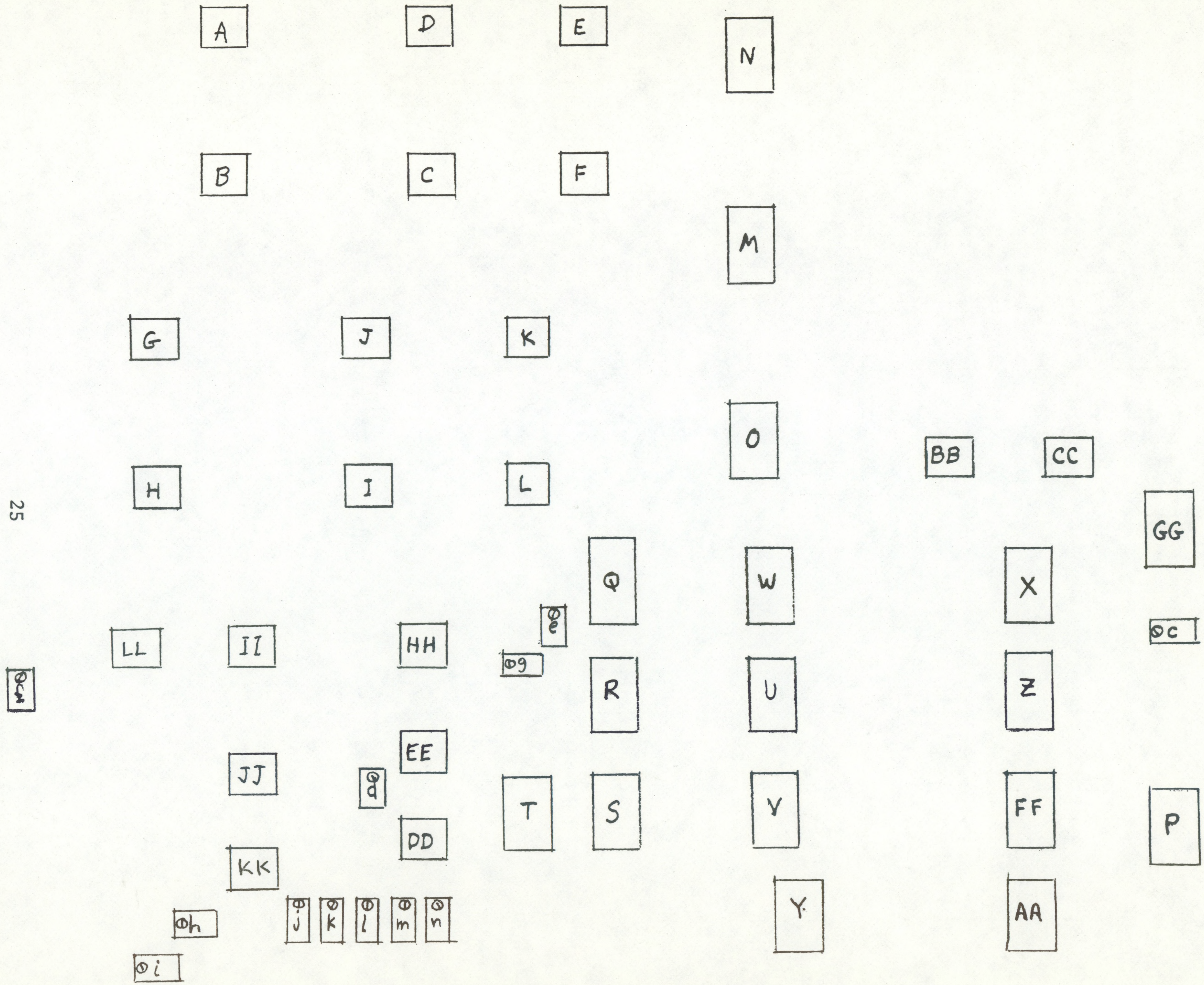
Automatic gain control circuit board layout.



Demodulator circuit board layout.



Calibration and log circuit board layout.



Covariance analyzer circuit board layout.

APPENDIX B

Derivation of Calibration

Refer to the block diagram of the C_n^2 system (Appendix A). Temporarily consider the second detector output disconnected and $V_2 = 0$. Now consider the output of the bandpass filter V_{31} when $V_2 = 0$. From Ref. 1, for one aperture,

$$C_n^2 = 4.48\, \sigma_x^2\, D^{7/3}\, L^{-3} \tag{1}$$

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,

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

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

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

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

$$\sigma_x^2 = \frac{2.3026^2}{4} \left(\frac{V_{31}}{2}\right)^2$$

$$\sigma_x^2 = 0.3314 \, V_{31}^2 \, . \qquad (3)$$

Combining (1) and (3),

$$C_n^2 = 1.48 \, D^{7/3} \, L^{-3} \, V_{31}^2 \, .$$

Now reconnect the second detector. For the tangent apertures, V_1 and V_2 are partially correlated. Then with V_2 connected, from reference (1), $V_3^2 = 1.63 \, V_{31}^2$ and

$$C_n^2 = 0.908 \, D^{7/3} \, L^{-3} \, V_3^2 \, . \qquad (4)$$

Decide on the following instrument calibration

$$C_n^2 = 10^{-12} \, V_4^2 \, . \qquad (5)$$

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

$$V_4 = K \, V_3 \, . \qquad (6)$$

Combining (4), (5), and (6), to eliminate C_n^2, V_3, and V_4,

$$K = 0.953 \times 10^6 \, D^{7/6} \, L^{-3/2} \, . \qquad (7)$$

Decide on the following log output calibration (V_5):

$$C_n^2 = 10^{-14} \log^{-1} V_5 . \tag{8}$$

Combining (5) and (8),

$$10^{-12} V_4^2 = 10^{-14} \log^{-1} V_5$$

$$V_5 = 2 + 2 \log V_4 . \tag{9}$$

Thus the log unit should be set so that

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

and

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

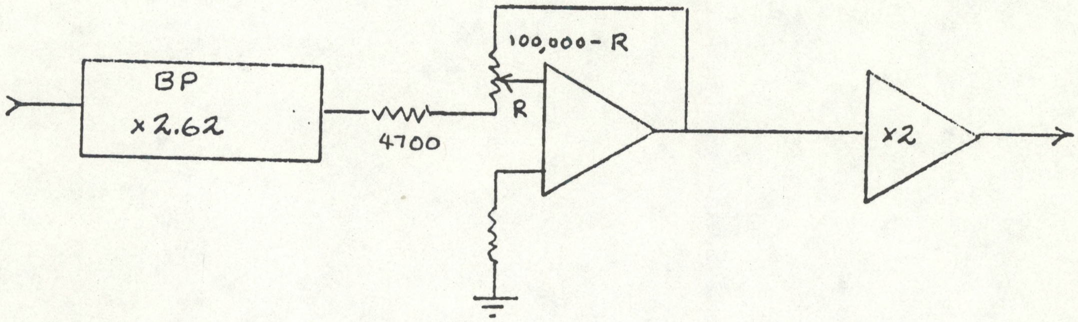
To determine the RMS voltage to be used to check the circuit gain, set $V_4 = 1$ volt ($V_5 = 2$ volts). Then from (7)

$$k = \frac{V_4}{V_3} = \frac{1}{V_3} = 0.953 \times 10^6 D^{7/6} L^{-3/2} .$$

For D = .15 m

$$V_3 = 9.60 \times 10^{-6} L^{3/2} . \tag{10}$$

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



$$K = 2 \times 2.62 \left(\frac{100,000 - R}{4700 + R}\right) . \tag{11}$$

Since

$$R = 100 P \tag{12}$$

where P is the digital pot setting, we can combine (7), (11), and (12) and obtain an expression for P in terms of L as

$$P = \frac{5240 - 4.89 \times 10^6 L^{-3/2}}{5.24 + 1.04 \times 10^5 L^{-3/2}} . \tag{13}$$

This function is plotted in Fig. 3.

Saturation Criteria

Assume $C_n^2 = 10^{-12}$ maximum. From reference 1, the transmitter and receiver diameters required to prevent saturation effects are

$$\alpha_r + \alpha_t > 1.95 (\sigma_T^2)^{3/5} \tag{14}$$

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 $\alpha_r = \alpha_t = D/\sqrt{\lambda L}$, (14) becomes

$$\frac{2D}{\lambda^{1/2}\ L^{1/2}} > 1.95\ !0.124\ (\frac{2\pi}{\lambda})^{7/6}\ L^{11/6}\ C_n{}^{2}1^{3/5}. \tag{15}$$

In terms of aperture diameter,

$$D > \lambda^{-1/5}\ L^{8/5}\ (C_n{}^2)^{3/5}. \tag{16}$$

In terms of path length,

$$L < D^{5/8}\ \lambda^{1/8}(C_n{}^2)^{-3/8}\ . \tag{17}$$

For D = 0.15 m, $\lambda = 0.94 \times 10^{-6}$ m, and $C_n{}^2 = 10^{-12}$, L < 1700 m.

MODIFICATION TO NOAA TECHNICAL MEMORANDUM ERL WPL-52, OPTICAL SYSTEM MODEL IV FOR SPACE-AVERAGED WIND AND C_n^2 MEASUREMENTS

Some design modifications have been made to the 15-cm wind and C_n^2 instruments as a result of a recent study[1]. The changes have been made in the following areas:

The preamplifier circuits now employ an integrating feedback loop that removes the DC offset generated by background light. This allows a higher first-stage gain and improves the signal-to-noise.

An improved signal detection circuit has been added that discriminates between signal and noise on the basis of the frequency spectrum. It is a much more dependable circuit when the path lengths are long. Also the 100k sensitivity pots have been placed on the front panel.

The calibration has been changed to take into account the single aperture operation and the saturation criteria has been made more stringent.

The changes in the circuits, calibration, and saturation lmits are reflected in the revised Fig. 3, APPENDIX A and APPENDIX B.

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[1] Ochs, G. R. and R. J. Hill (1982): A study of factors influencing the calibration of optical C_n^2 meters, NOAA Tech Memo ERL WPL-106.

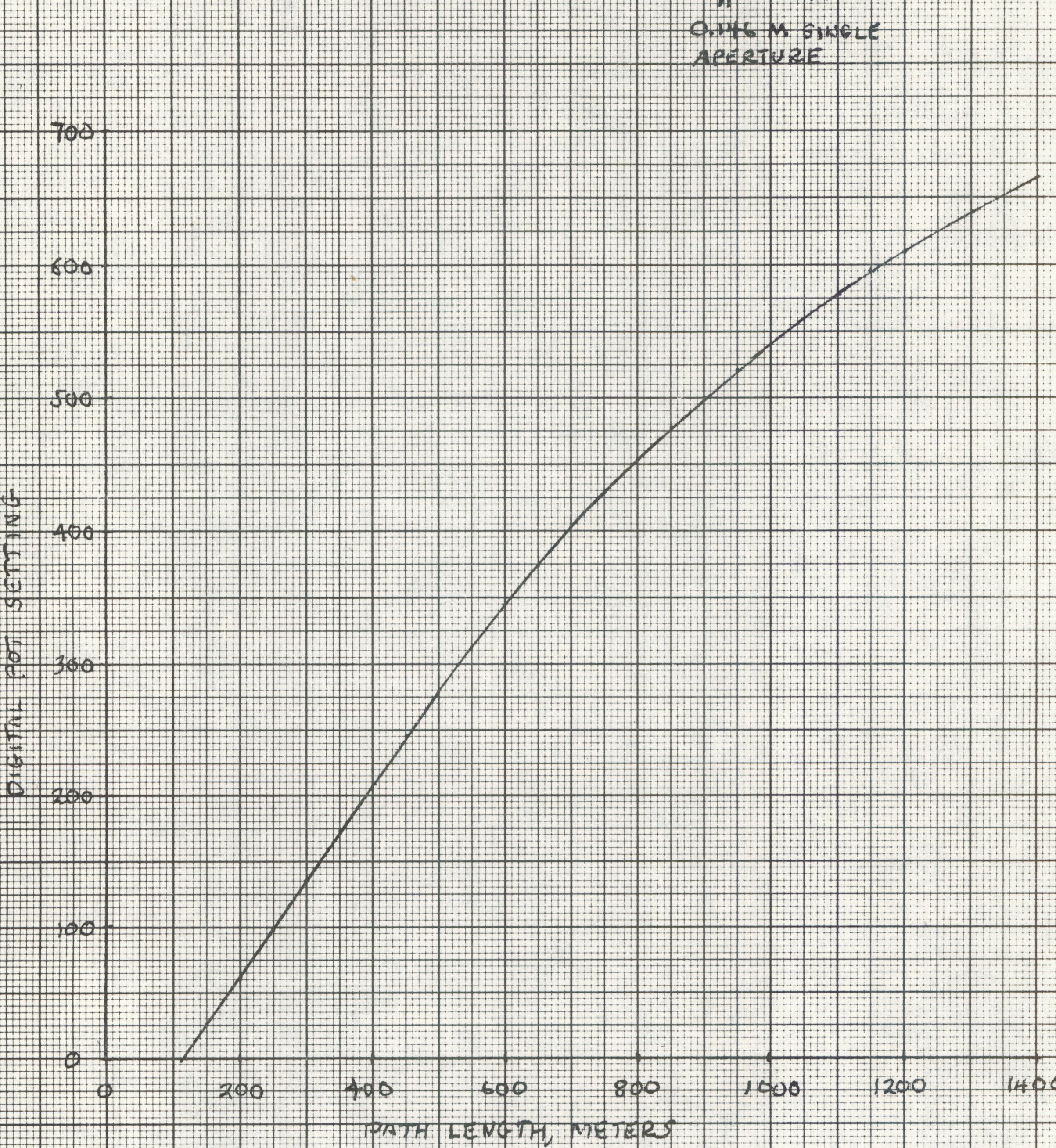
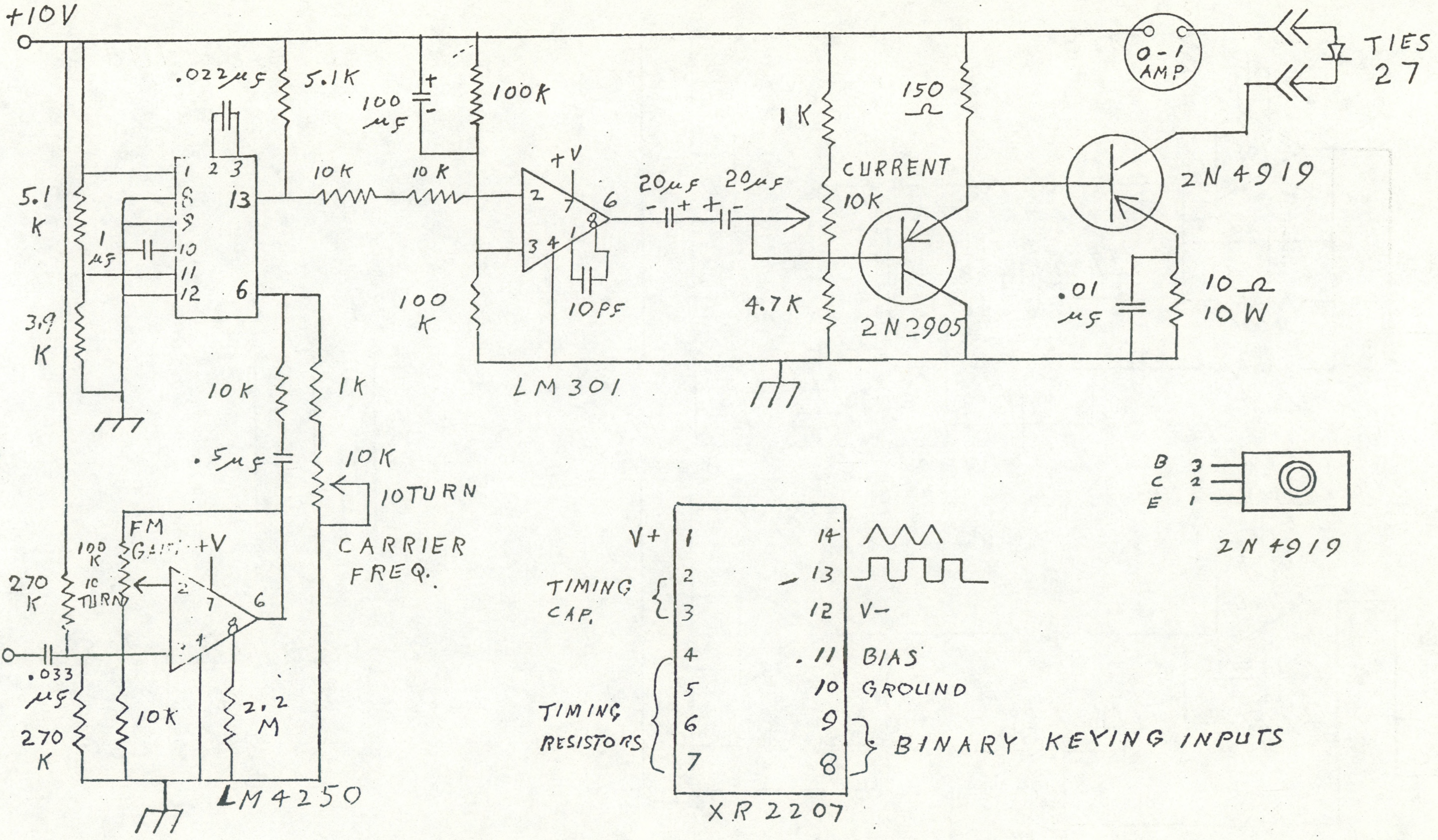


Fig. 3. Calibration setting versus path length.

APPENDIX A

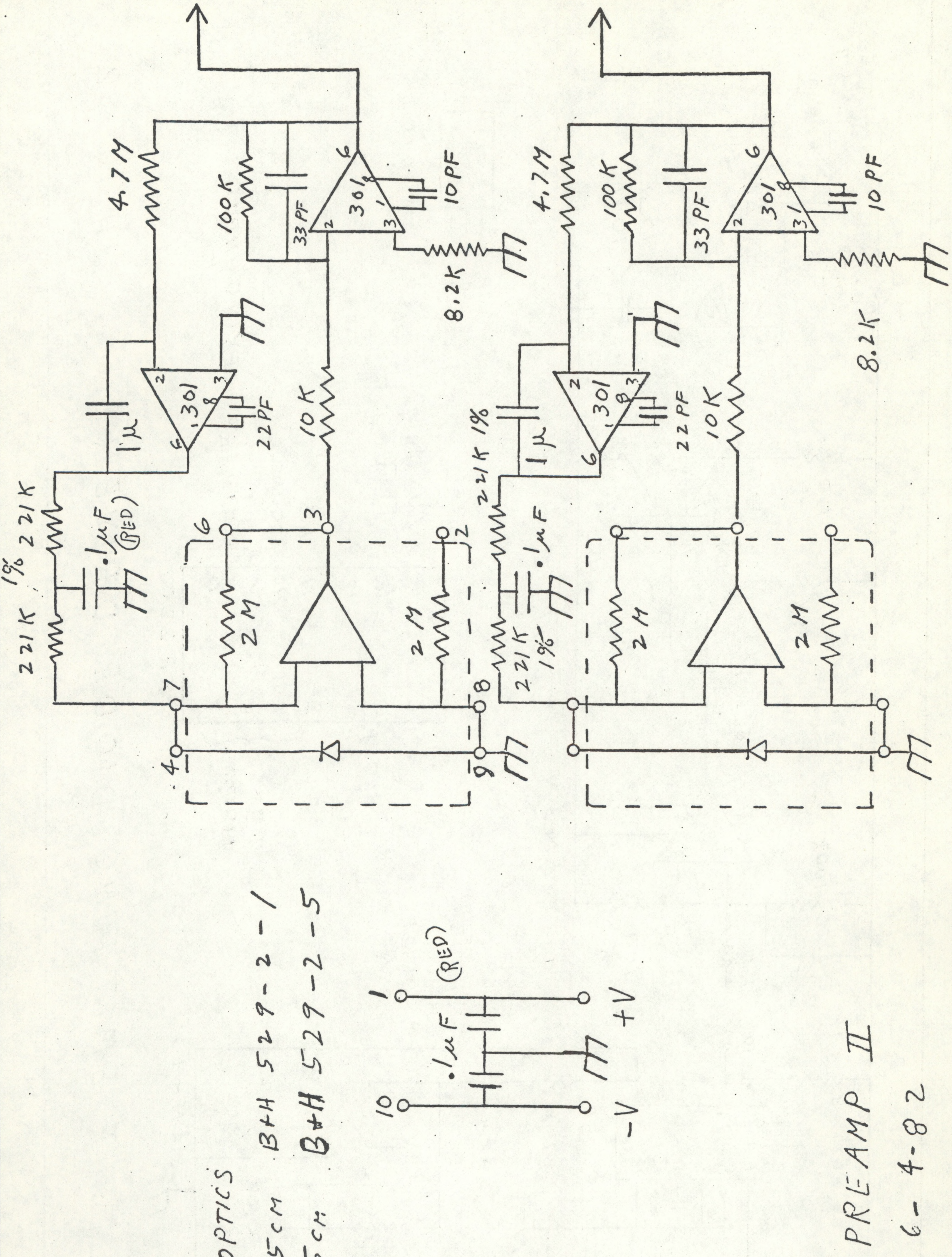
Circuit Diagrams and Layout.

Light emitting diode driver circuit.
Photodiode preamplifier.
Automatic gain control circuit.
Demodulator circuit.
Calibration and log circuit.
Automatic gain control circuit layout.
Demodulator circuit layout.
Calibration and log circuit layout.



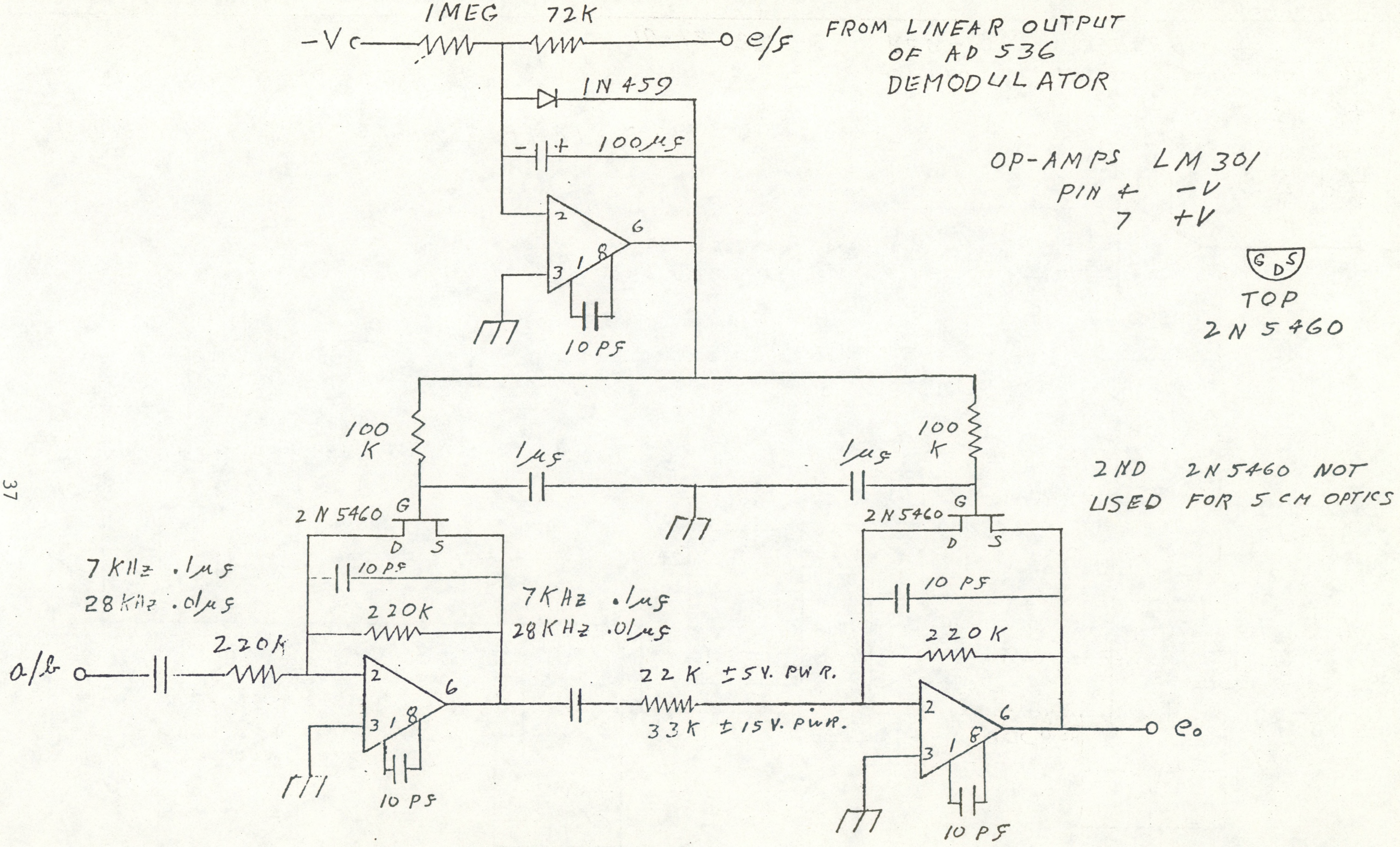
LIGHT EMITTING DIODE DRIVER

11-12-82



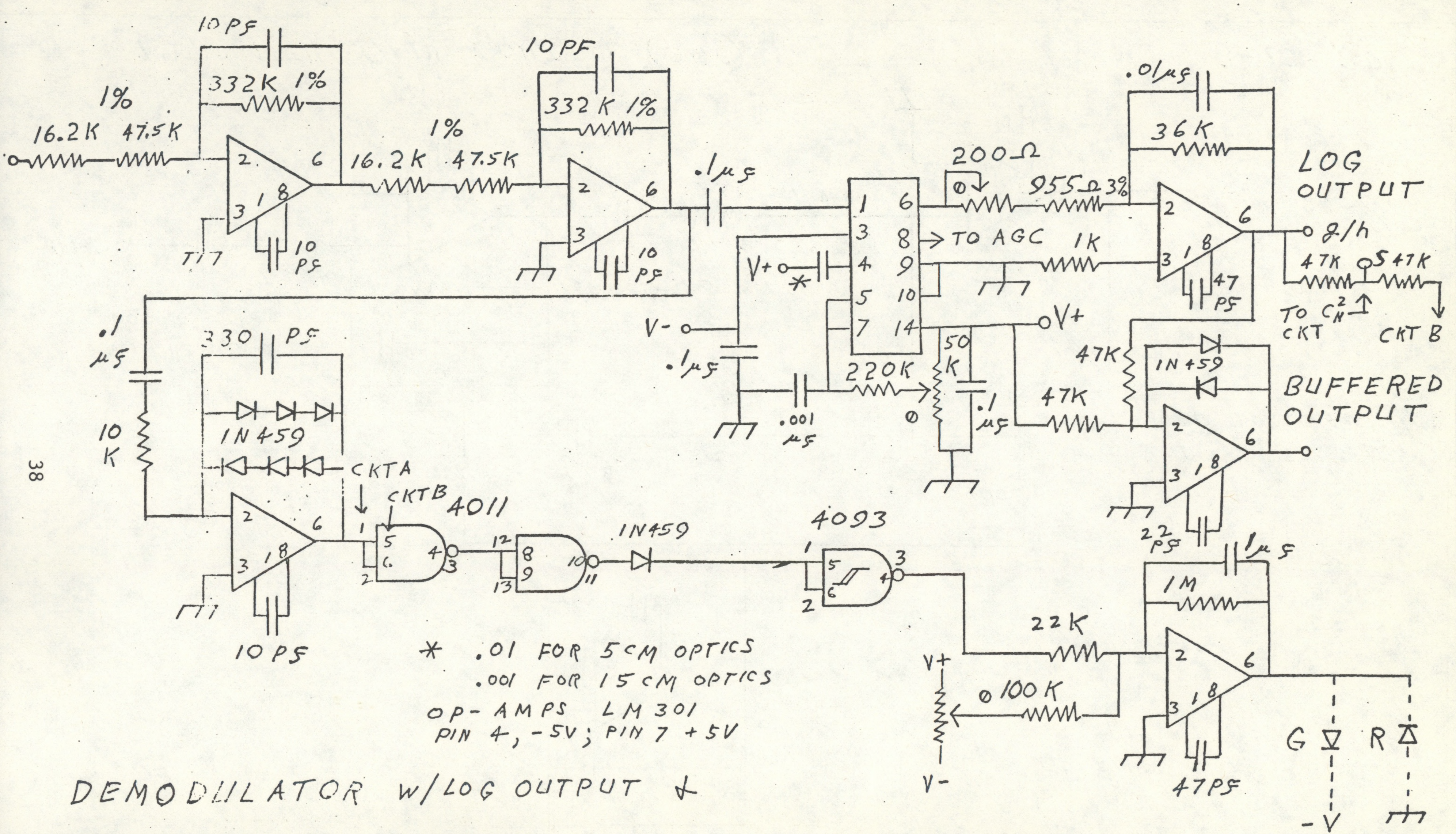
OPTICS
15cm B+H 529-2-1
5cm B+H 529-2-5

PREAMP II
6-4-82



AUTOMATIC GAIN CONTROL (AGC)

8-13-82



* .01 FOR 5CM OPTICS
.001 FOR 15CM OPTICS

OP-AMPS LM 301
PIN 4, -5V; PIN 7 +5V

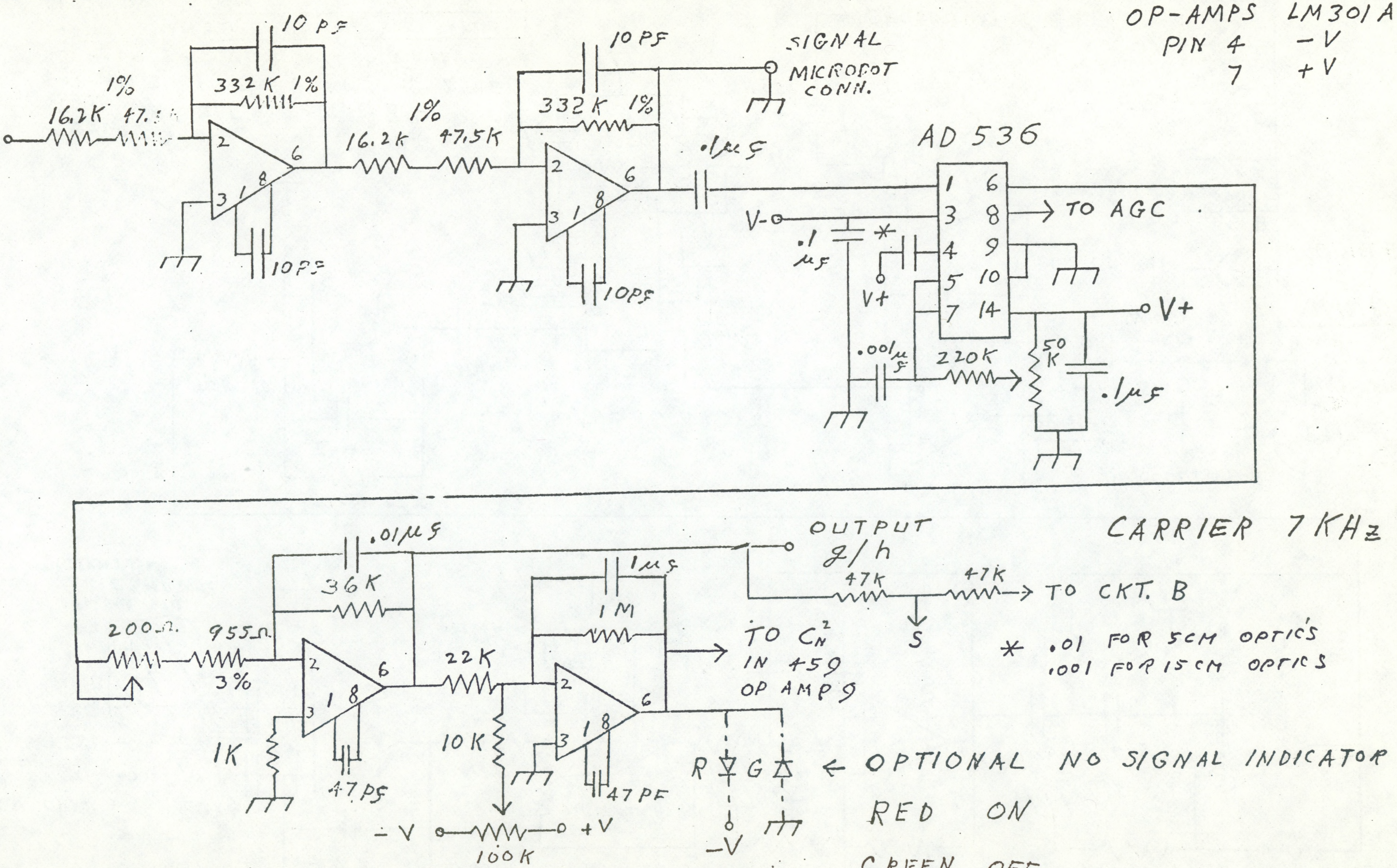
OPTIONAL INDICATION OF NO SIGNAL
RED-ON GREEN-OFF

DEMODULATOR W/LOG OUTPUT &

NO SIGNAL INDICATOR II

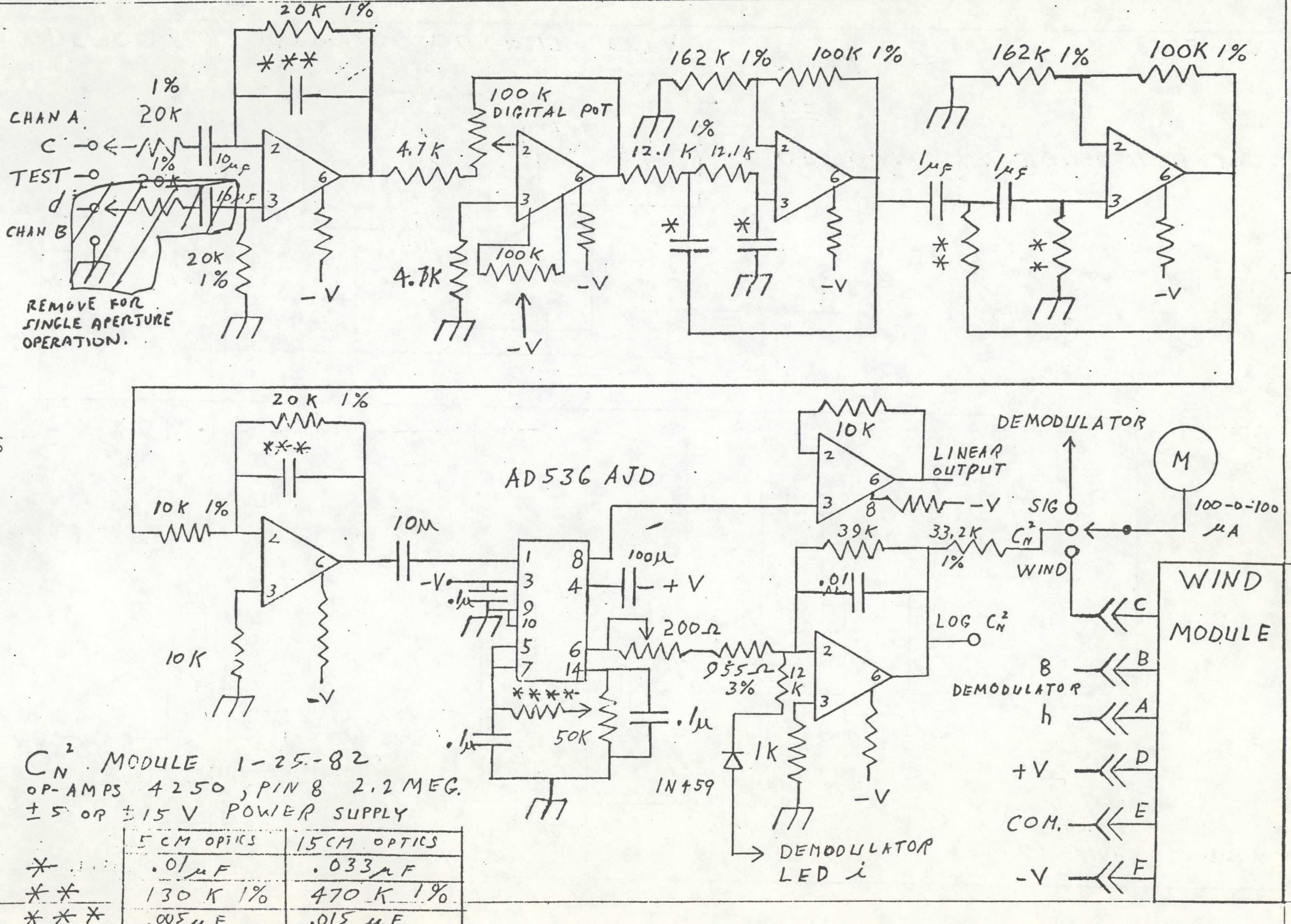
CKT. A

10-12-82



DEMODULATOR W/LOG OUTPUT CKT.A

8-13-82



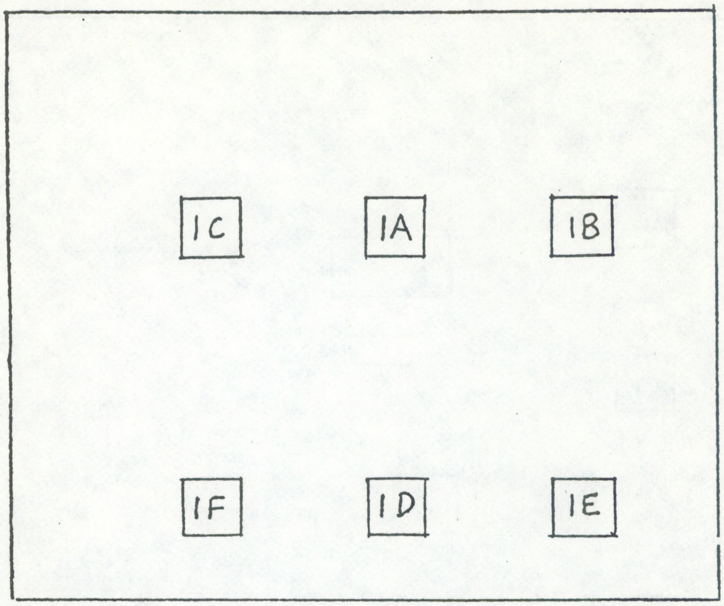
C_N^2 MODULE 1-25-82

OP-AMPS 4250, PIN 8 2.2 MEG.

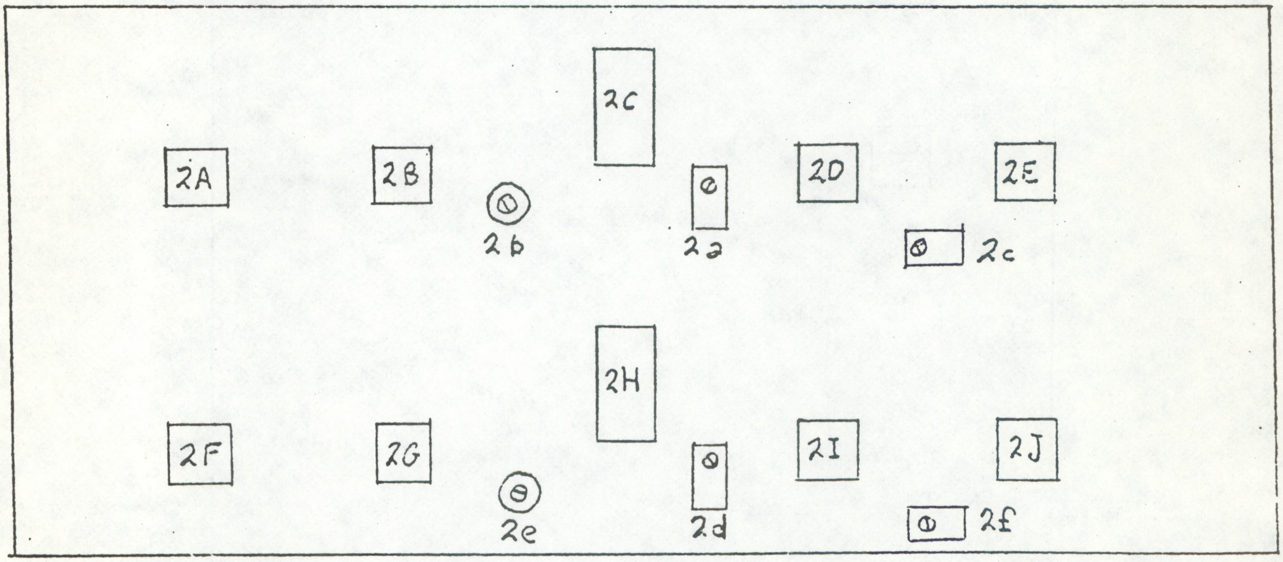
± 5 OR ± 15 V POWER SUPPLY

	5 CM OPTICS	15 CM OPTICS
*	.01 μF	.033 μF
**	130 K 1%	470 K 1%
***	.005 μF	.015 μF

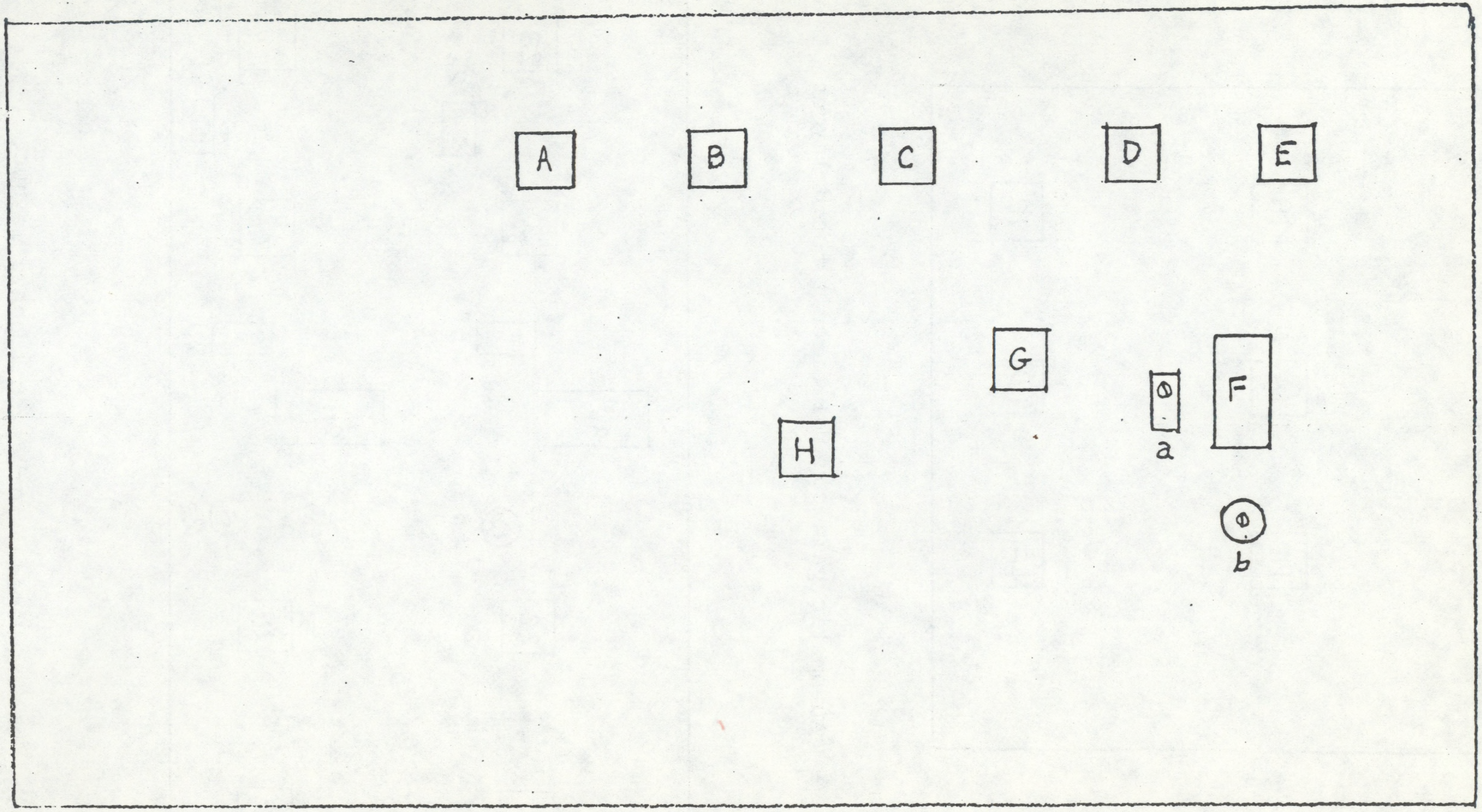
**** 50K ±5V POWER SUPPLY



Automatic gain control circuit board layout.



Demodulator circuit board layout.



Calibration and log circuit layout.

APPENDIX B

Derivation of Calibration

Refer to Fig. 2. Temporarily consider the second detector output disconnected and $V_2 = 0$. Now consider the output of the bandpass filter V_{31} when $V_2 = 0$. From Ref. 1, for one aperture,

$$C_n{}^2 = 4.48\ \sigma_x{}^2\ D^{7/3}\ L^{-3} \qquad (1)$$

where $\sigma_x{}^2$ 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

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

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

$$\sigma_x{}^2 = \frac{2.3026^2}{4} \; \frac{V_{31}}{2}^{\,2}$$

$$\sigma_x{}^2 = 0.3314 \; V_{31}{}^2 \; . \qquad (3)$$

Combining (1) and (3),

$$C_n{}^2 = 1.48 \; D^{7/3} \; L^{-3} \; V_{31}{}^2 \; . \qquad (4)$$

Decide on the following instrument calibration

$$C_n{}^2 = 10^{-12} \; V_4{}^2 \; . \qquad (5)$$

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

$$V_4 = K \; V_{31} \; . \qquad (6)$$

Combining (4), (5), and (6), to eliminate $C_n{}^2$, V_3, and V_4,

$$K = 1.22 \times 10^6 \; D^{7/6} \; L^{-3/2} \; . \qquad (7)$$

Decide on the following log output calibration (V_5):

$$C_n^2 = 10^{-14} \log^{-1} V_5 \, . \tag{8}$$

Combining (5) and (8),

$$10^{-12} V_4^2 = 10^{-14} \log^{-1} V_5$$

$$V_5 = 2 + 2 \log V_4 \, . \tag{9}$$

Thus the log unit should be set so that

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

and

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

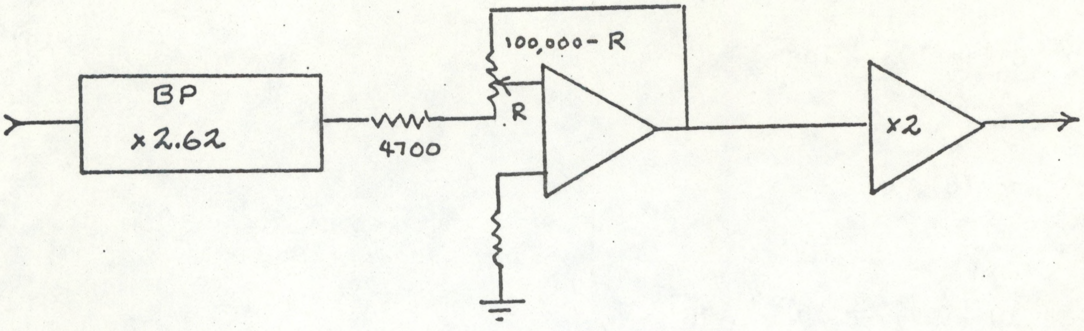
To determine the RMS voltage to be used to check the circuit gain, set $V_4 = 1$ volt ($V_5 = 2$ volts). Then from (7)

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

For D = .146 m

$$V_3 = 7.74 \times 10^{-6} \, L^{3/2} \, . \tag{10}$$

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



$$K = 2 \times 2.62 \left(\frac{100,000 - R}{4700 + R}\right) . \qquad (11)$$

Since

$$R = 100 P \qquad (12)$$

where P is the digital pot setting, we can combine (7), (11), and (12) and obtain an expression for P in terms of L as

$$P = \frac{5240 - 6.06 \times 10^6 L^{-3/2}}{1.29 \times 10^5 L^{-3/2} + 5.24} . \qquad (13)$$

This function is plotted in Fig. 3.

Saturation Criteria

Assume $C_n^2 = 10^{-12}$ maximum. From reference 1, the transmitter and receiver diameters required to prevent saturation effects are

$$\alpha_r + \alpha_t > 5.4 \ (\sigma_T^2)^{3/5} \qquad (14)$$

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 $\alpha_r = \alpha_t = D/\sqrt{\lambda L}$, (14) becomes

$$\frac{2D}{\lambda^{1/2}\ L^{1/2}} > 5.4\ [0.124\ (\frac{2\pi}{\lambda})^{7/6}\ L^{11/6}\ C_n{}^2]^{3/5}. \qquad (15)$$

In terms of aperture diameter,

$$D > 2.7\ \lambda^{-1/5}\ L^{8/5}\ (C_n{}^2)^{3/5}. \qquad (16)$$

In terms of path length,

$$L < .54\ D^{5/8}\ \lambda^{1/8} (C_n{}^2)^{-3/8}\ . \qquad (17)$$

For $D = 0.146$ m, $\lambda = 0.94 \times 10^{-6}$ m, and $C_n{}^2 = 10^{-12}$, $L < 905$ m.