A Self-Zeroing Capacitance Probe for Water Wave Measurements

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1.0 INTRODUCTION

The wave probe developed at the Air-Sea Interaction Research Facility was designed to measure the surface elevation fluctuations of water waves. Design criteria included being linear in response, self-zeroing to the mean water level, having multiple operating ranges so that the instrument's maximum output could be matched to the maximum surface elevation over varying conditions, and be as noise-free as possible.

Historically, research efforts utilizing the measurement of wave surface elevations at sea or in the laboratory have been divided along two main approaches: using a resistive change or a capacitive change which is induced by a change in water level, and thus a measure of surface elevation. Representative of the resistive-type of instrument is that described by the National Oceanographic Instrumentation Center (1974), and that used by Mitsuyasu and Honda (1974). Capacitive-type instruments have been discussed by McGoldrick (1965, 1969, 1971) and Mitsuyasu (1968), among others.

The wave probe described here is of the capacitive-type, incorporating several features as mentioned above which were previously unavailable. These added design criteria both increase the ease of operation and the reliability of the results.

2.0 CIRCUIT DESIGN AND CONSTRUCTION

2.1 Background and Development

Any insulated conductor may be used as a probe. The principle of the probe is to use the insulated conductor and the tank as the two plates of a capacitor. Any change in the water level would change the dielectric effect between the plates, which is then measured via impedance balancing.

A basic characteristic of the capacitive-type probes used previously has been impedance balancing via an adjustable impedance bridge or tunable tank circuit within the probe circuit. The circuit would then be configured for a data run and then adjusted in the quiescent (zero signal) condition to effect a zero output voltage by balancing the impedance (capacitance) of the probe apparatus. The mechanism by which zeroing was accomplished was basically a subtraction or cancellation of the impedance (capacitance) of the entire probe assembly. For small wave heights, the capacitance changes that occur because of wave action may be quite possibly only 10^{-3} of the total probe apparatus capacitance. The frustrations that can result in attempting to maintain a satisfactory zero calibration or to compensate for the lack of it in such circumstances is obvious.

The capacitance probe that is the subject here avoids this problem by "bootstrapping" a guard circuit (shield) to the probe sense line. In effect, the capacitance that exists in a shielded cable between the center conductor and the shield is in this circuit reduced by a factor approaching 10^5.

This is accomplished by driving the shield of the probe sense line to eliminate (10^{-5}) the voltage potential that would otherwise exist across the intervening dielectric. A second outer shield is grounded to effect normal system shielding. Thus triax cable (Triaxial, double shielded) and connectors are used between the circuit and the wire probe used for the elevation measurements.

In many previously used probe systems, variations in the capacitance of the probe coupling apparatus (cable, etc.) was transferred to the output data. For small signal levels, this could have been a significant source of error, either directly or through measurement equipment nonlinearities. In the probe presented here, the effective capacitance of the probe coupling apparatus is reduced to a negligible value. Thus this probe achieves automatic self-zeroing to the mean water level with a time constant easily adjustable, effectively canceling the cable length effects, cable flexing effects, etc., and providing long term stability during measurements.

2.2 Circuit Principles and Design

The fundamental block diagram of the circuit is shown in Figure 2.1. An oscillator is used to generate a 20 KHz sine wave, which is directed through two different branches of the circuit. The first branch leads through the pulse forming network (I) to a latch circuit. The second branch leads to a negative feedback (NFB) amplifier. It is here that cable effects are canceled, and the water waves introduce their surface elevation information by varying the capacitance C_x. The larger C_x becomes, the smaller the gain becomes of the NFB amplifier. The path then leads on to the pulse forming network (II) to the latch circuit.

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The function of the pulse forming network is to transform the sine waves into square waves whose pulse width is determined by the amplitude of the sine waves. Thus in the second branch, the water waves cause the pulse width to vary with changes in water surface elevation. Within the first branch, no such variation is caused in the pulse width.

Both pulse forming branches lead to the latch circuit. Here the pulse widths of the signals from the two pulse forming networks are compared. The pulse duration of the output of the latch depends on the difference of the two pulse widths compared. When the value of the C_x capacitance increases, the latch pulse output width increases also. Receiving the latch output, a filter network transforms it into a DC signal which is then passed to a DC amplifier. It is here that the various range selections are implemented, by adjusting the gain of the DC amplifier. In order to reduce the effects of 60 Hz noise, the signal is passed through a 60 Hz notch filter, and finally through another DC amplifier network to produce the final output signal.

Because the performance of components is not totally uniform (5% tolerance on resistors, for example), the output levels of different wave probes of the identical circuit design will be slightly different, even for identical water surface changes. This is compensated at the time of calibration, so that each probe circuit board will have its own set of calibration constants.

2.3 The Detailed Circuit

The complete circuit is shown in Figure 2.2, and was arranged to fit on a standard plug-in type circuit card. An integrated circuit, labeled PB13, of the type MC1458CP, is used in the 20 KHz oscillator. The amplitude of the sine waves produced is 10 v peak-to-peak. PB16, which is half of an MC1458CP, serves as the NFB amplifier. The two pulse forming networks from Figure 2.1 are formed within PB14 (LM339N) and PB15 (7400N). The latch network receiving the two pulse forming branches (see Figure 2.1) in Figure 2.2 is labeled PB11, of the type 74279. The filter to transform the latch output into a DC level is at PB10, consisting of the 22 KΩ resistors and one 0.047 μf capacitor. DC amplification occurs in three stages at PB09 (half of MC1458CP), PB08 (half of MC1458CP), and PB06 (CA3140). The gain adjustment occurs at one stage of the three stage DC amplification, at PB09, where gain is adjusted by selecting a resistor by switch selection. The resistor selected becomes part of the negative feedback, and is located on PB19.

PB01 (half of MC1458CP) and twin filters on PB02 constitute the 60 Hz notch filter. The notching frequency is dependent on the value of the resistor and capacitor on the input side of the twin filters, and is given by

$$f = \frac{1}{2\pi RC}$$

where f is the frequency dominated by the notch, R is the resistor value in ohms, and C is the capacitor value in farads. The frequency characteristic curve of a typical notch filter measurement

is shown as Figure 2.3. Using the notch filter suppresses the 60 Hz noise by at least 15 dB. The final output emerges from PB01 (half of MC 1458CP), and PB21 (CA3140), which form the output DC amplifier. The wave forms at each stage for testing purposes are illustrated in Table 2.1.

2.4 Circuit Board Layout and Wiring Diagrams

The circuit components were installed on a standard IC circuit card (Vector 3682-4), using standard IC sockets, and wire-wrapping techniques for interconnections. The components were installed on 21 IC sockets, arranged as shown in Figures 2.4 and 2.5, giving the socket and pin-side view respectively. A numbering code is used to give both the socket location and pin number for the connections in each of the wiring diagrams, Figures 2.6 to 2.26. As an example, consider the wiring diagram of Figure 2.6 on the pin side of the illustration, where pin 7 is shown to connect to "0316." This is an instruction to connect this pin to PB03 on pin 16. Pin 1 is seen to connect to pin 2, while pin 2 is connected to "0213," which is PB02 and pin 13. This numbering code is used throughout the wiring diagrams. The circuit card itself is PB00.

In addition to the connections between sockets, connections are also needed between the sockets and the IC circuit card plug-in tabs. These are given in Figure 2.27, where the circuit card itself is considered to be PB00. A complete listing of components is given in the Appendix.

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3.0 WIRE PROBE CONSTRUCTION

Any well insulated conductor may be used as a probe. The characteristics of the insulation, such as dielectric constant, thickness, etc., will effect the response per unit length. Thus wire selection will be influenced by the wave conditions expected, and a separate calibration would be needed for each wire type.

For our laboratory application, we chose a #30 AWG solid copper wire manufactured by Belden as "heavy armored polythermaleze." The usual use for this wire is to wrap electric motors, make inductors, etc. Sizes down to #44 were also tried, but no measurable increase in frequency response was noted. With such a small size as #44, the probes proved to be too fragile, so that a #30 AWG was finally selected for our application.

To effect a negligible conductance, the submerged (unprotected) end of the cut wire must be sealed against water. In our application, a monofilament fishing line was joined to the wire at the submerged end to provide the necessary tension in the probe when placed under constant tension from a standard rubber band. Additionally, it must be noted that a uniform wire depth of immersion is important to maintain the resulting calibration and the desired interchangeability of wires, since the circuit here described responds to

$$\frac{\Delta C}{C} \, ,$$

where C is the capacitance, and ΔC is the change in capacitance caused by the wave motion. This

arrangement is shown in Figure 3.1.

The joint between monofilament and wire was first made by a knot which was then covered with standard epoxy, followed by a red heat shrink tube (T & B type). Once shrunk, the extra wet epoxy was ejected from the ends of the heat shrink tube, and used to coat the entire tube exterior with epoxy. After proper curing, the final coat was a thin film of silicon rubber (RTV). The probe wire was then attached to a triax connector, as shown in Figure 3.2, with care being taken to insure a uniform immersion depth and a good electrical connection at the triax connector (remove enough wire coating to connect electrically). The immersion depth used in our laboratory application is 15 cm. Once mounted to the triax connector, the probes can be easily removed or replaced.

4.0 LIMITATIONS

An important limiting factor for wire probes measuring the surface elevation of water waves is the frequency limiting effects of the meniscus. Its diameter defines a spot size for the measurements. As the wave lengths approach this spot size diameter, the probe can no longer accurately measure the waves. As shown by Sturm and Sorrell (1973) and discussed by Long and Huang (1976), a practical limit of approximately 12 to 15 Hz exists for even the smallest of probe diameters, due to the meniscus. Thus, even though the circuit itself can accurately measure capacitance changes at frequencies far beyond this, the water waves are unable to cause such high frequency capacitance variations due to the presence of the meniscus. Additionally, frequencies

under 0.1 Hz can not be accurately followed due to the circuit's self-zeroing feature, without first changing the time delay value in the circuit.

5.0 CALIBRATION

Numerous concepts may be considered for calibration of surface elevation probes. The selection should depend upon the physical system and available facilities in which the probes will be employed. One method which has been used at our facility is to group several probes together within a radius of a centimeter or two, and use smooth sine waves of low frequency (about 1.5 Hz) generated by the hydraulic wave generator. The amplitude was accurately measured at the probe location, and the output voltage was digitized by computer interfaced equipment. This was repeated for a variety of wave amplitudes, and the output voltages noted for the various ranges. This produced results that are presented graphically in Figure 5.1.

6.0 SUMMARY

The wave probe developed at the Air-Sea Interaction Research Facility has met the design criteria of being linear in response, self-zeroing to the mean water level, having multiple operating ranges for maximum resolution, and being as noise free and accurate as possible. It is a reliable probe that is well suited to laboratory conditions, with the added flexibility of being adaptable for field work with the proper choice of coated probe wire and calibration resistors.

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7.0 ACKNOWLEDGEMENTS

8.0 REFERENCES

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APPENDIX

LIST OF COMPONENTS

Description	Quantity
Integrated Circuit	
CM1458CP	5
CA3140	2
74219N	1
7400N	1
LM339N	1
Resistor	
100 Ω, 1/4W, 5%	2
330 Ω, 1/4W, 5%	2
1.5 KΩ, 1/4W, 5%	1
1.8 KΩ, 1/4W, 5%	1
2.7 KΩ, 1/4W, 5%	1
3.9 KΩ, 1/4W, 5%	3
4.7 KΩ, 1/4W, 5%	3
5.6 KΩ, 1/4W, 5%	6
8.2 KΩ, 1/4W, 5%	1
10 KΩ, 1/4W, 5%	1
12 KΩ, 1/4W, 5%	1
22 KΩ, 1/4W, 5%	4
39 KΩ, 1/4W, 5%	1
47 KΩ, 1/4W, 5%	1
68 KΩ, 1/4W, 5%	2
82 KΩ, 1/4W, 5%	2
100 KΩ, 1/4W, 5%	3
120 KΩ, 1/4W, 5%	1
220 KΩ, 1/4W, 5%	1
270 KΩ, 1/4W, 5%	2
390 KΩ, 1/4W, 5%	2
1 MΩ, 1/4W, 5%	1
6.8 MΩ, 1/4W, 5%	1
Capacitor	
0.001 μf 50V 5%	2
0.0027 μf 50V 5%	3
0.01 μf 50V 5%	3
0.022 μf 50V 5%	1
0.033 μf 50V 5%	5
0.047 μf 50V 5%	2
0.068 μf 50V 5%	2
3.3 μf 35V 10%	2
4.7 μf 35V 10%	3

Table 1. Wave Forms of Each Stage.

Part Location	Pin Number	Wiring Code	Wave Form	Description
PB13	07	1307	∿∿∿	20 KHz Sine Wave, 10V P-P
PB16	01	1601	∿∿∿	20 KHz Sine Wave, 10V P-P
PB14	02	1402	⊓⊔⊓⊔	20 KHz Square Wave, 16V
PB14	13	1413	⊓⊔⊓⊔	20 KHz Square Wave, 16V
PB15	03	1503	⊓⊔⊓⊔	20 KHz Square Wave, 3.8V
PB15	11	1511	⊓⊔⊓⊔	20 KHz Square Wave, 3.8V
PB15	06	1506	⊔⊓⊔⊓	20 KHz Negative Pulse, 4.2V
PB15	08	1508	⊔⊓⊔⊓	20 KHz Negative Pulse, 4.2V
PB11	07	1107	⊓⊔⊓⊔	20 KHz Positive Pulse, 3.8V
PB09	01	0901		DC, −2V
PB08	01	0801		DC, −2V
PB06	06	0606		DC, 0 V
PB09	07	0907		DC, 0 V
PB01	01	0101		DC, 0 V
PB01	07	0107		DC, 0 V
PB21	06	2106		DC, 0 V
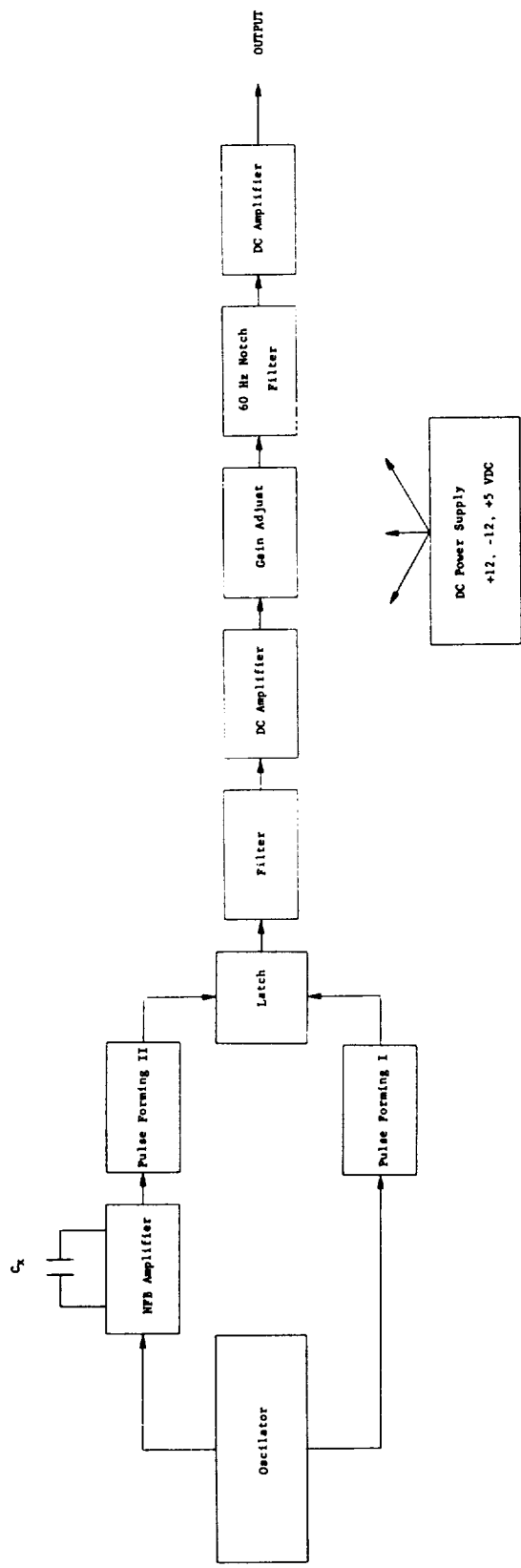
Figure 2.1. The fundamental block diagram of the circuit.

14

Figure 2.2. The detailed circuit diagram.

15
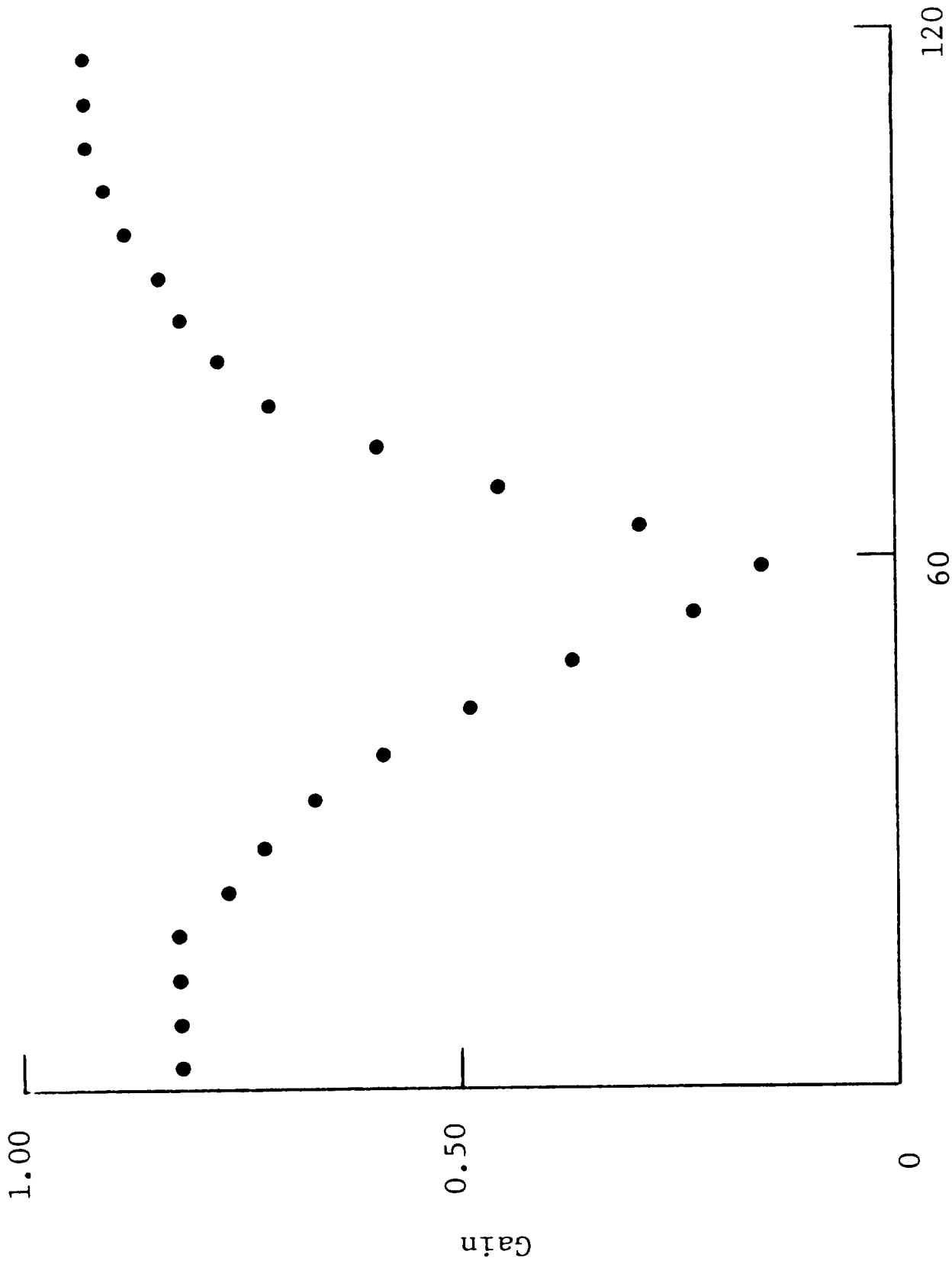
Figure 2.3. The frequency characteristic curve of the 60-Hz notch filter.
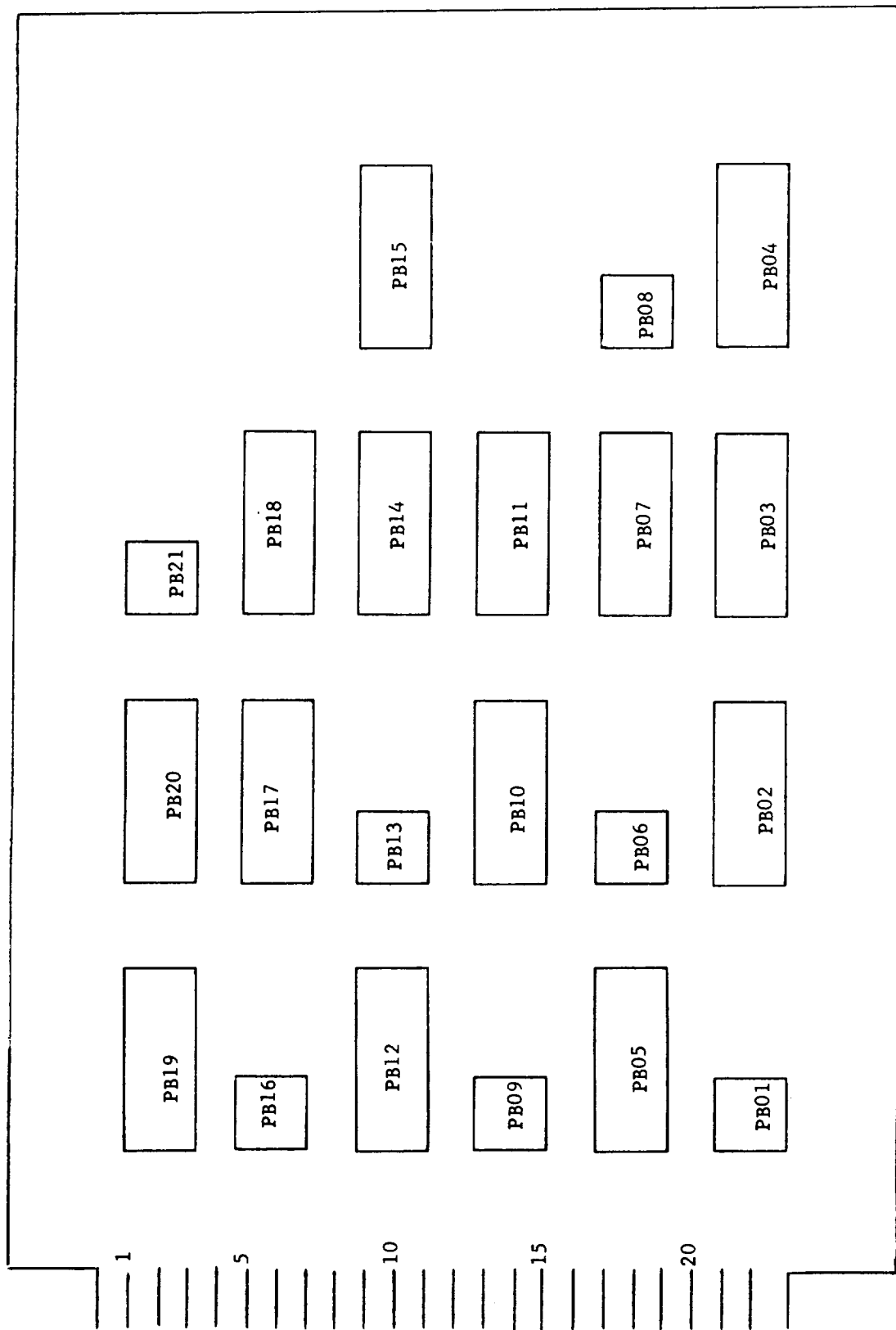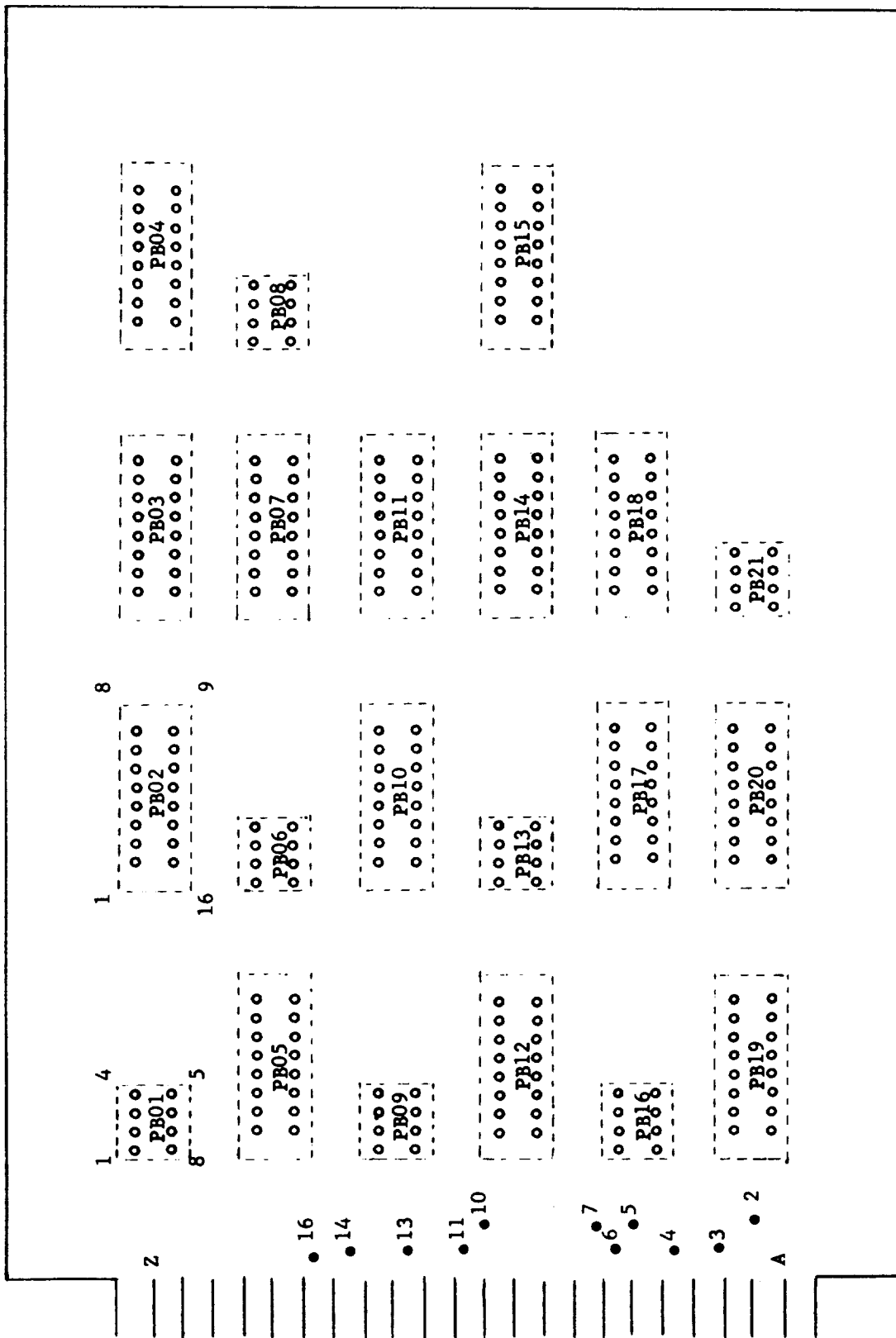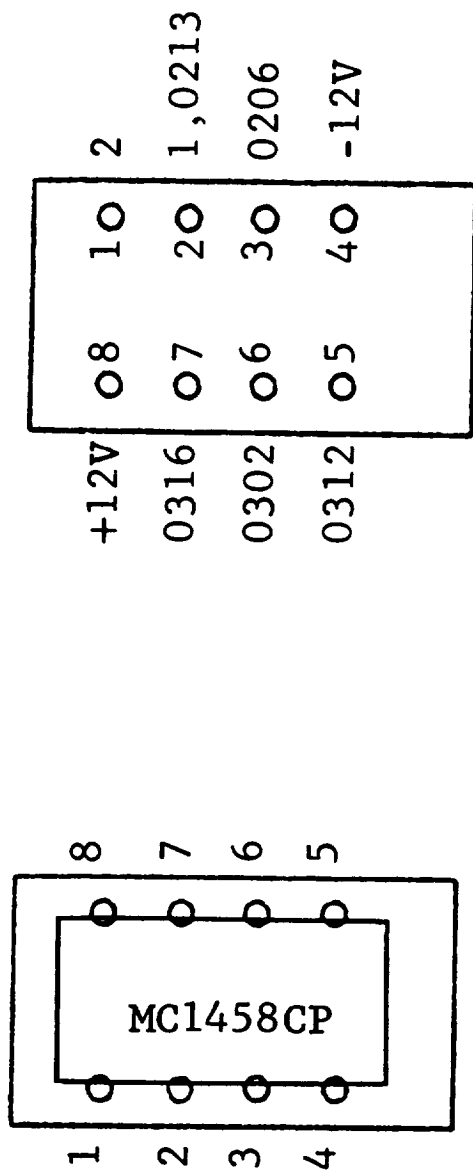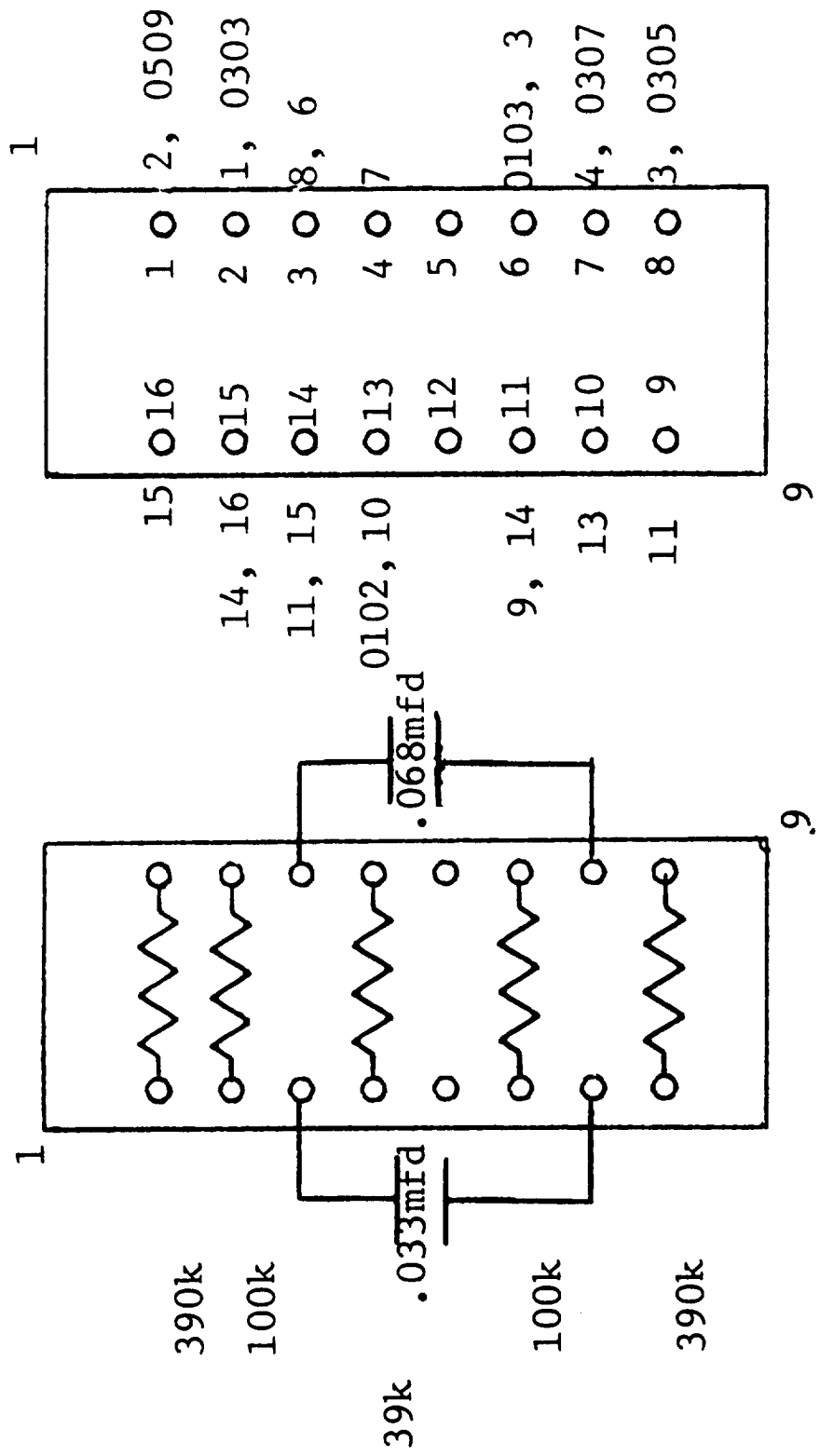
16

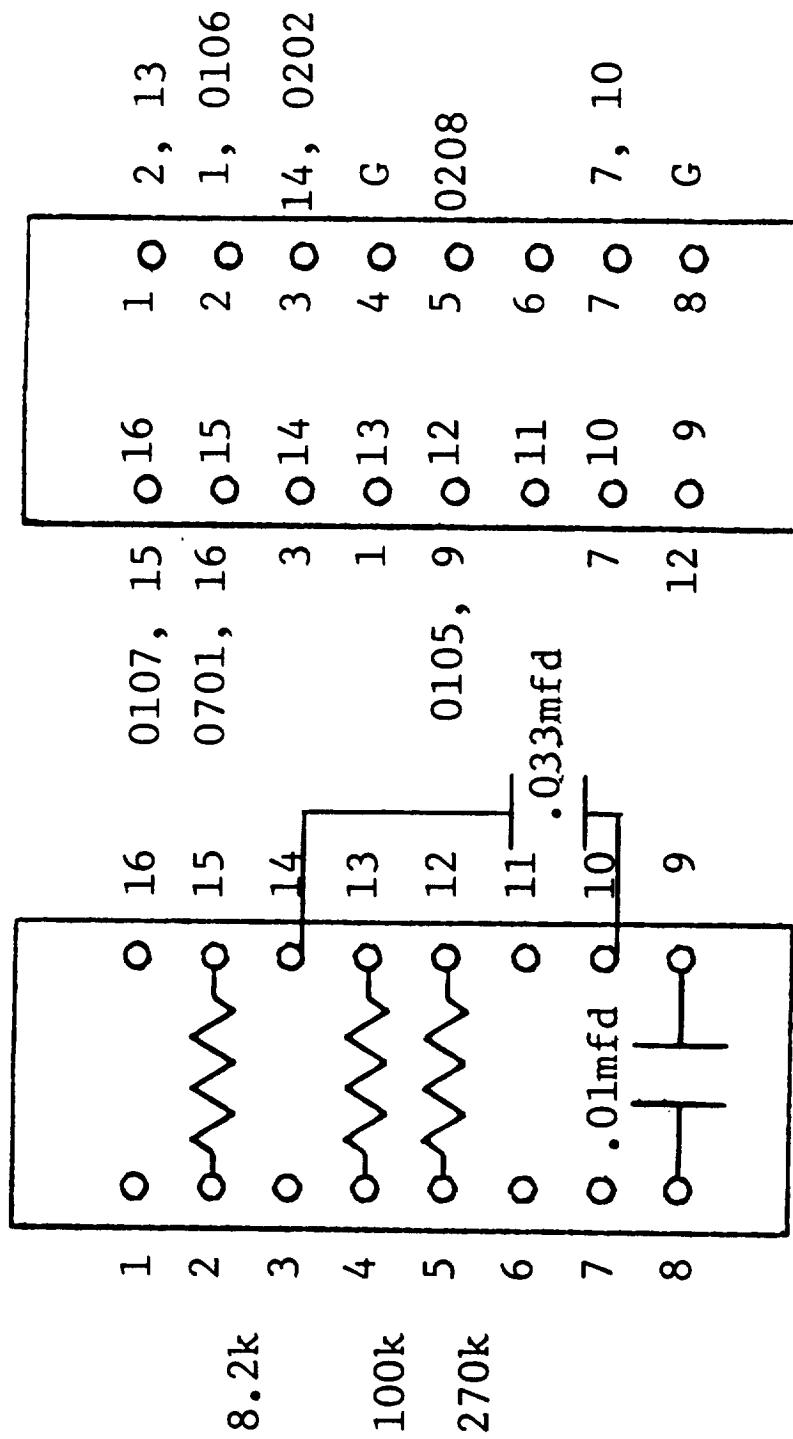Figure 2.4. The circuit card, socket-side view.

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Figure 2.5. The circuit card, pin-side view.

MC1458CP

8 7 6 5
1 2 3 4

PB01

2   +12V
1,0213   0316
0206   0302
-12V   0312

1○ 8○
2○ 7○
3○ 6○
4○ 5○

Figure 2.6. Wiring diagram with interconnections.

19

PB02

1

2, 0509
1, 0303
8, 6
7
0103, 3
4, 0307
3, 0305

1 ○ 1
2 ○ 2
3 ○ 3
4 ○ 4
5 ○ 5
6 ○ 6
7 ○ 7
8 ○ 8

15 ○16
16 ○15
14 ○14
13 ○13
12 ○12
11 ○11
10 ○10
9 ○ 9

9

15
14, 16
11, 15
0102, 10
9, 14
13
11

.068mfd

.033mfd

390k
100k
39k
100k
390k

1

9

Figure 2.7. Wiring diagram with interconnections.

Figure 2.8. Wiring diagram with interconnections.

0803

1008

0802

G

PB04
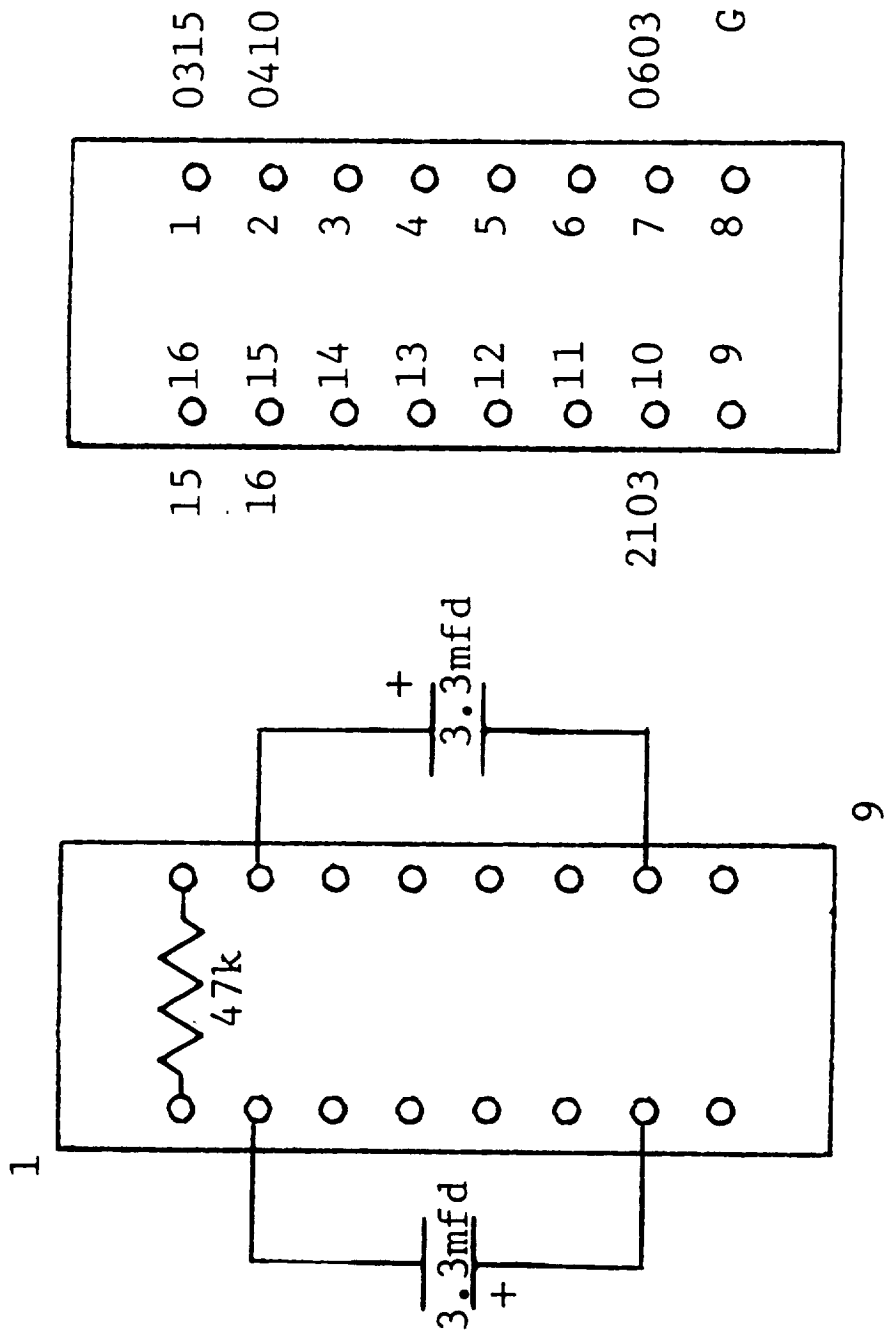
0702
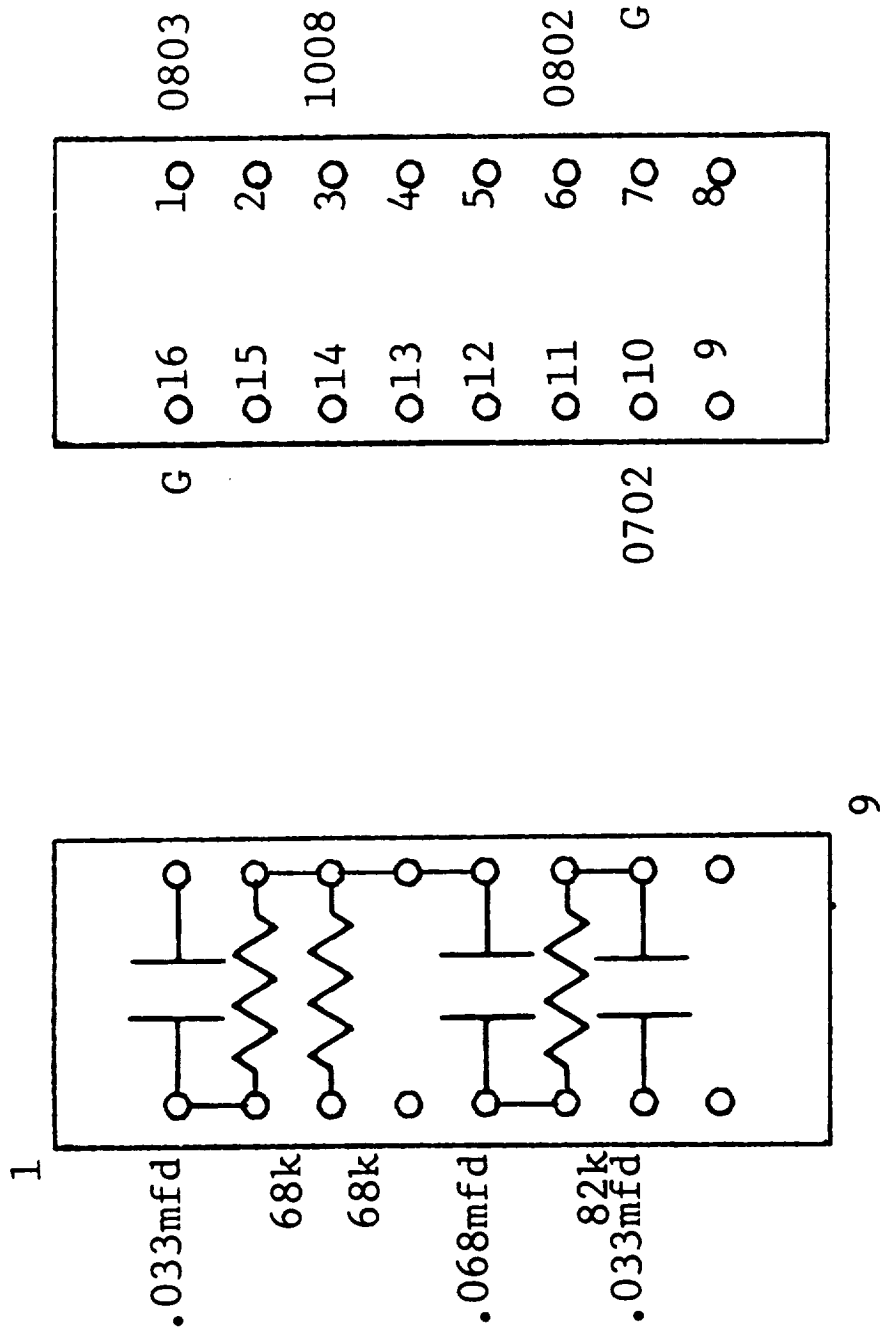
Figure 2.9. Wiring diagram with interconnections.

22

PB05

1 O	7, 0906	
2 O		
3 O		
4 O	0603	
5 O	6	
6 O	5, 0602	
7 O	1, 8	
8 O	7	

9 O 16
O 15
O 14
O 13 G
O 12 G
O 11 10
O 10 0606, 11
O 9   0201, 16

0907,

120k

1M
12k
82k
1.5k
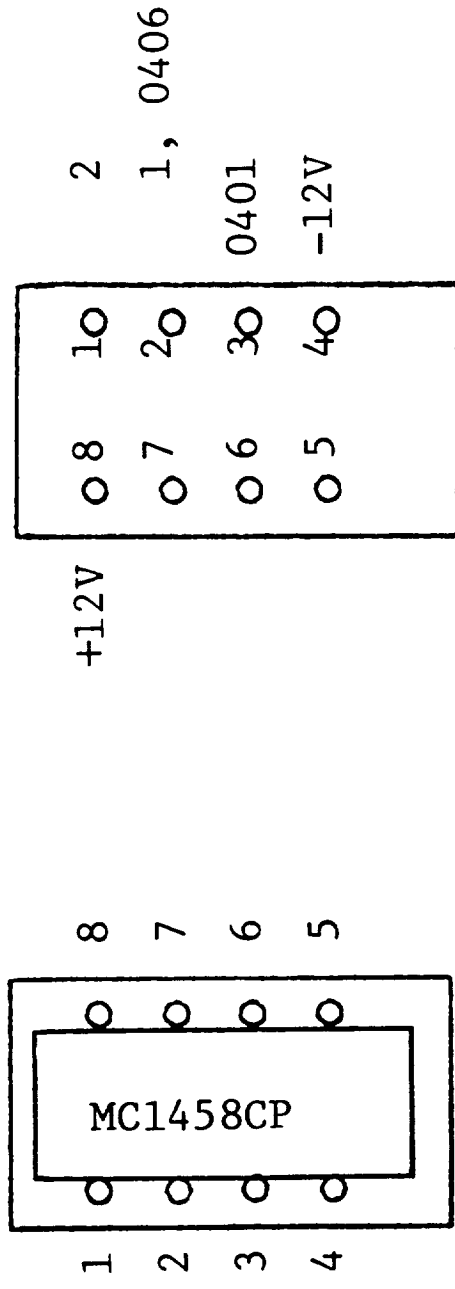.01mfd
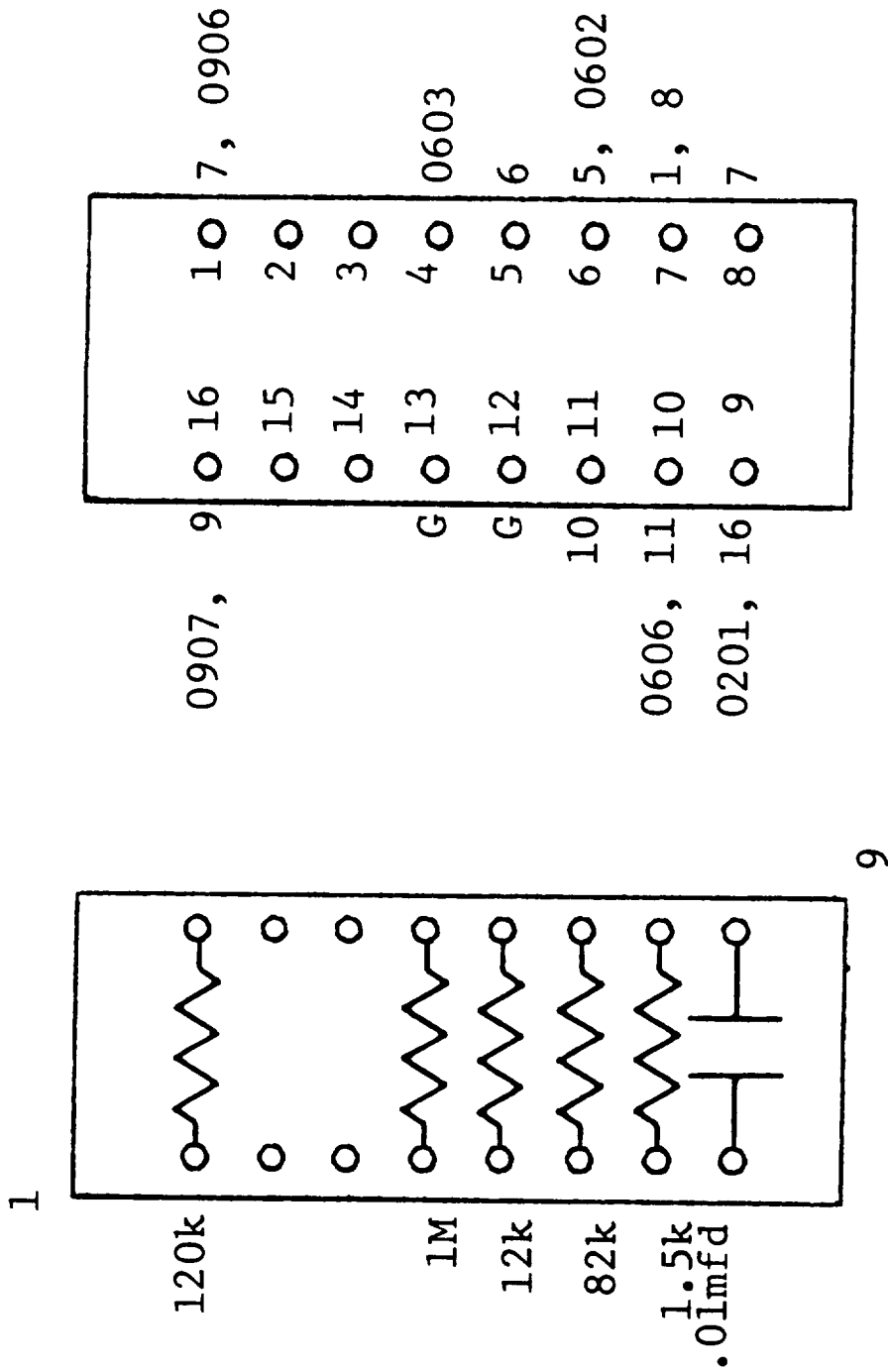
Figure 2.10. Wiring diagram with interconnections.

23
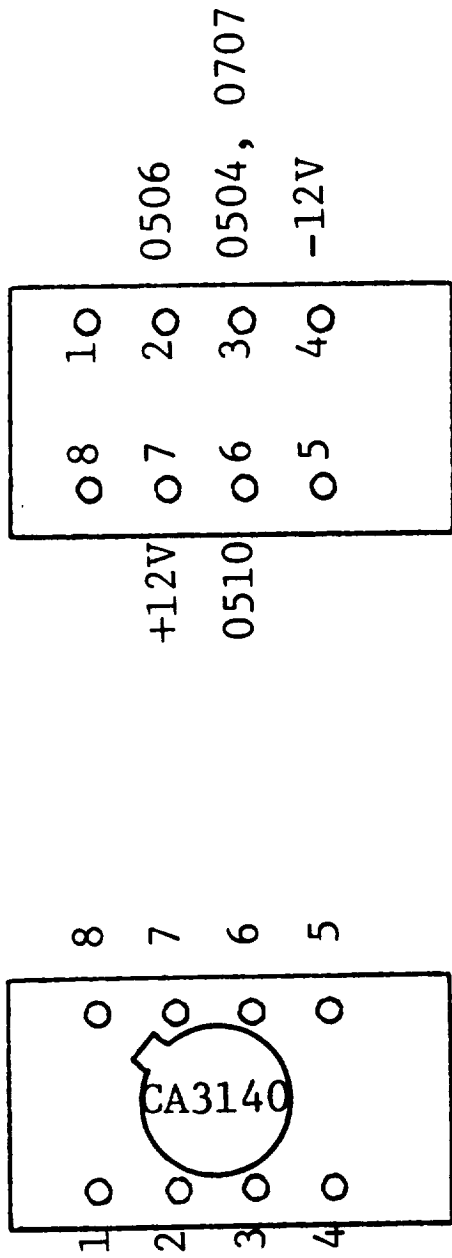
Figure 2.11. Wiring diagram with interconnections.

PB06

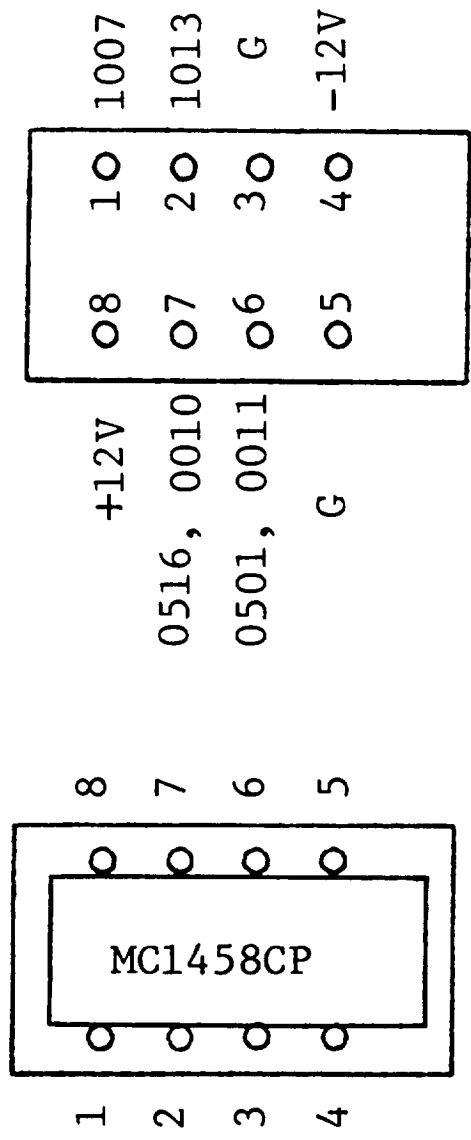24

Figure 2.12. Wiring diagram with interconnections.

Figure 2.13. Wiring diagram with interconnections.

26

Figure 2.14. Wiring diagram with interconnections.

27

Figure 2.15. Wiring diagram with interconnections.

28

Figure 2.16. Wiring diagram with interconnections.
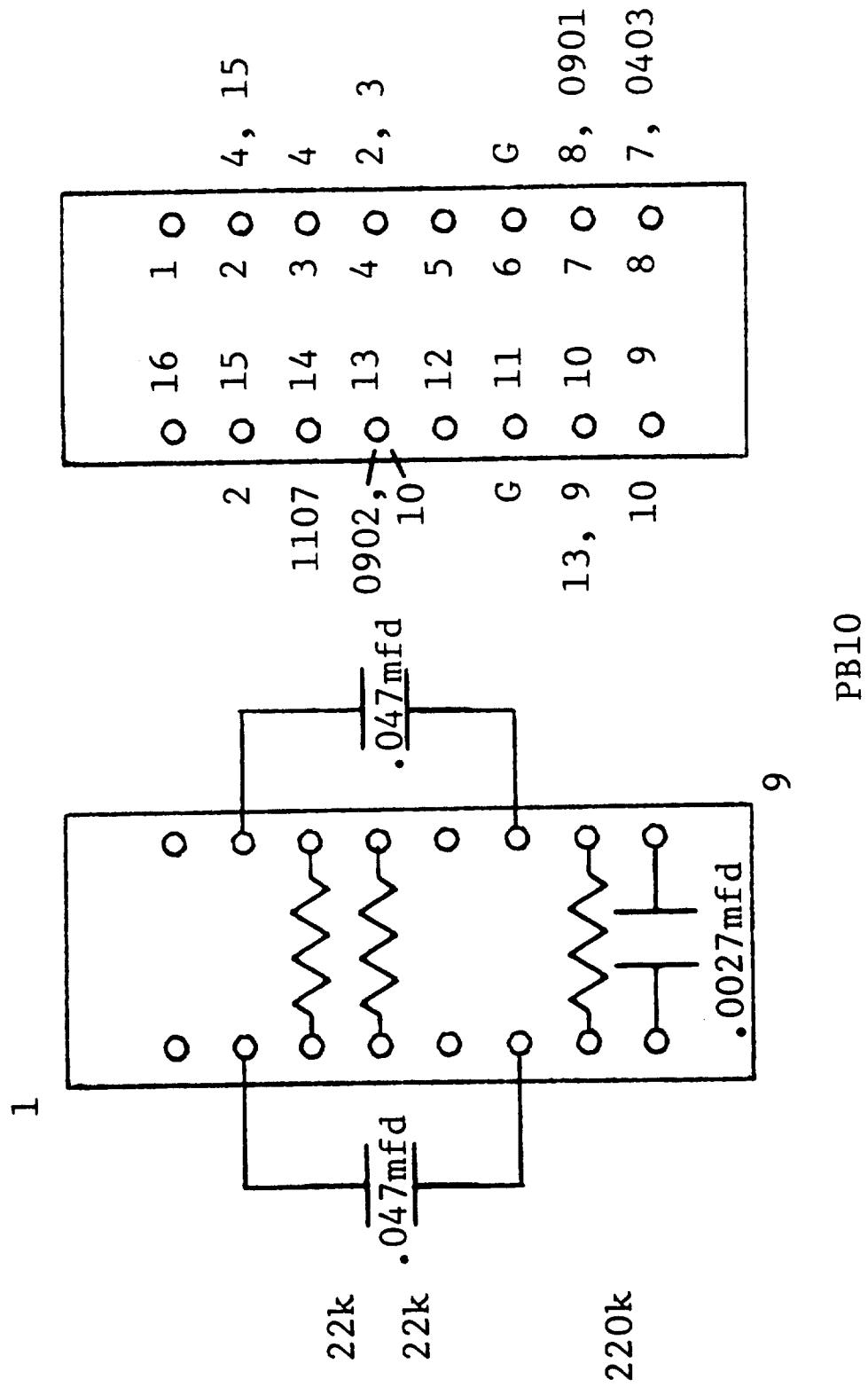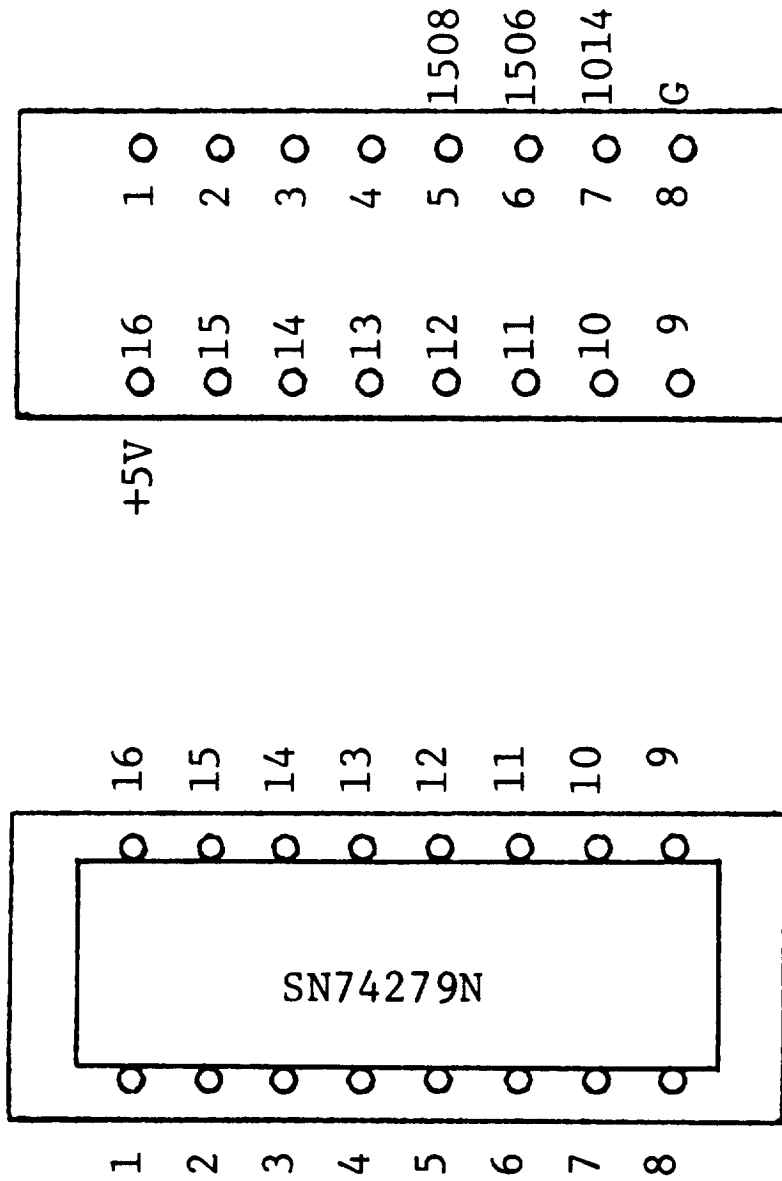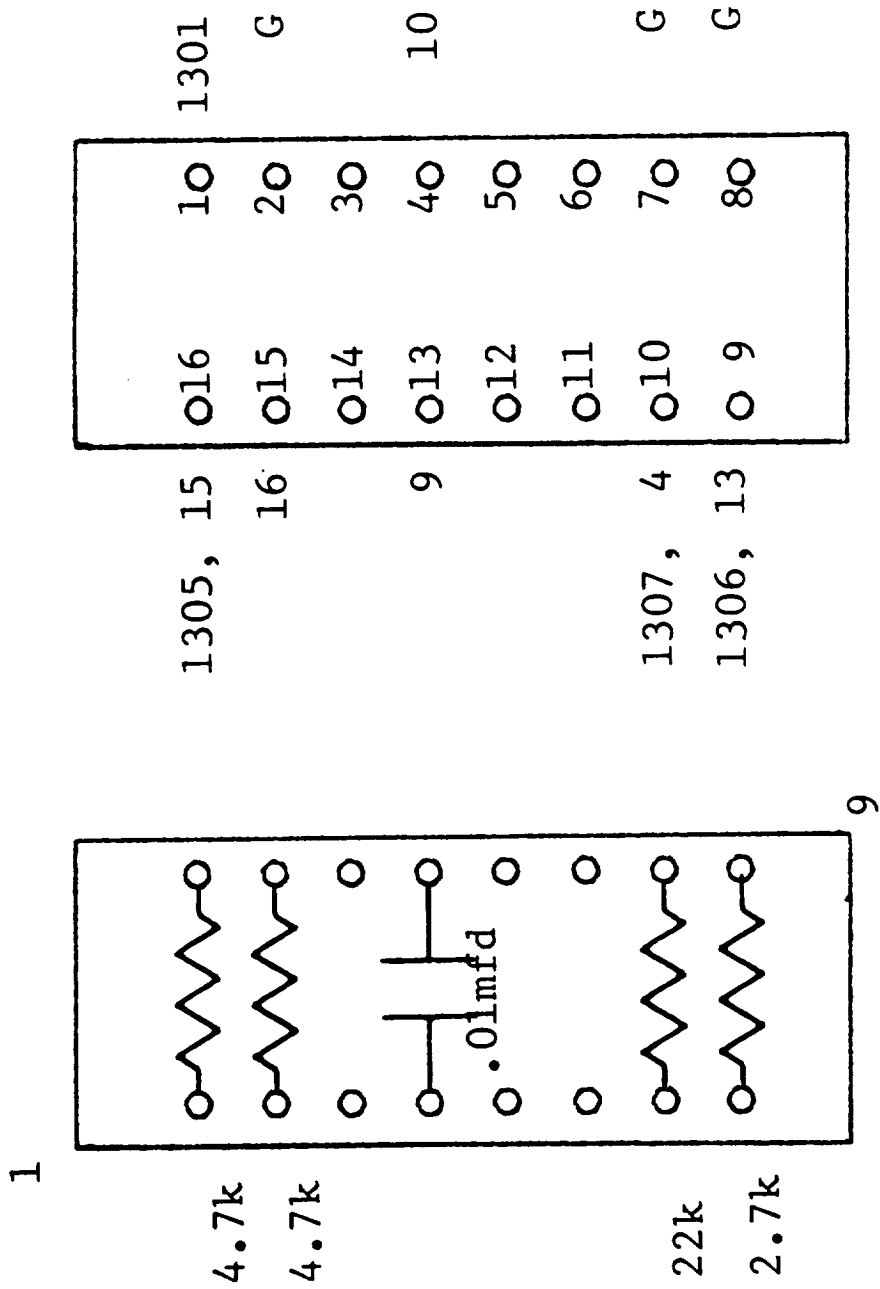
Figure 2.17. Wiring diagram with interconnections.
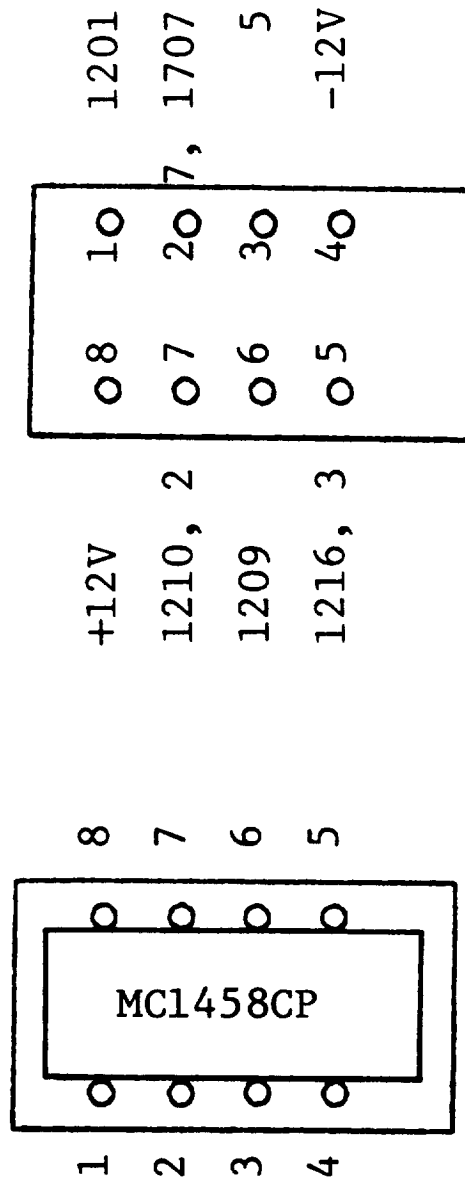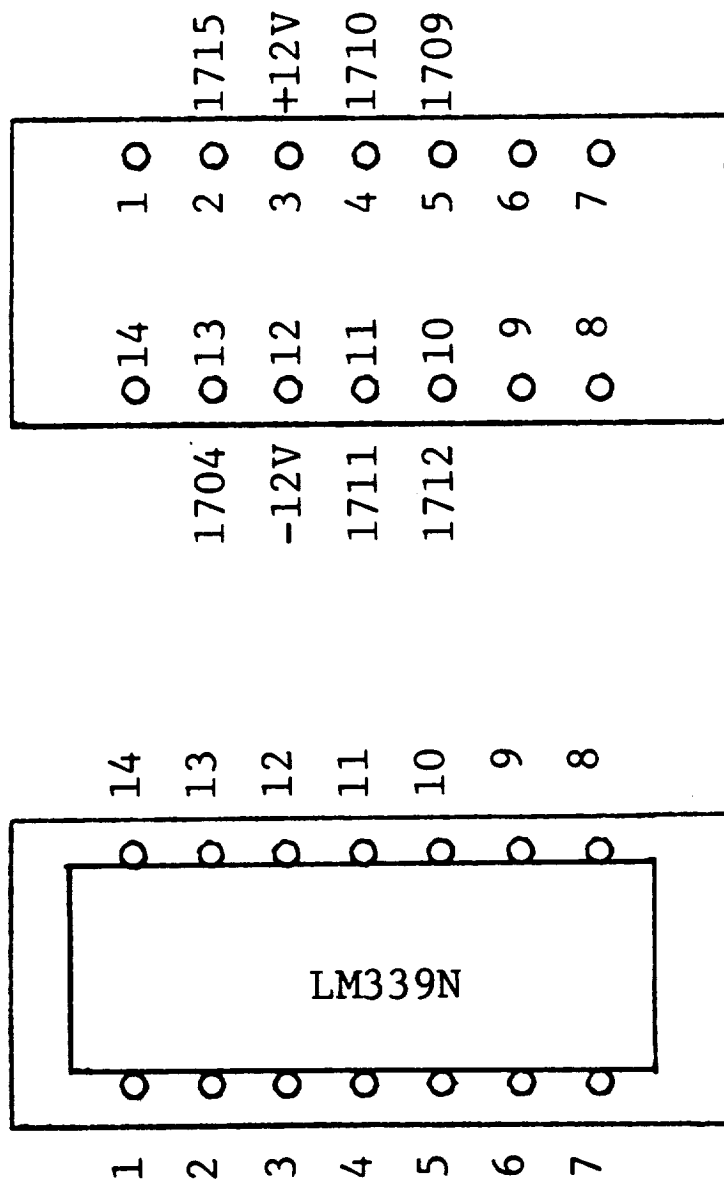
Figure 2.18. Wiring diagram with interconnections.

Figure 2.19. Wiring diagram with interconnections.

PB14
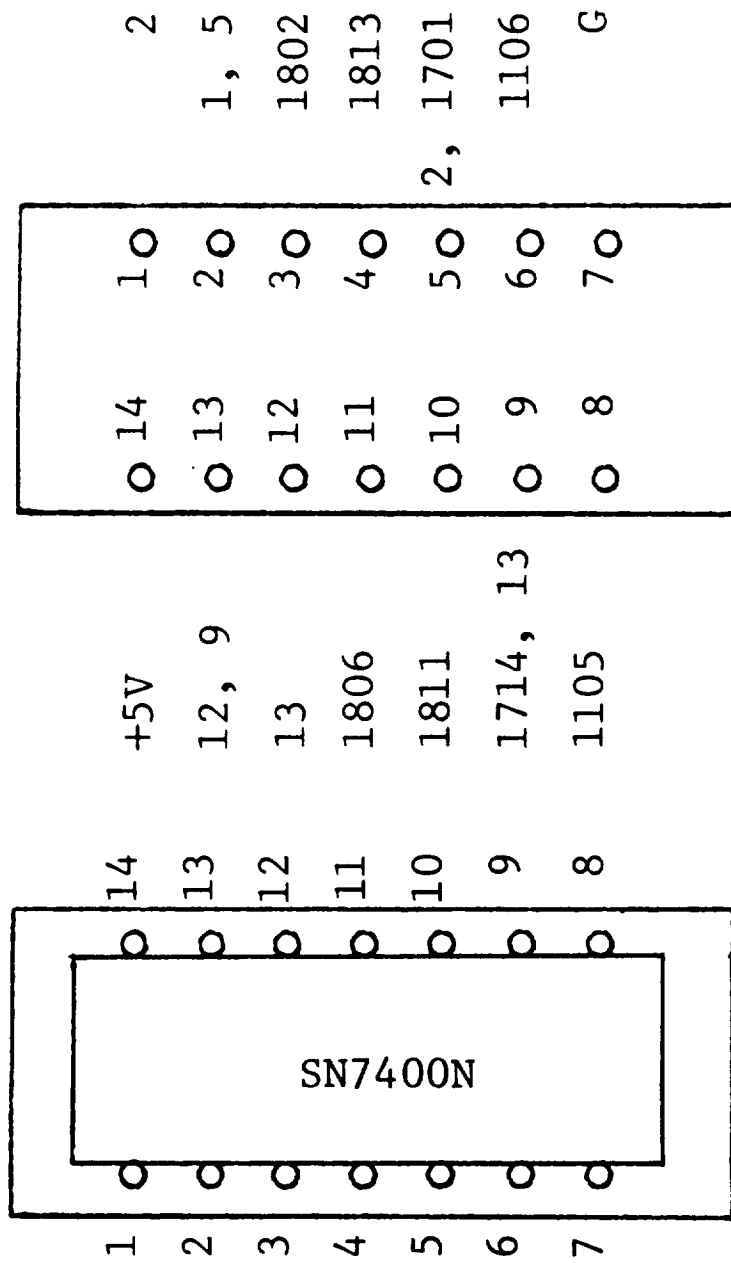
Figure 2.20. Wiring diagram with interconnections.

PB15

Pin	Connection
1	2
2	1, 5
3	1802
4	1813
5	2, 1701
6	1106
7	G
14	+5V
13	12, 9
12	13
11	1806
10	1811
9	1714, 13
8	1105

SN7400N

Figure 2.21. Wiring diagram with interconnections.

34

2, 1505
1
+5V
1413
1602, 2001
G
1302, 2007
G

	1	O	O	16	
	2	O	O	15	
	3	O	O	14	
	4	O	O	13	
	5	O	O	12	
	6	O	O	11	
	7	O	O	10	
	8	O	O	9	

+5V
1402
1713
1714
1410
1411
1404
1405

1509,

1

9

5.6k
3.9k
5.6k
3.9k
5.6k
5.6k
5.6k
5.6k

PB17

Figure 2.22. Wiring diagram with interconnections.

35

1503

1511

G

G

1 2 3 4 5 6 7 8

16 15 14 13 12 11 10 9

13

1504, 15

1510, 9

11

100

100

.001mfd

.001mfd

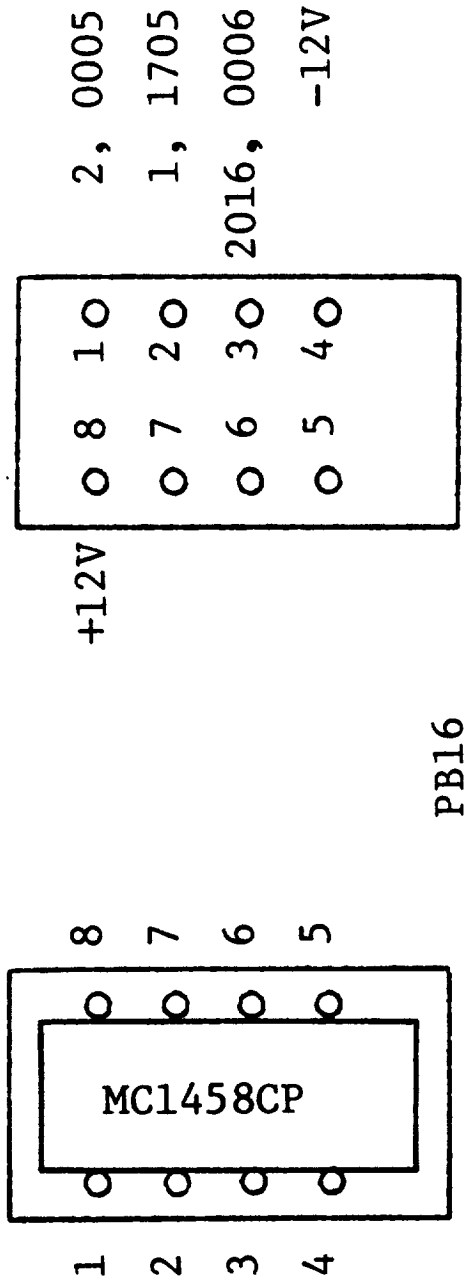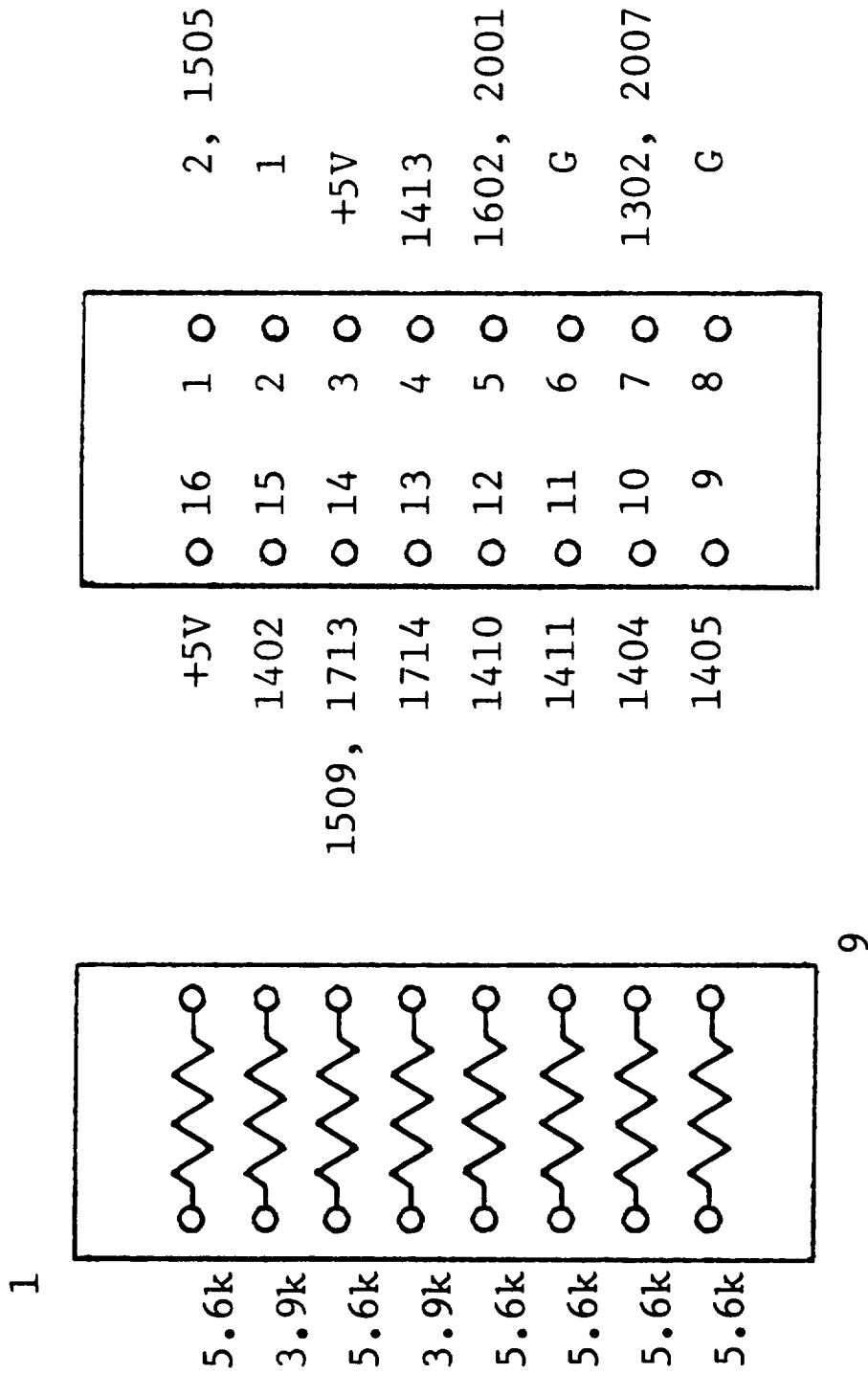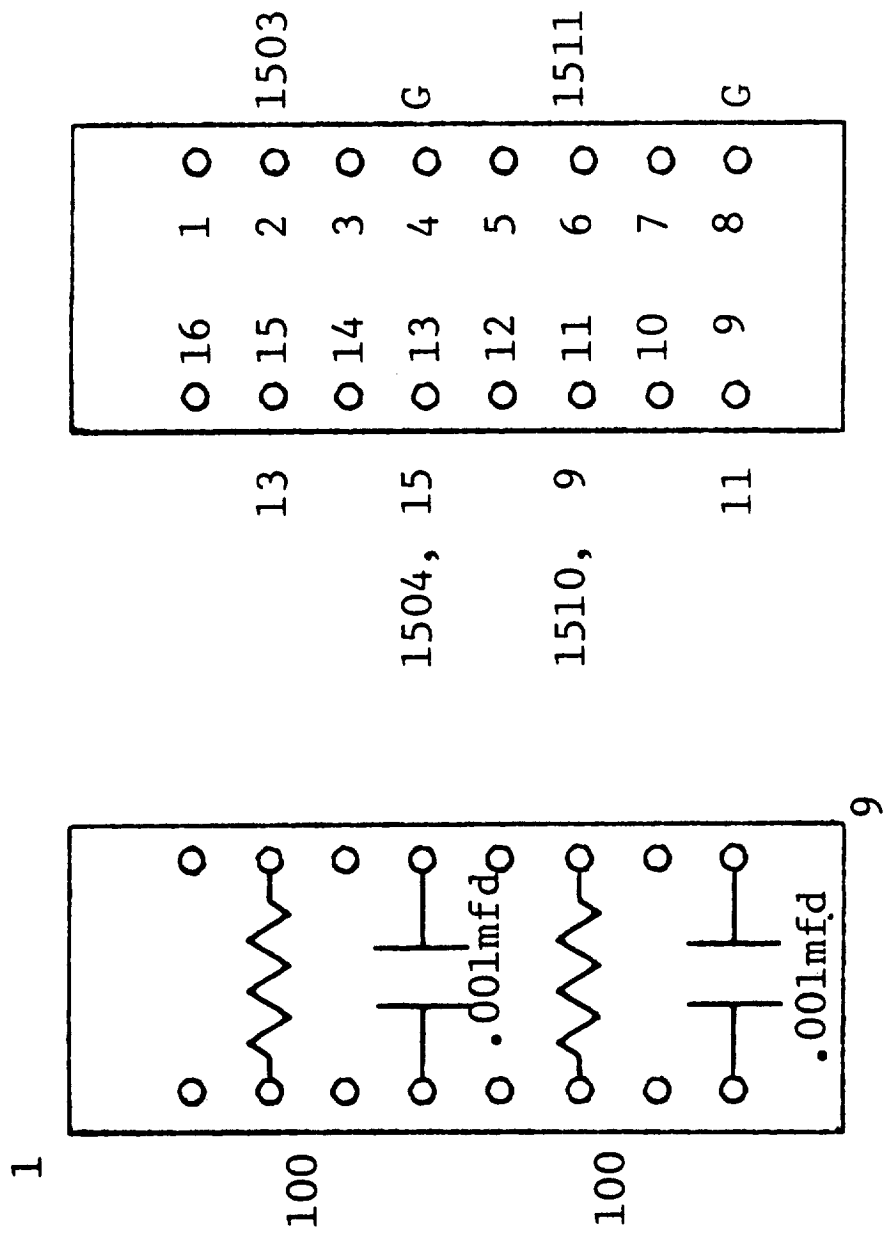PB18

Figure 2.23. Wiring diagram with interconnections.

36

Figure 2.24. Wiring diagram with interconnections.

37

1705

G

G

5

4, 2102

12, 2106

1707

G

1 O		O 16	1603, 10
2 O		O 15	2103, 14
3 O		O 14	15
4 O		O 13	12
5 O		O 12	6, 13
6 O		O 11	0016, 9
7 O		O 10	16
8 O		O 9	11

330

6.8M .0027mfd

270k .033mfd

330

4.7k .022mfd

1

9
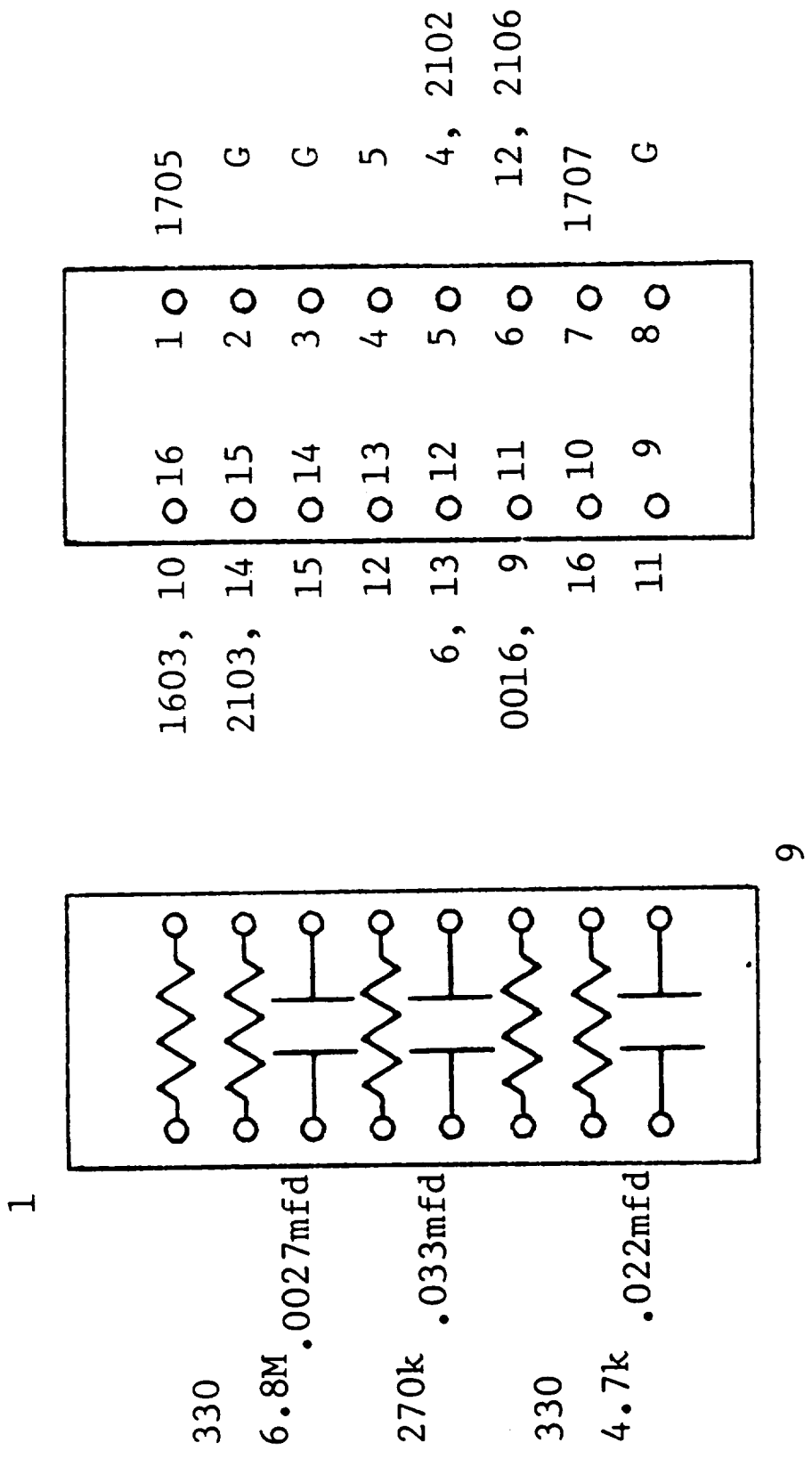
PB20

Figure 2.25. Wiring diagram with interconnections.
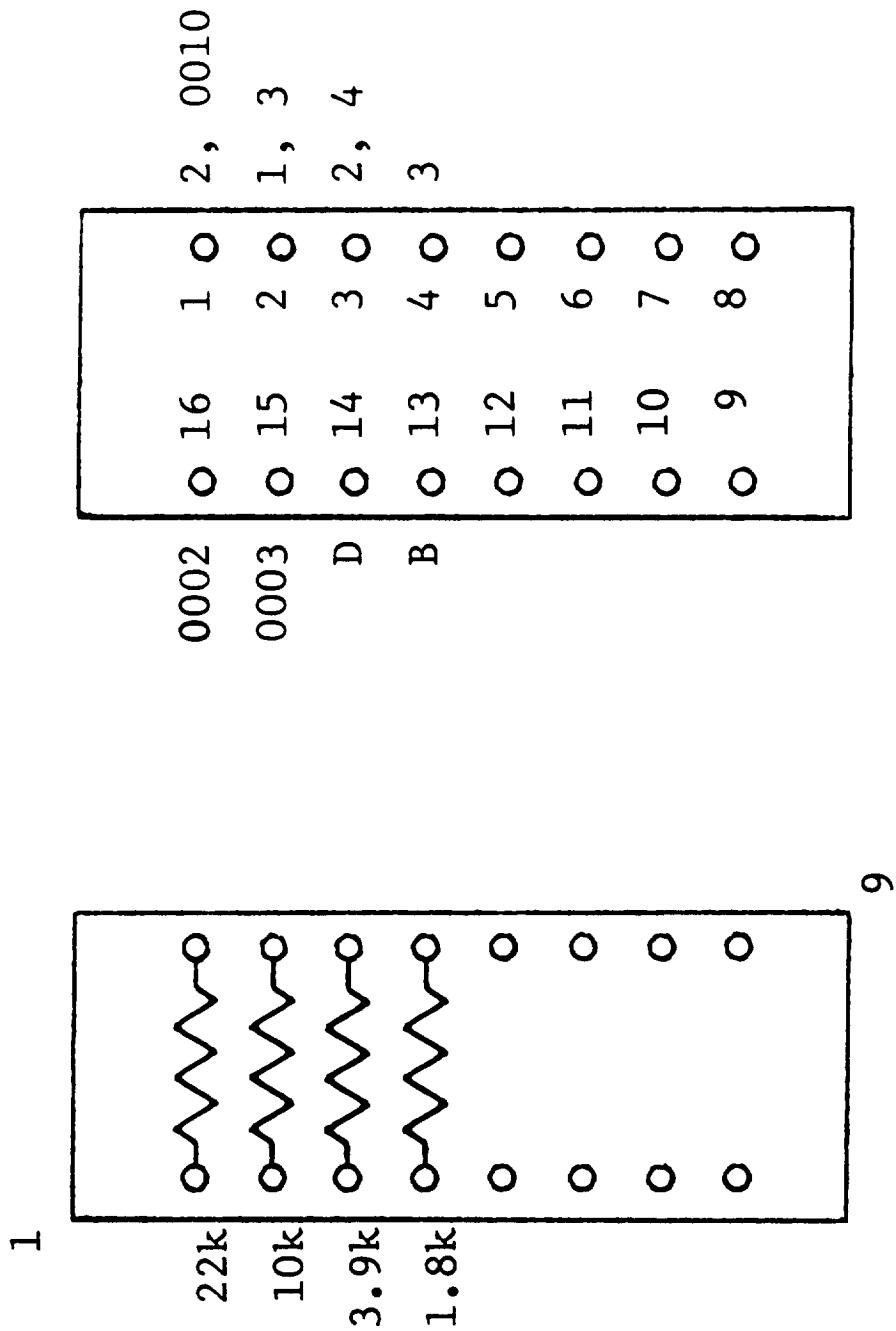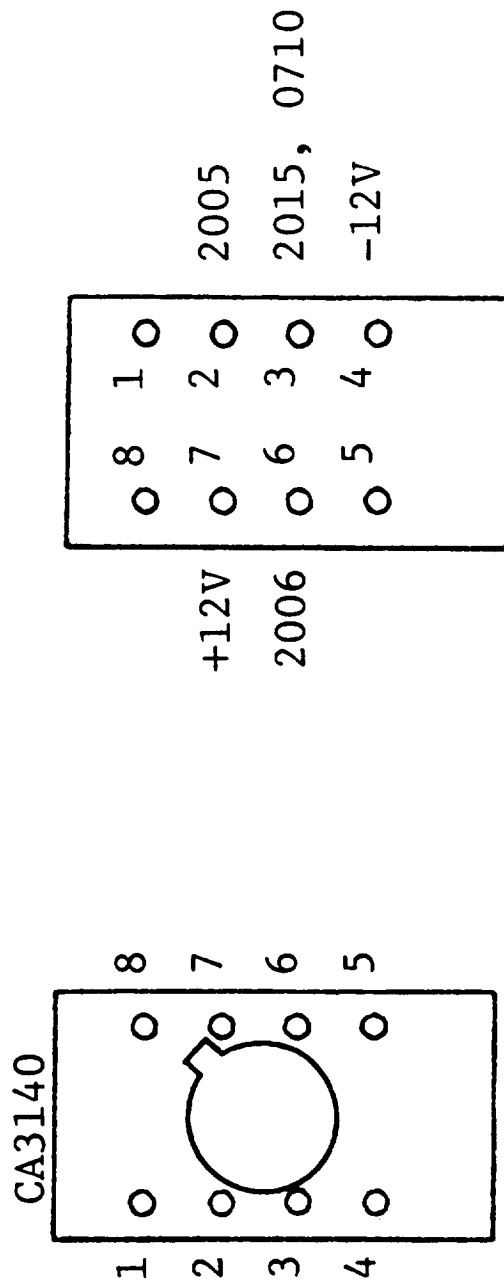
Figure 2.26. Wiring diagram with interconnections.

PB21

CA3140

+5V

Z 1116, 1514, 1716 1703

PB00

Analog Out
•16 2001
•14 +12v 0108, 0607, 0808, 0908, 1308, 1608, 2107, 1403
•13 -12v 0604, 0804, 0904, 0104, 1304, 1604, 2104, 1412
•11 0906 (Gain Adjust)
•10 0907, 1901

Gain Adjust

•7 0005 (Guard)
•6 1603 {C_x} 1601, 0007, E, F, G (Guard)
•5 F, 0005, G
•4 1914
•3 1915 1913
•2 1916

A 0304, 0308, 0407, 0416, 0512, 0513, 0708, 0903, 0905, 1006,
1011, 1108, 1202, 1207, 1208, 1507, 1706, 1708, 1804, 1808,
2002, 2003, 2008

Ground

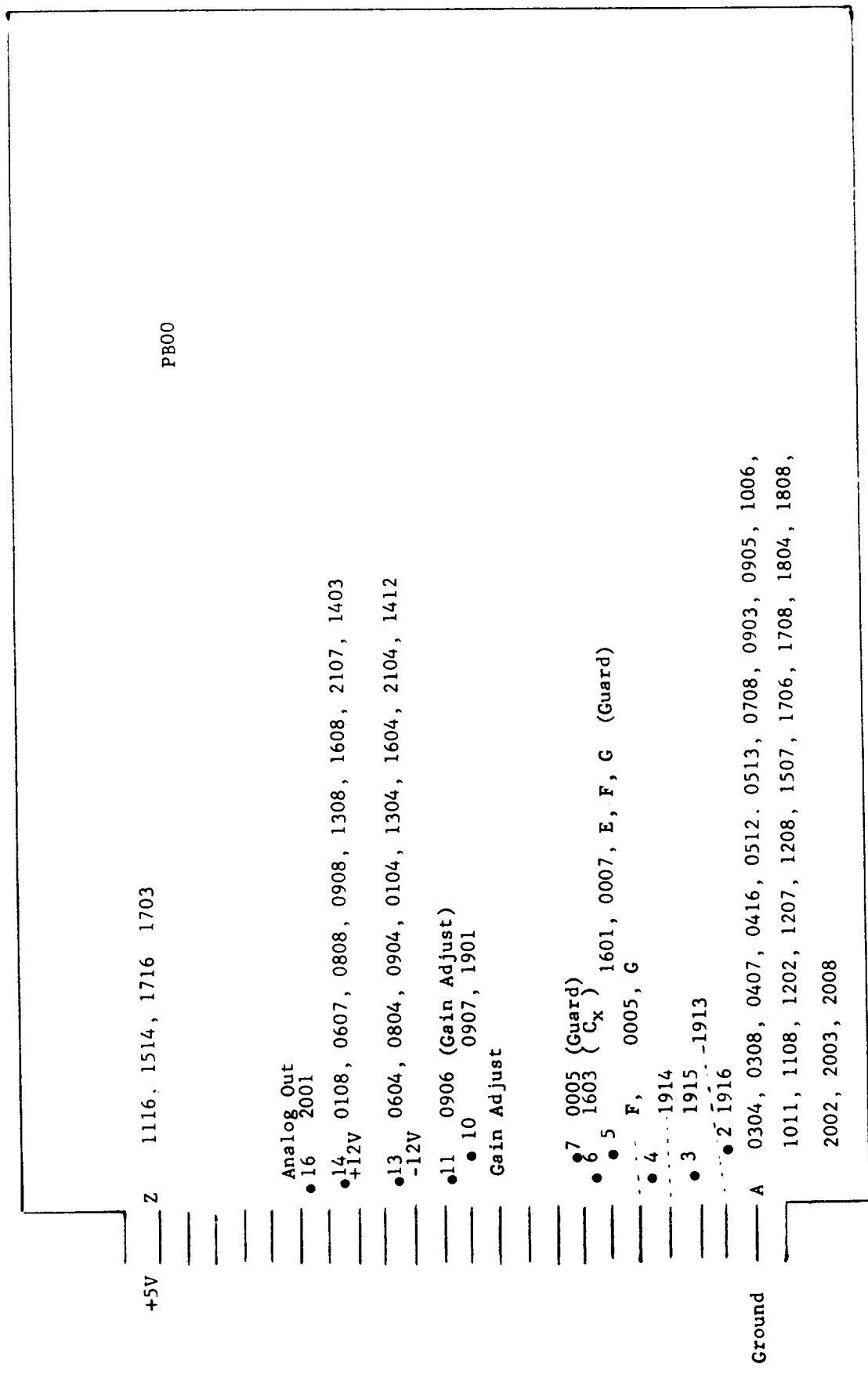Figure 2.27. Plug-in tab connections.
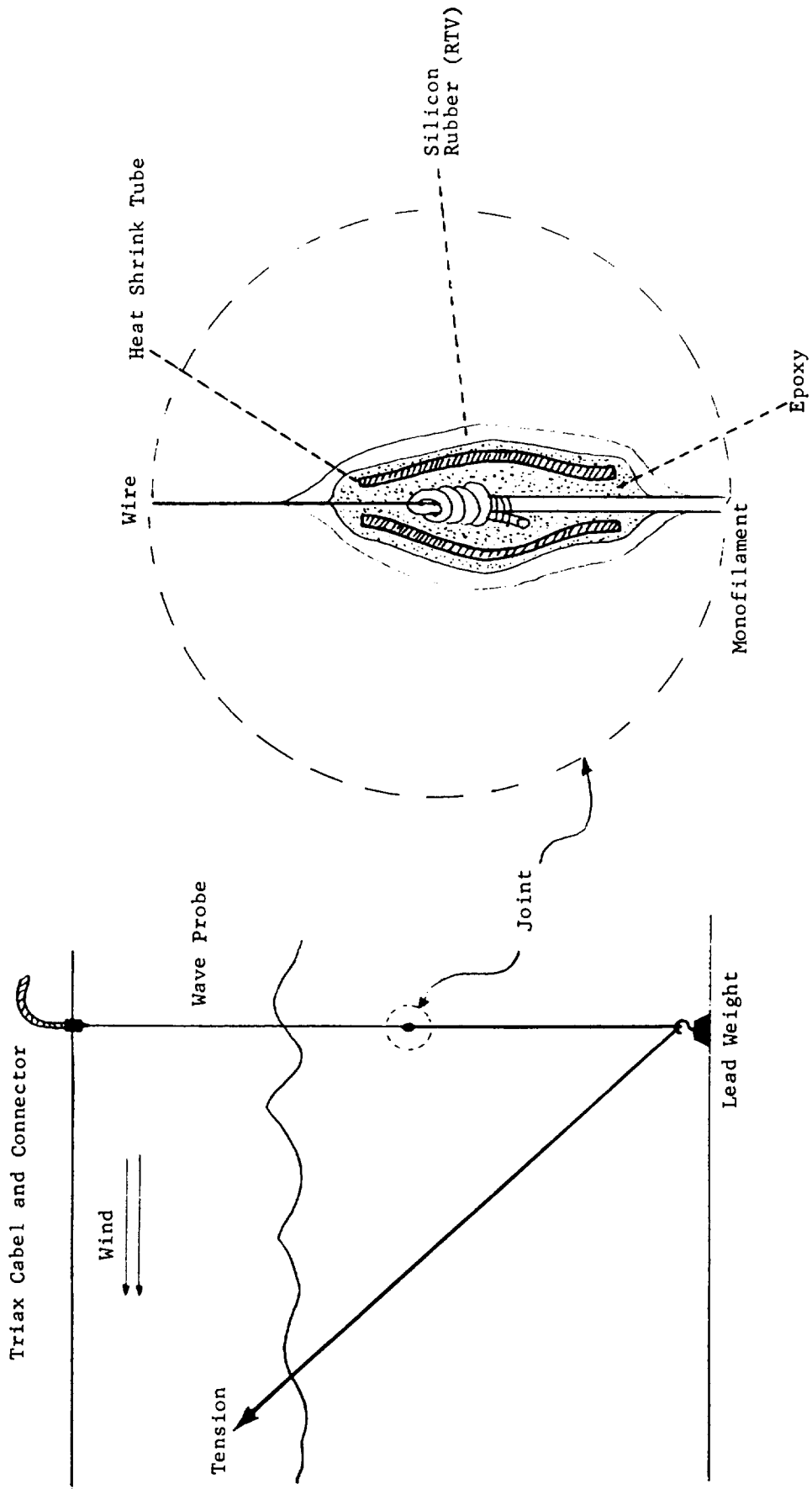
Figure 3.1. Laboratory arrangement of the wire probe.

Triax Cabel and Connector

Wave Probe

Wind

Tension

Joint

Lead Weight

Heat Shrink Tube

Silicon Rubber (RTV)

Wire

Monofilament

Epoxy

41
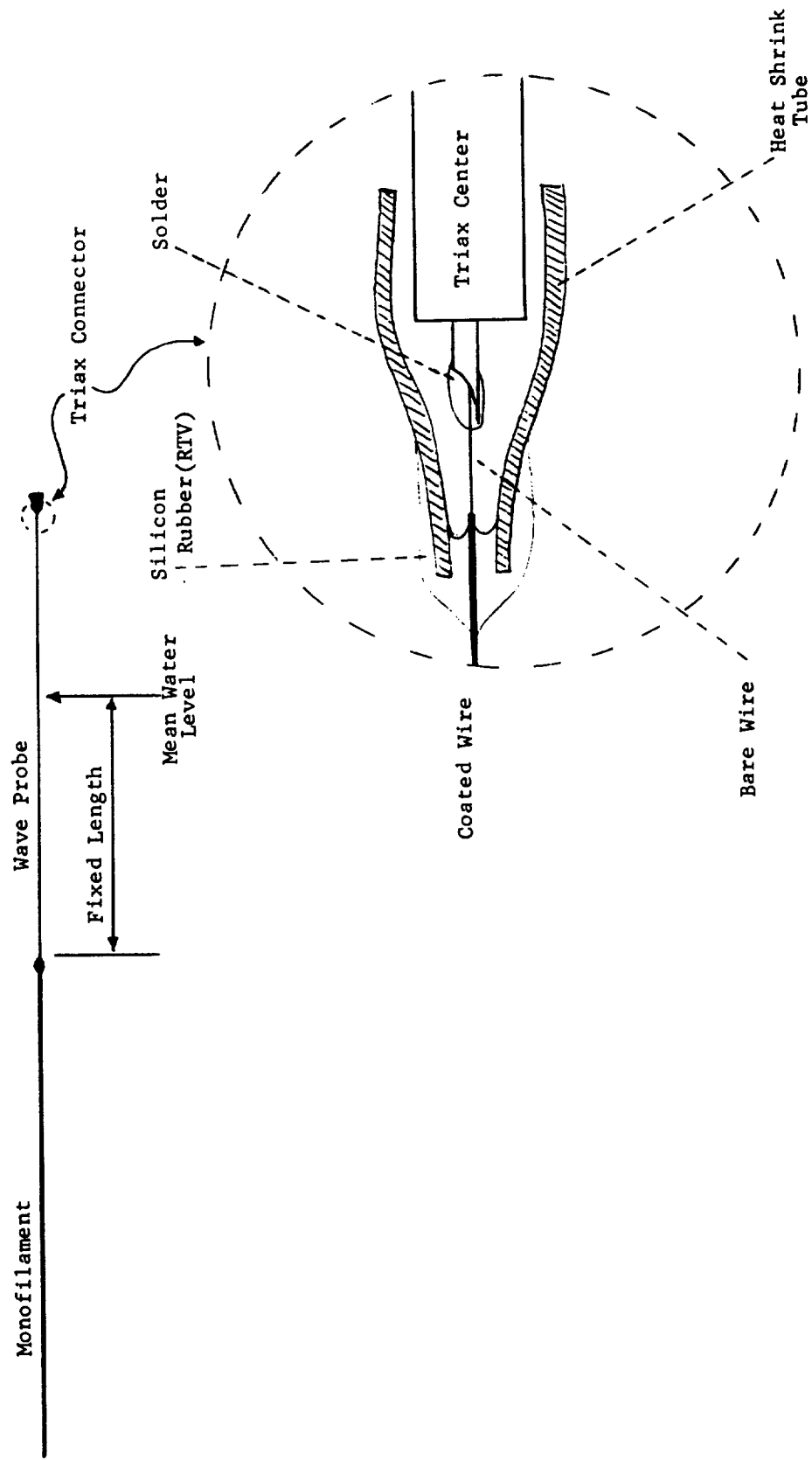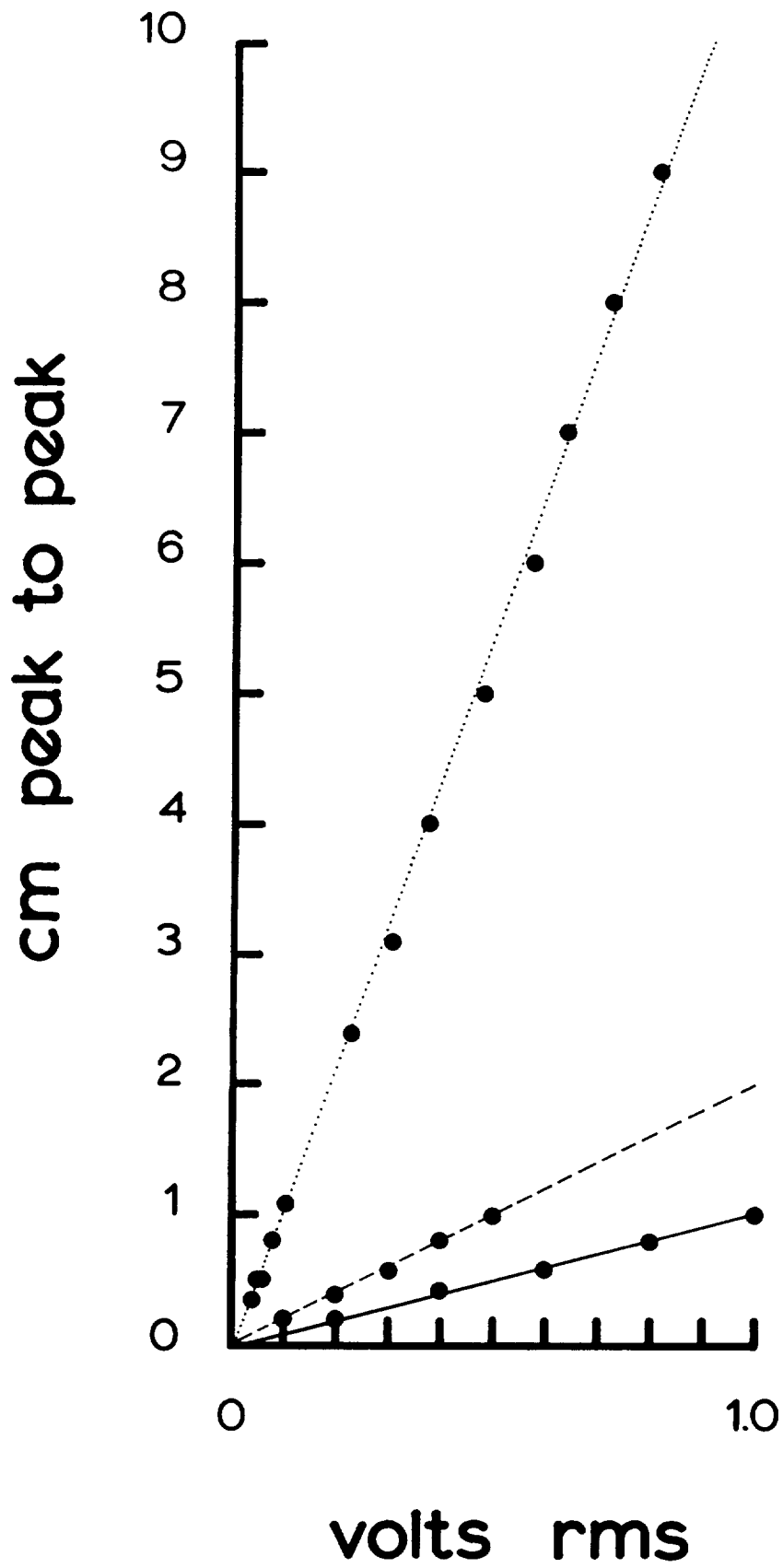
Figure 3.2. The triax connection.

Figure 5.1. Typical results of probe calibration.

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The wave probe developed at the Air-Sea Interaction Research Facility was designed to measure the surface elevation fluctuations of water waves. Design criteria included being linear in response, self-zeroing to the mean water level, having multiple operating ranges so that the instrument's maximum output could be matched to the maximum surface elevation over varying conditions, and be as noise-free as possible. The purpose of this publication is to provide a detailed description of the design and construction of this probe.

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