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AN IMPROVED IOWA SEDIMENT CONCENTRATION ANALYZER,(U)
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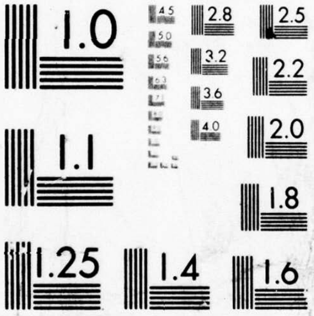

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AN IMPROVED IOWA SEDIMENT CONCENTRATION ANALYZER

by

John R. Glover

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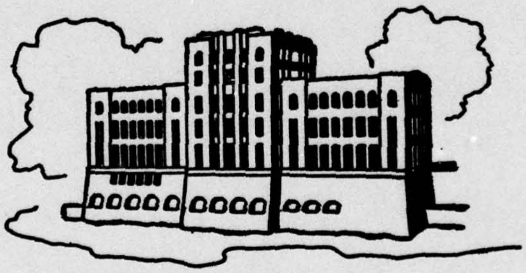

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Iowa Institute of Hydraulic Research
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Iowa City, Iowa
October 1977

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The Iowa Sediment Concentration Measuring System (ISCMS) is an electro-optical instrument designed for measuring suspended sediment concentrations in situ. The instrument employs a small light source and sensor which responds to particles interrupting the light from the sensor. The improved model has a higher carrier frequency to eliminate the influence of particle velocity on mean measurements and to improve the high-frequency response of the system. This change in carrier frequency required that 11 circuits be redesigned. A particle generator, consisting of small partially drilled holes in a rotating disk, was used to evaluate instrument performance. The results of tests conducted with this generator showed that mean concentration measurements for particle velocities as high as 7.3 m/s were unaffected by particle velocity. Also, the -3-db upper frequency limit occurs at a particle velocity greater than 3.7 m/s.

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AN IMPROVED IOWA SEDIMENT CONCENTRATION ANALYZER

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John R. Glover

The Iowa Sediment Concentration Measuring System (ISCMS) is an electro-optical instrument designed for measuring suspended sediment concentrations *in situ*. The instrument employs a small light source and sensor which responds to particles interrupting the light from the sensor. The improved model has a higher carrier frequency to eliminate the influence of particle velocity on mean measurements and to improve the high-frequency response of the system. This change in carrier frequency required that all circuits be redesigned. A particle generator, consisting of small partially drilled holes in a rotating disk, was used to evaluate instrument performance. The results of tests conducted with this generator showed that mean concentration measurements for particle velocities as high as 7.3 m/s were unaffected by particle velocity. Also, the -3-db upper frequency limit occurs at a particle velocity greater than 3.7 m/s.

AN IMPROVED IOWA SEDIMENT CONCENTRATION ANALYZER

I. INTRODUCTION

The Iowa Sediment Concentration Measuring System (ISCMS) described herein is an improved model of the original instrument reported by Glover, et al. (1969), for the measurement of suspended sediment concentration *in situ*. Although the transducer had been modified as reported by Locher, et al. (1974), the electronics had remained essentially unchanged. Several deficiencies that were subsequently discovered as a result of usage were high-frequency response limitation and incorrect indication of mean concentrations when particle velocity was high. This latter problem is one associated with filtering and was reported by the Delft Waterloopkundig Laboratorium (1975). The work by Locher et al. (1974) also discussed this effect, but from a different point of view, and doesn't recognize the association with measurement of mean concentrations in high-fluid-velocity flows. The solution to both problems required that a higher carrier frequency be used for modulation by the sand particles. The higher carrier frequency makes it possible to increase the frequency response of the instrument and to extend the upper limit of the particle-velocity range by increasing the frequency of the -3-db cutoff point of the high-pass filter. Although the concept of this frequency change is a simple enough modification, the implementation is more difficult. The 50-kHz oscillator with both its frequency and amplitude stability requirements was not commercially available as was the 10-kHz oscillator used in the first model. To preserve the linearity performance of the detector, faster operational amplifiers were required. Even the phototransistor when operated with a load ten times less than before was at its limit of performance. As a result, all the electronic circuits had to be either designed or redesigned to accomodate the shift to the 50-kHz carrier frequency.

For presentation purposes, the circuits are described following a signal-flow concept, originating with the oscillator card and terminating with the card for final processing of the detected signal. The two circuit cards in between are the source-sensor and high-pass filter card and the detector and low-pass filter card. Following the presentation of circuit descriptions is an evaluation of the improved performance of the instrument. Appendix A contains the instrument calibration procedures, and a description of instrument operation.

II. OSCILLATOR AND AGC CARD

The oscillator for generating the 50-kHz sine wave used to drive the light source is a Wein-bridge oscillator with an operational amplifier as the gain element. A continuous-acting automatic-gain-control (AGC) loop to reduce distortion by keeping the amplifier in its *linear range is included.* The Wein-bridge elements, R_5, R_6, R_7, R_8, C_2, and C_3 in figure 1 supply positive feedback around the amplifier to induce oscillation at the frequency where the positive feedback peaks. The frequency of this oscillation is given by the following equation:

$$f = \frac{1}{2\pi C_2 (R_7+R_8)} = \frac{1}{2\pi C_3 (R_5+R_6)} \qquad (1)$$

where the components are defined as shown in figure 1. For $(R_7+ R_8)$ $(R_5+ R_6)$ and $C_2=C_3$, the ratio of the positive input signal to the amplifier output signal *is one-to-three. Then, for a gain of three from the amplifier,* the loop gain is unity and oscillation results. To avoid distortion, the ideal gain of unity is maintained by the continuous-acting AGC circuit composed of the field-effect transistor (FET), T1, R1, R2 and R4. The amplifier gain is controlled by the total resistance between the negative input and ground. With the FET acting as a voltage-controlled resistor, the gain of the amplifier can be automatically adjusted by detecting the voltage level at the output of the amplifier. Components D1, C1, and R3 detect this output signal and supply the bias to the FET for controlling the effective resistance to ground.

Since the operating point of the FET is temperature dependent, the amplitude of the oscillator has to be stabilized by a second precision AGC circuit. The first requirement for this stabilization must be detection of the oscillator output by a technique which eliminates the characteristics of the components used in the circuit. The second requirement is gain control by the detected signal of the amplifier in series with the oscillator signal. Again, operational amplifiers are well suited for these requirements. The tee-network in the feedback loop of amplifier 2 shown in figure 1 controls the gain as the bias changes on the FET which acts as a voltage-controlled resistor. The bias is generated by detecting the output of amplifier 2 and comparing it with a reference voltage. The difference between the detected signal and the reference signal is integrated and the averaged signal is the bias of transistor T2. Because all the temperature sensitive elements are in the feedback loops, changes in their characteristics are suppressed by the gains of the loops. The result is a very stable output signal suitable for driving the light source.

III. SOURCE-SENSOR AND HIGH-PASS FILTER CARD

To establish the operating point for the light sensor, a dc current is passed continuously through the light source with the ac component superposed. The operating point of the light sensor is chosen to give the best linearity of the sensor by observing the change in ac sensitivity as the dc operating point changes. The operating point of the light source is not as critical as long as the ac component is not distorted. In addition to linearity problems, power dissipation in both the sensor and source becomes sufficient to heat the probe and to cause it to shift its operating point as the velocity of the fluid in which the probe is immersed varies.

For generating the combined dc and ac signal, the signal from the oscillator is added to the dc signal by amplifier 1 (see figure 2). Transistor T1 is a current booster needed to accomodate the low ac resistance of the light source. The sensor is operated in the grounded emitter configuration because this gives a better physical connection for mounting the device.

The light source is a P-N gallium arsenide diode, TIL24, manufactured by Texas Instruments and is designed to emit near-infrared light when forward biased. Although the simplest, continuous light, resulting from a dc current being passed through the diode, is not desirable as light for modulation by the sand particles because the sensor is free to respond to all other sources of light that fall within its spectral bandwidth. To provide an identity to the light to be detected, an alternating current is superimposed on the dc current and frequencies below the alternating component are filtered out after being detected by the light sensor.

The sensor is also a Texas Instrument product, a model TIL 604, N-P-N planar silicon phototransistor. Both sensor and source are semiconductor devices with temperature dependent characteristics. Figure 3 shows the influence of temperature on the source current as temperature increases for two different probes, while figure 4 shows the effect temperature has on the detected sensor signal. Figure 4, of course, is a combined effect of the two devices since the source temperature was the same as the sensor temperature. In addition to a change in light intensity from the source as temperature changes, the wavelength of the light also changes. Since the sensor sensitivity is also wavelength dependent, the influence of each parameter is difficult to distinguish. The similarity of slopes of the curves in figure 3 suggests that both light sources have similar temperature characteristics. The constant difference between the curves is probably because of a different distance between the sensor and source. The operating point of the sensor was the same for both probes, and as mentioned above, it is controlled by the dc component of current in the light source. The combined sensor-source behavior does not exhibit this similarity; thus temperature compensation becomes probe dependent. Also, the nonlinear behavior would complicate a compensating system significantly. Neither grounder emitter or collector configurations demonstrated a detectable advantage with the 1000-ohm load and 5-volt supply.

The signal from the sensor is amplified by the variable-gain amplifier A2 prior to the filtering of the low-frequency components. The gain of this amplifier is adjustable to permit correction for sensitivity changes caused by temperature and/or absorption as detected when sediment is not present in the probe field. The universal active filter, UAF21, is configured as a high-pass Butterworth filter with a -3 db frequency of 25 kHz. It is necessary to remove the low-frequency contributions introduced by the dc current for biasing the light sensor in order to eliminate particle-velocity sensitivity in mean measurements. The UAF21, by itself, is a two-pole active filter. The third pole is provided by the coupling between the light sensor and amplifier A2. Specific details on the operation and concept of the active filter are given by Tobey, et al (1971). Figure 5 shows oscilloscope traces of the sensor and filtered sensor signals for different velocities of particles as generated by the particle generator discussed in Section VI. The effectiveness of the filter in removing the dc-component of the signal to give an amplitude modulated signal for detection is clearly demonstrated.

IV. DETECTOR AND LOW-PASS FILTER CARD

The detector for demodulating the amplitude-modulated 50-kHz probe signal is a linear detector composed of amplifiers A1, A2, and A3 shown in figure 6. Following the detector is a universal active filter, UAF41, for removing the carrier signal from the detected signal. This filter is configured as a low-pass third-order Bessel filter with its -3 db frequency set at 2500 Hz. To obtain a frequency response of dc, the filtered detected signal is added to a fixed reference voltage to give a final signal that is zero for zero sediment concentration. It would be possible to ac couple the detected signal, but then correction for drift and clear-water absorption would not readily be possible. Also, indications of mean concentrations would have to be made by different techniques than simple averaging.

The detector is a precision absolute-value circuit. The switching amplifier, A1, is a fast, precision-settling FET operational amplifier with a slew rate of 500 v/μsec. Low-value resistors are employed for all three stages to reduce capacitance effects. Amplifier A2 gives a constant load to the switching amplifier A1 and improves the rectification. The oscilloscope traces shown in figure 7 show the outputs of amplifiers A1, A2, and A3 with a 50-kHz input signal.

The universal active filter UAF41 is configured as a three-pole Bessel filter. Bessel filters have the desired characteristic of passing rectangular pulses with minimum distortion and with a delay time that is linearly proportional to the phase shift. Because of the nature of the single sediment particles entering and leaving the sensing volume, the zero overshoot characteristic of the Bessel filter is most desirable.

The addition, as mentioned above, of the dc signal corresponding to zero sediment concentration is accomplished by amplifier, A4. The reference voltage is the negative supply voltage. A final single-pole filter with a time constant of 0.02×10^{-3} sec is included with this amplifier.

V. ZERO INDICATOR AND VOLTAGE-TO-FREQUENCY CARD

The two remaining functions to aid in the processing of the signal representing the sediment concentration are a voltage-to-frequency converter for long-time integrations and an output-signal zero indicator for accurate indication of the correct setting of the ZERO control. The setting of this control is influenced by temperature changes, changing light absorption, background light, and fluid velocity. This indication of zero voltage, controlled by the ZERO control and more correctly defined as the acceptable deviation from zero, is given by two lights located on the front panel. These lights define the voltage range of ± 20 mv from zero. The upper light is on when the voltage is less than +20 mv, and the lower light is on when the voltage is less than -20 mv. Hence, an acceptable zero is indicated when only the upper light is on.

For normal operation there are periods when particles are not present in the sensing volume of the probe, and during these intervals the upper light should be on. The work reported by Locher, et al. (1974) indicates that concentrations up to 11,000 mg/l of 0.25 mm sand satisfy this condition. An oscilloscope is also useful in indicating these periods, but the sensitivity, when adjusted to give a proper deflection when particles are present, is inadequate for indicating the correct setting of the ZERO control. Hence, the two panel lights are used to give a continuous indication of the signal when particles are not present in the probe field. This technique, it must be cautioned, does not work when the sediment concentration is large enough to eliminate time periods when particles are not present. Therefore, the oscilloscope must still be used in interpreting the signal for proper adjustment of the ZERO control.

The circuits for controlling the panel lights are shown in figure 8, and consist of two operational amplifiers configured as threshold detectors to drive the light emitting diodes (LED) defining the voltage region near zero. The inputs to these circuits are in parallel with the voltage-to-frequency converter input.

The very nature of a limited number of particles entering and leaving the probe field also required a technique other than meter deflection for estimating the mean voltage. The integrating voltage-to-frequency converter accomplishes the integration operation for mean indication and the time of integration is controlled by the time necessary to determine the mean frequency. The converter is this instrument is biased to a frequency of 10-kHz for zero input voltage. The calibration coefficient is 1000 Hz/volt, thereby causing voltages of +1 volt and -1 volt to give frequencies of 11-kHz and 9-kHz, respectively. The full-scale and offset errors are adjustable to zero, so the transfer linearity is one of the most meaningful measures of accuracy of the converter. This unit has a maximum transfer linearity error of ± 2 mv, so it is more than adequate to process the signals corresponding to sediment concentrations. Since this converter is a commercially available unit, its operating characteristics are not repeated here. Figure 9 depicts how it is incorporated in the instrument.

VI. INSTRUMENT EVALUATION

To evaluate the improved performance of the ISCMS, a plastic disk with uniformly spaced partially drilled holes was attached to a variable-speed motor. The probe was positioned so that as the disk rotated, the holes interrupted the light field. Signals generated by the rotating disk are shown in figures 10 and 11. The velocity of a "particle" was determined by measuring the frequency of the signal. For the signals shown, the velocity ranged from 0.37 m/s to 7.3 m/s. Significant amplitude reduction is not detectable until a velocity of 1.5 m/s (figure 10d) is reached. A thirty percent (-3 db) reduction in amplitude occurs at a velocity between 3.7 m/s and 7.3 m/s (figures 11b and 11c). Not visually obvious from the oscilloscope traces is the constant value of the mean of the signal. However, integration by an integrating voltage-to-frequency converter verifies that the mean voltage is constant for velocities as high as 14 m/s.

VII. CONCLUSION

The results of the work described herein are really all contained in the oscilloscope traces shown in figures 10 and 11. The electronic circuits function properly and with the stability necessary for reliable operation. The circuits in the previous instruments did this also. It was, however, the limitations imposed by the carrier frequency, which was too low, and inadequate filtering of the low-frequency components introduced by the dc component of the light. As figures 10 and 11 depict, these limitations have been reduced to a level which eliminates them from consideration. The temperature drift, although not eliminated, is monitored by the two level sensors which should function adequately under normally encountered sediment concentrations.

The one remaining serious limitation which this work did not address is the dependence of the signal on particle position in the probe field. As reported by Locher et al. (1974), there are significant differences in the instrument response as particles enter into or exit from the probe field. These differences mean that the instantaneous output of the ISCMS cannot be correlated with the instantaneous suspended sediment concentration within the probe field. In spite of this, however, the improvements reported herein make the instrument even more suitable for laboratory investigation requiring the measurement of suspended sediment.

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GLOVER, J.R., BHATTACHARYA, P.K., and KENNEDY, J.F., 1969. "An Electro-Optical System for Measurement of Mean and Statistical Properties of Sediment Suspensions." IIHR Report No. 120, Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City, Iowa.

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TOBEY, G.E., GRAEME, J.G., and HUELSMAN, L.P., 1971. "Operational Amplifiers," Chapter 8, McGraw-Hill Book Company, New York, New York.

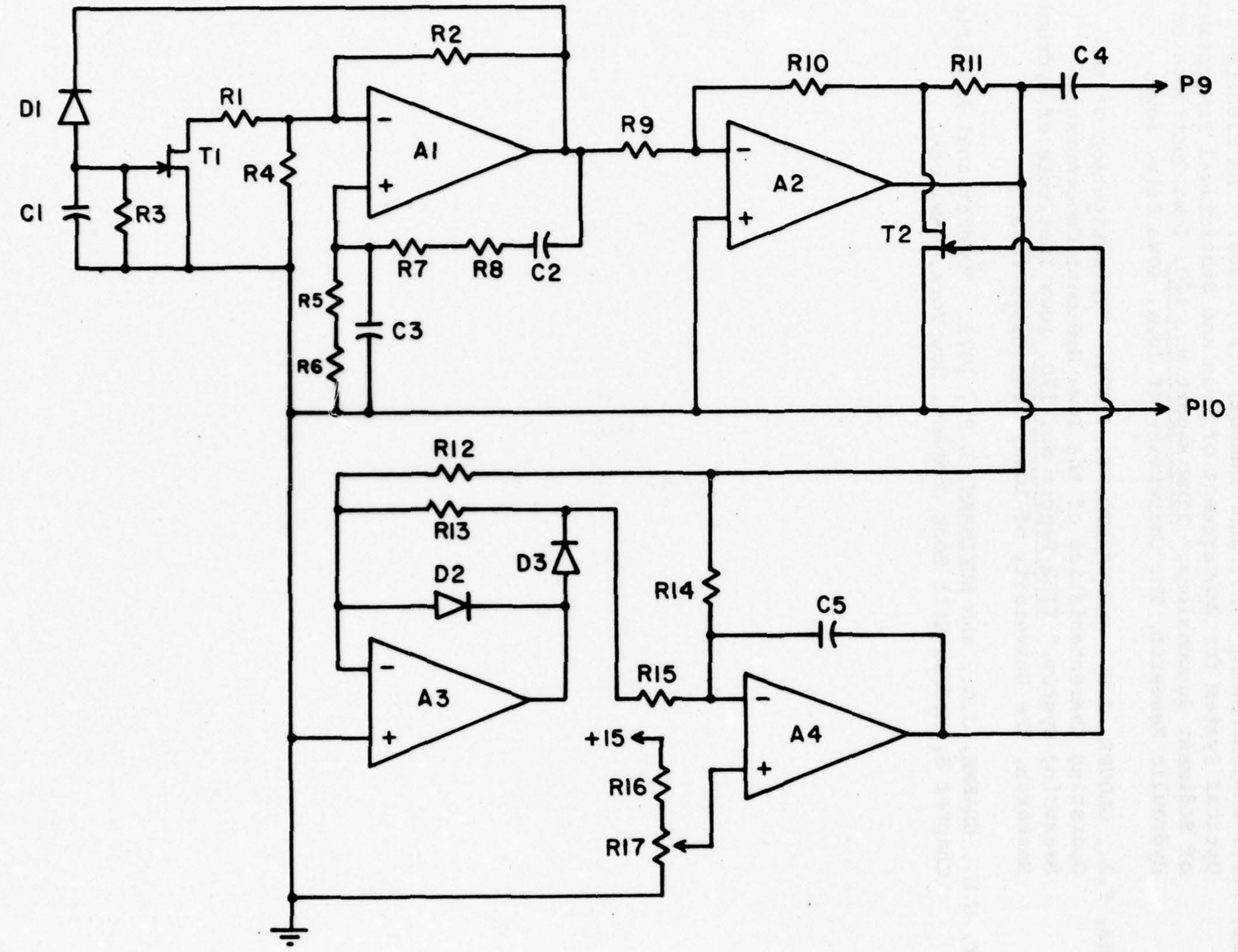


Figure 1. Oscillator and AGC card

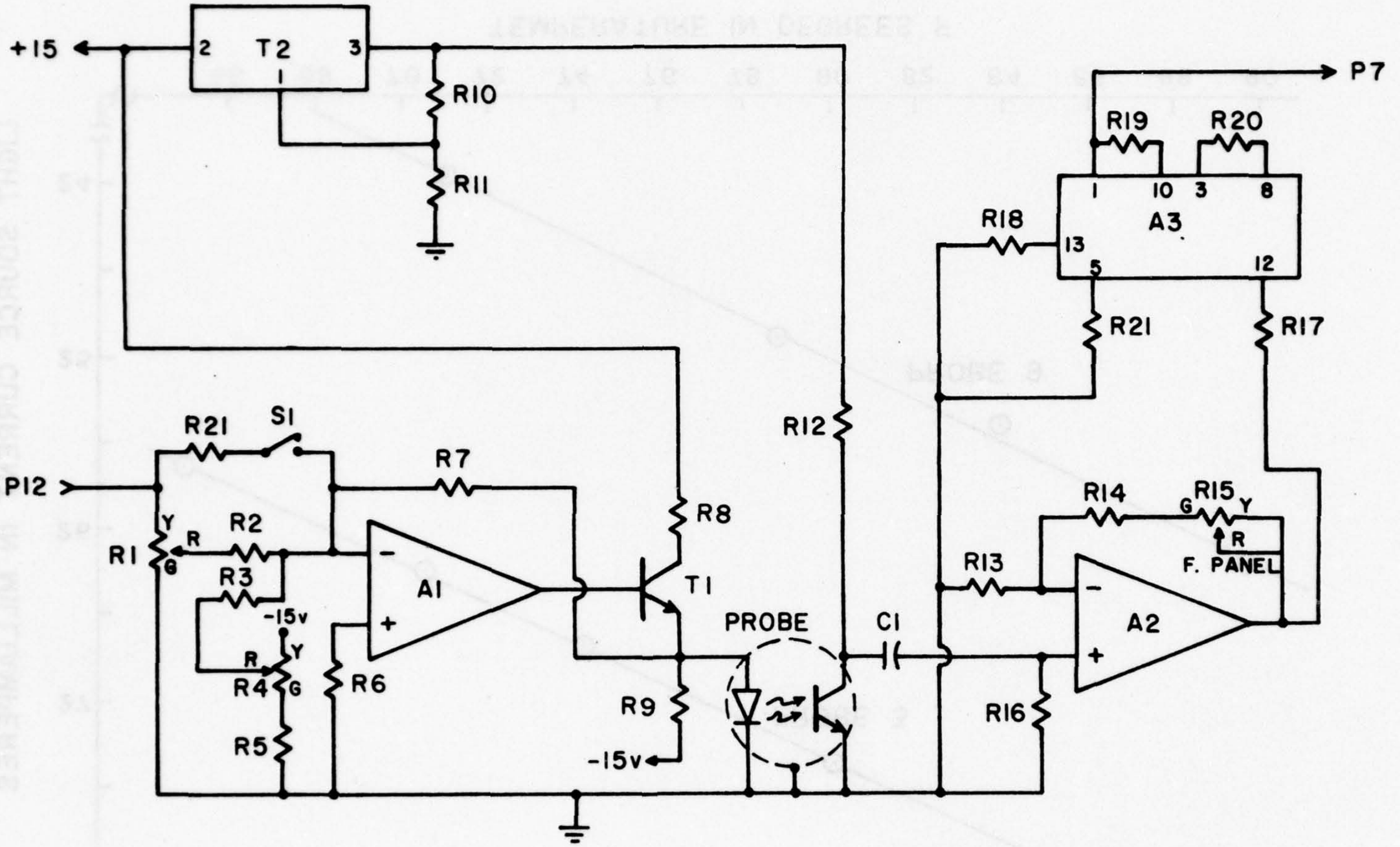


Figure 2. Source-Sensor and High-Pass filter card

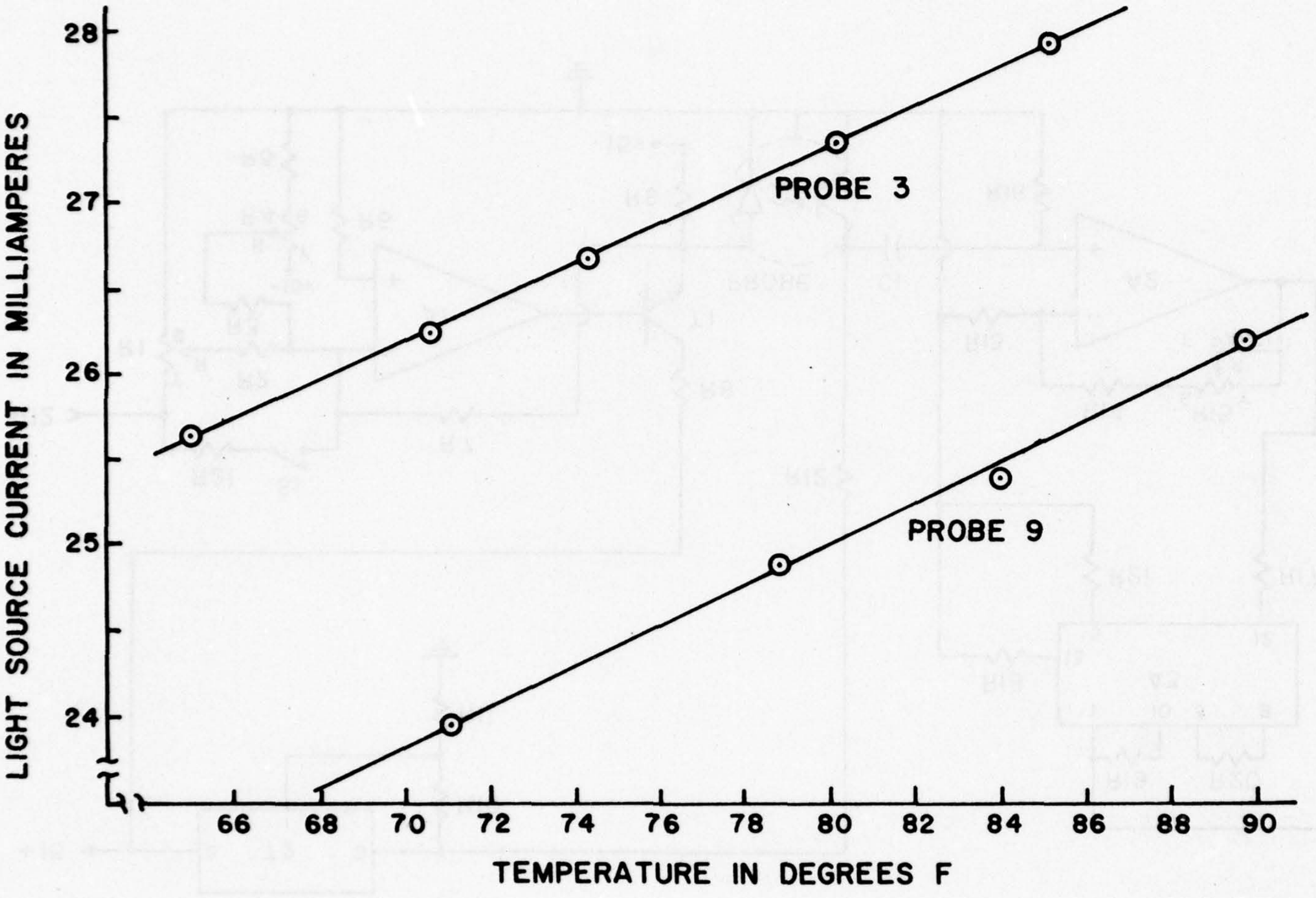


Figure 3. Temperature Characteristics of the Light Source

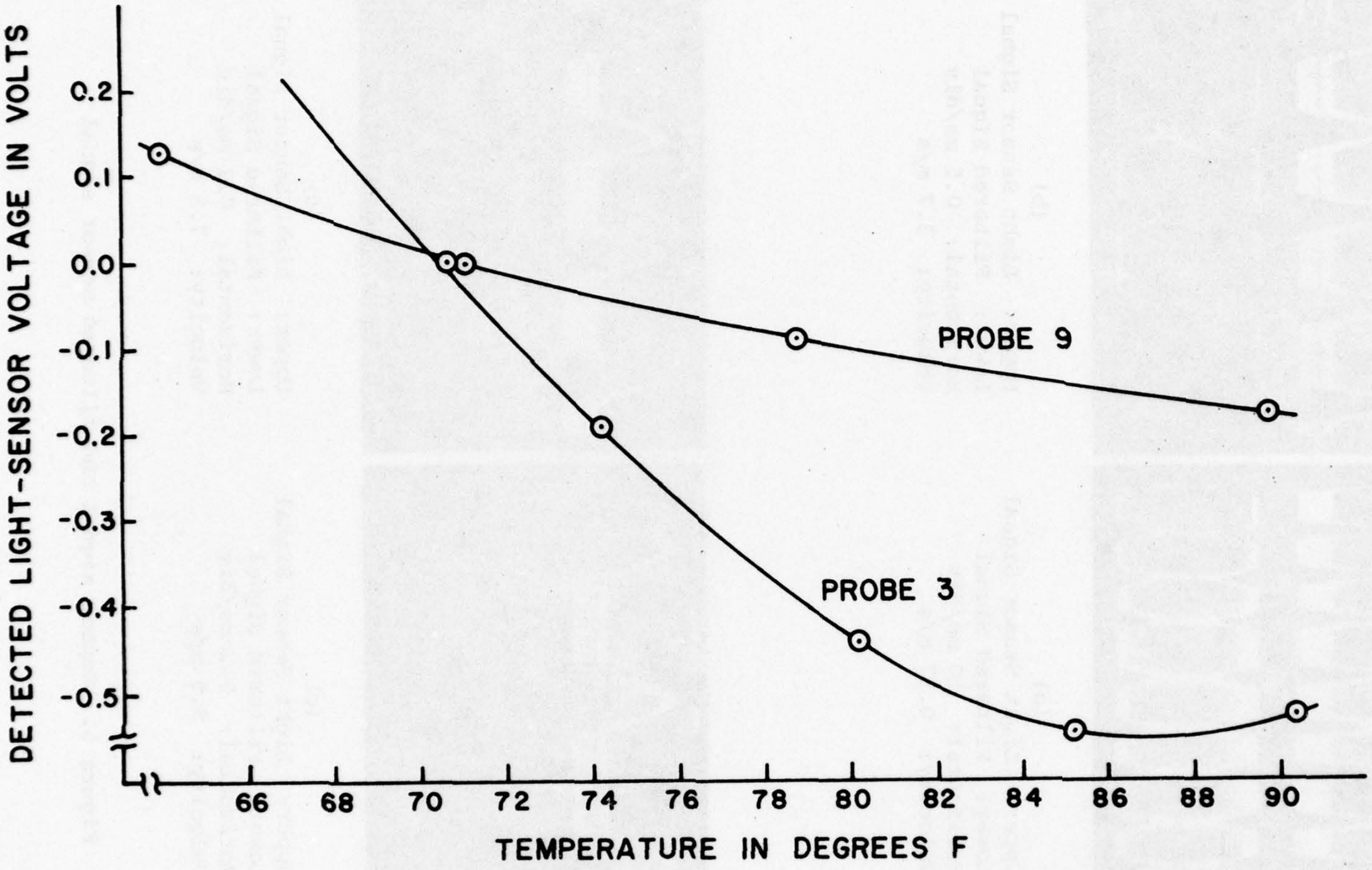
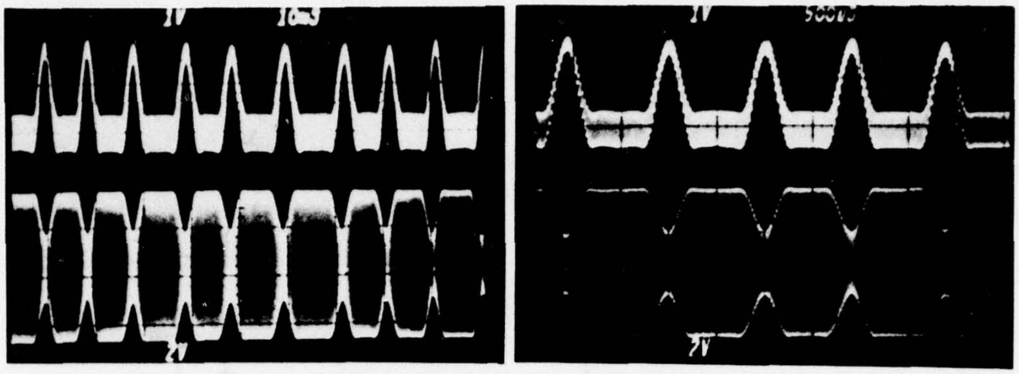
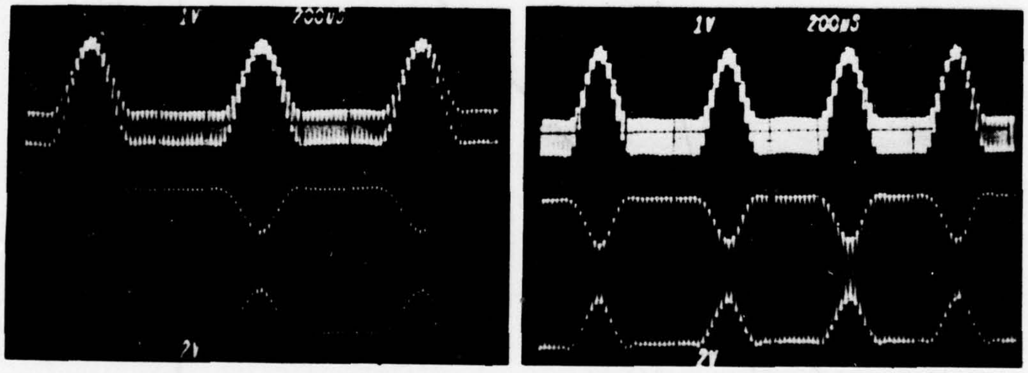


Figure 4. Temperature Characteristics of the Source-Sensor Combination



(a)
Upper: Light Sensor Signal
Lower: Filtered Signal
Horizontal: 10 ms/div
Velocity: 0.37 m/s

(b)
Upper: Light Sensor Signal
Lower: Filtered Signal
Horizontal: 0.5 ms/div
Velocity: 3.7 m/s



(c)
Upper: Light Sensor Signal
Lower: Filtered Signal
Horizontal: 0.2 ms/div
Velocity: 5.5 m/s

(d)
Upper: Light Sensor Signal
Lower: Filtered Signal
Horizontal: 0.2 ms/div
Velocity: 7.3 m/s

Figure 5. Sensor signal and filtered sensor signal

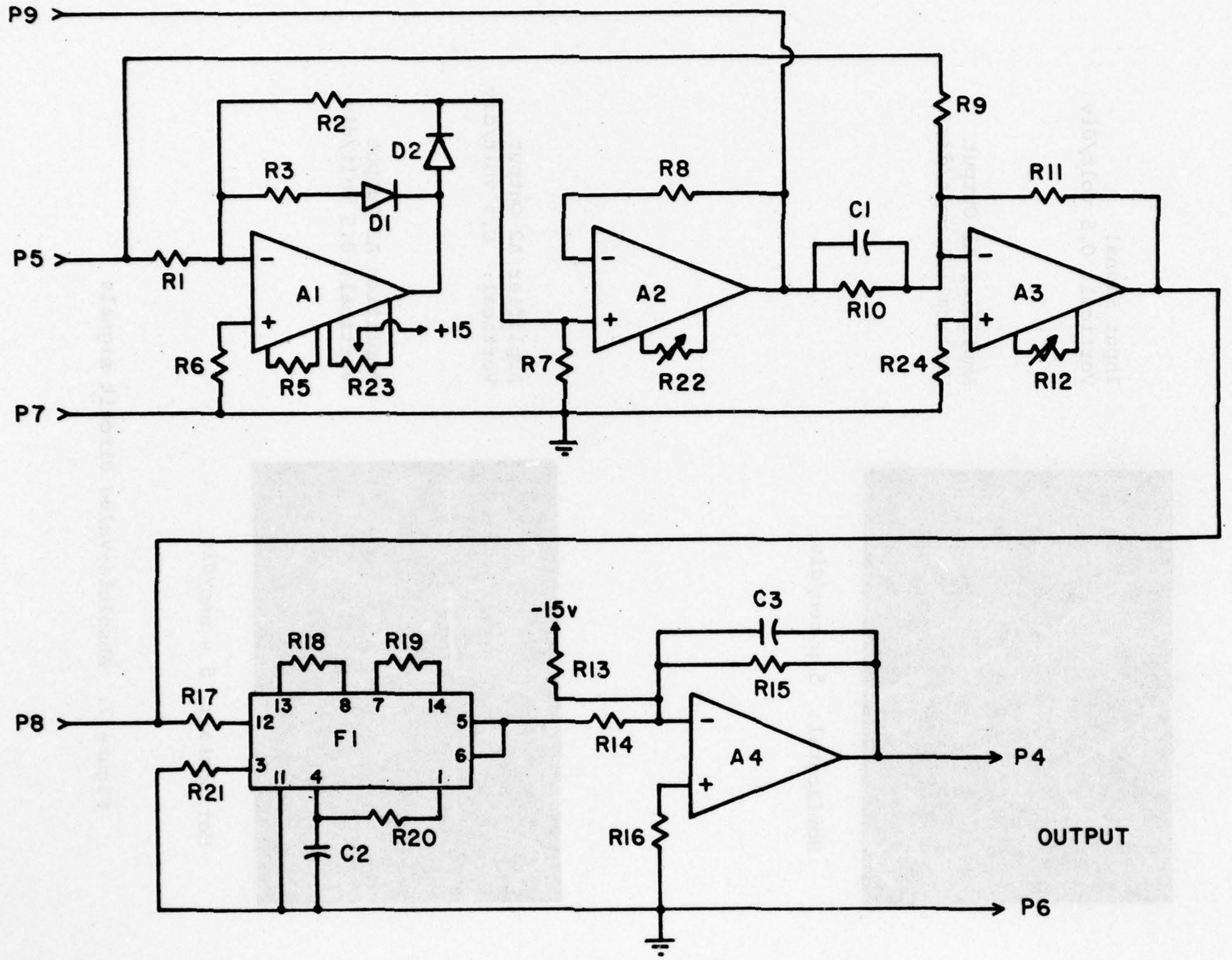
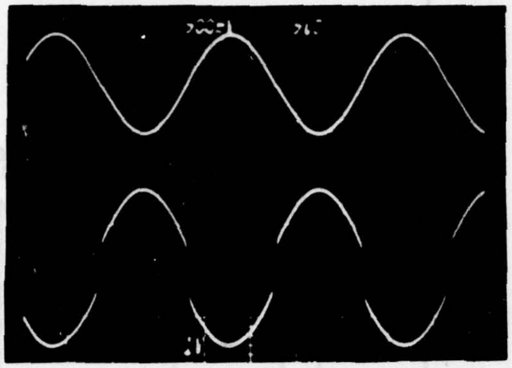


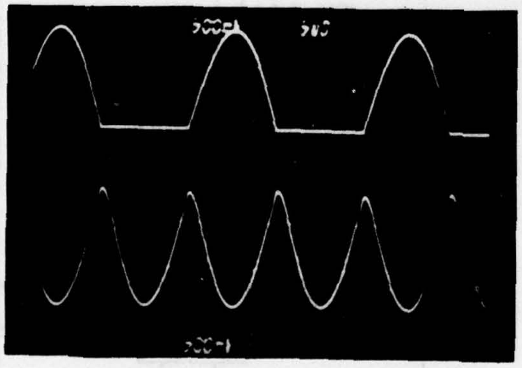
Figure 6. Detector and Low-Pass Filter Card



Input Signal
Vertical: 0.5 volt/div

Amplifier A1 Output
Vertical: 1 volt/div

Horizontal: 5 μ sec/div



Amplifier A2 Output
Vertical: 0.5 volt/div

Amplifier A3 Output
Vertical: 0.5 volt/div

Horizontal: 5 μ sec/div

Figure 7. Absolute-value circuit signals

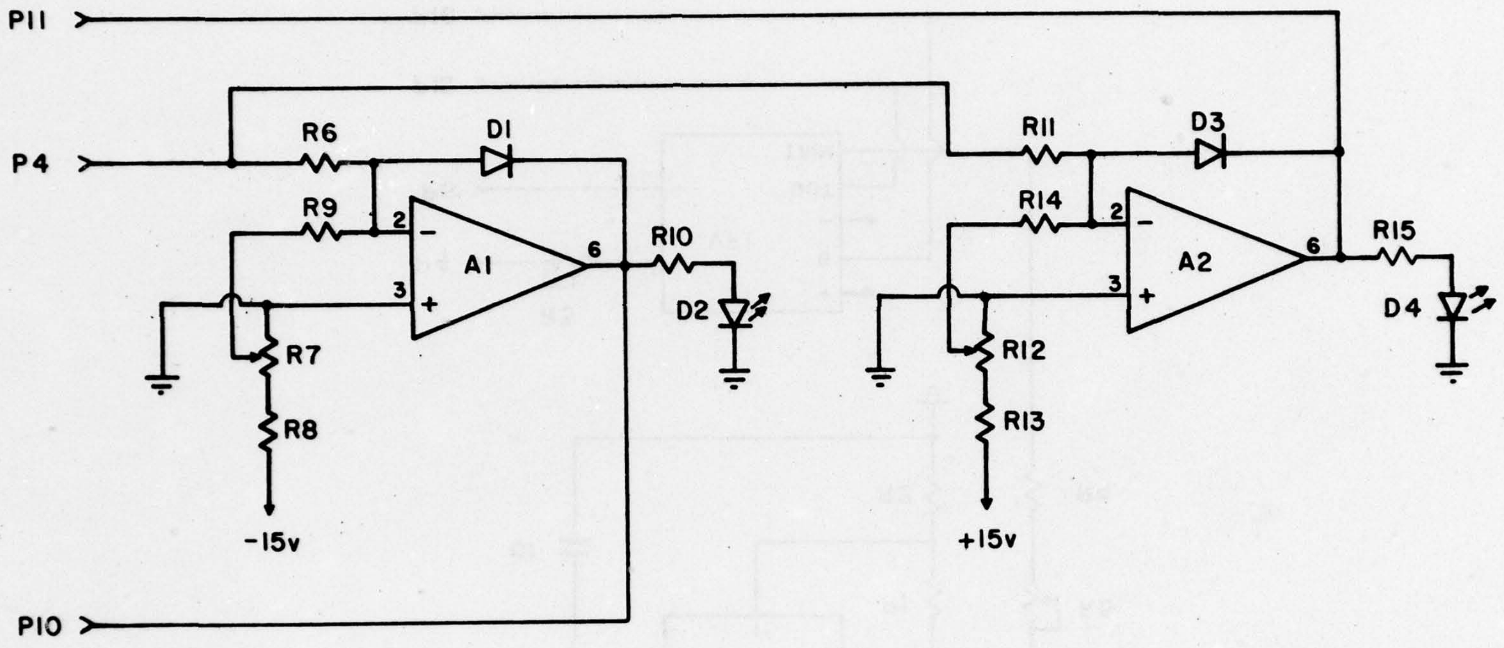


Figure 8. Zero Indicator Circuits

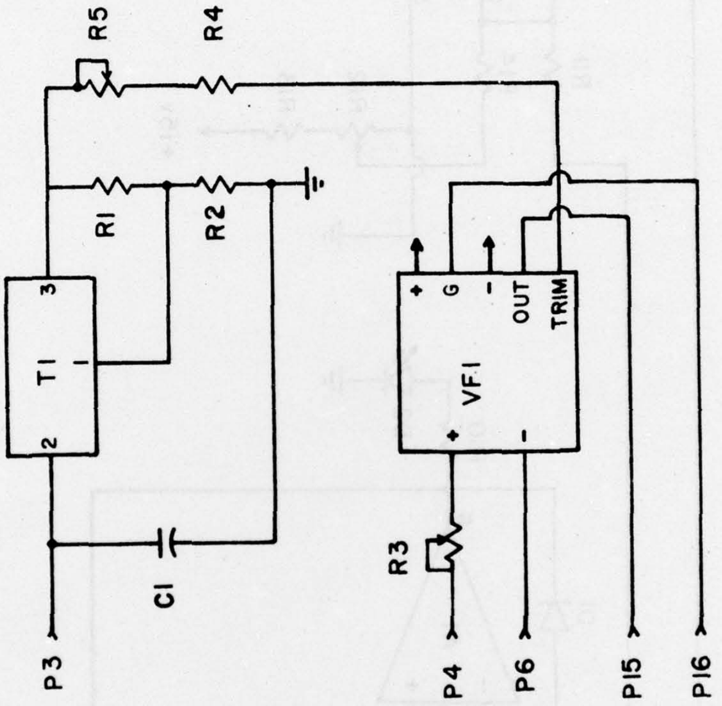
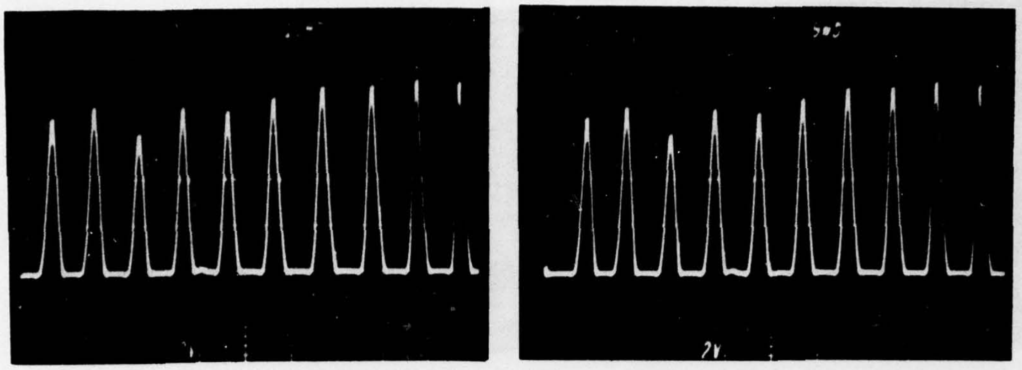
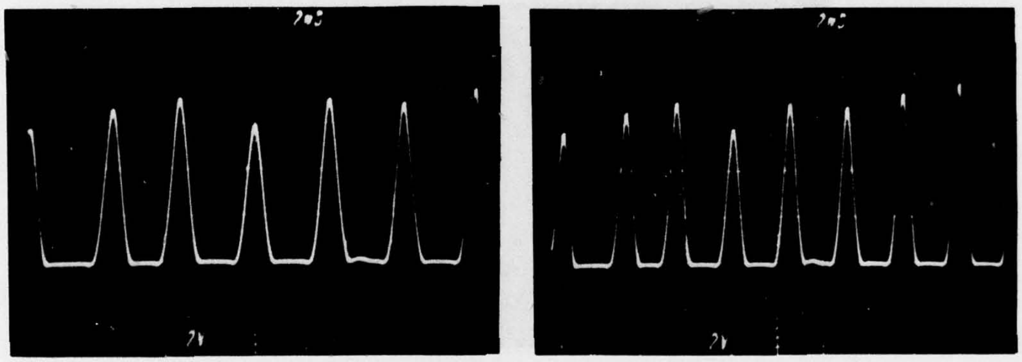


Figure 9. Voltage-to-Frequency Converter Circuit



(a)
Horizontal: 10 ms/div
Vertical: 2 volts/div
Velocity: 0.37 m/s

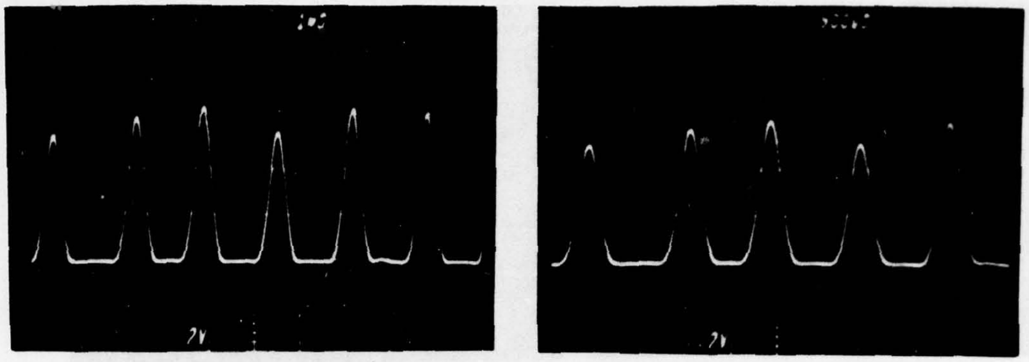
(b)
Horizontal: 5 ms/Div
Vertical: 2 volts/div
Velocity: 0.73 m/s



(c)
Horizontal: 2 ms/div
Vertical: 2 volts/div
Velocity: 1.1 m/s

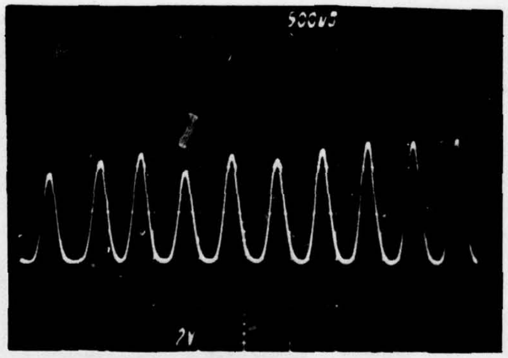
(d)
Horizontal: 2 ms/div
Vertical: 2 volts/div
Velocity: 1.5 m/s

Figure 10. Response for different generated particle velocities



(a)
Horizontal: 1 ms/div
Vertical: 2 volts/div
Velocity: 2.2 m/s

(b)
Horizontal: 0.5 ms/div
Vertical: 2 volts/div
Velocity: 3.7 m/s



(c)
Horizontal: 0.5 ms/div
Vertical: 2 volts/div
Velocity: 7.3 m/s

Figure 11. Response for different generated particle velocities

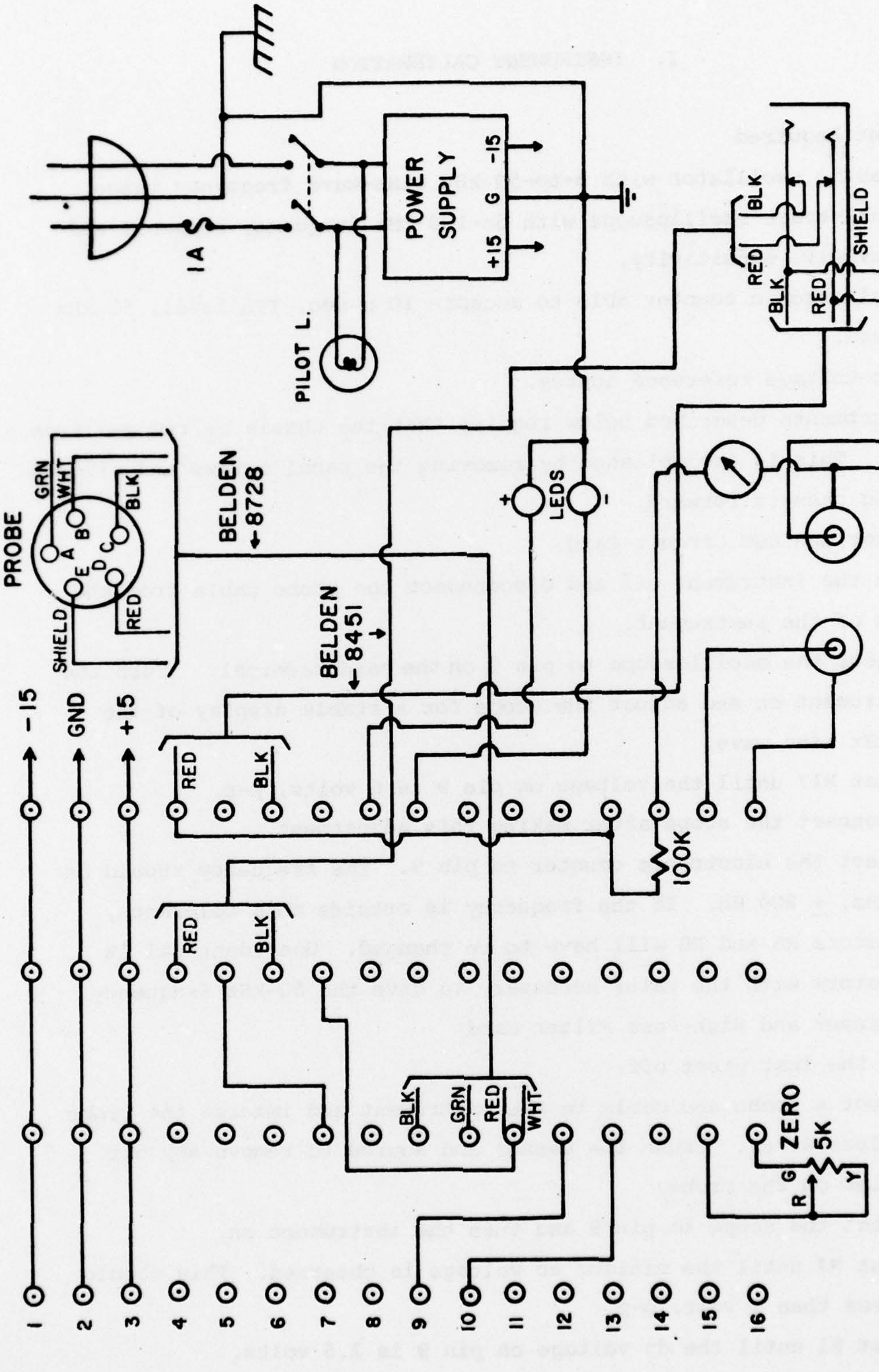


Figure 12. Chassis Wiring Diagram

APPENDIX A

I. INSTRUMENT CALIBRATION

A. Equipment Required

1. An audio oscillator with 5-to-50 kHz sine-wave frequency range.
2. A dual-trace oscilloscope with dc-100-kHz frequency response and 10 mv/div. sensitivity.
3. An electronic counter able to accept 10 μ sec, TTL level, 50-kHz pulses.
4. A dc-voltage reference source.

The adjustments described below require that the chasis be removed from the cabinet. This is accomplished by removing the panel screws and sliding the panel and chassis forward.

B. Oscillator and AGC Circuit Card.

1. Turn the instrument off and disconnnect the probe cable from the back of the instrument.
2. Connect the oscilloscope to pin 9 on the card terminal. Turn the instrument on and adjust the scope for a stable display of the 50-kHz sine wave.
3. Adjust R17 until the voltage on pin 9 is 6 volts, p-p. Disconnect the scope after making this adjustment.
4. Connect the electronic counter to pin 9. The frequency should be 50 kHz, ± 200 Hz. If the frequency is outside this tolerance, resistors R6 and R8 will have to be changed. Use identical 1% resistors with the value necessary to give the 50-kHz frequency.

C. Source-Sensor and High-Pass Filter Card

1. Turn the instrument off.
2. Connect a probe and cable to the instrument and immerse the probe in clear water. Brush the sensor and source to remove any air bubbles on the probe.
3. Connect the scope to pin 9 and turn the instrument on.
4. Adjust R4 until the minimum ac voltage is observed. This should be less than 1 volt, p-p.
5. Adjust R1 until the dc voltage on pin 9 is 2.5 volts.

6. Adjust R4 until the ac voltage on pin 9 is 1 volt, p-p. The above adjustments described for this card are also necessary when a new or different probe is connected to the instrument. The calibration of the remaining cards, however, is not necessary when the probe is changed.

D. Detector and Low-Pass Filter Card

1. Turn the instrument off, disconnect the probe, and remove the source-sensor and high-pass filter card from its socket.
2. Connect the audio oscillator to pin 5 and set its frequency to-5 kHz and amplitude to 20-mv, p-p.
3. Connect the scope to pin 8 and turn the instrument on.
4. Adjust R23 for symmetry of the rectified sine wave. Scope sensitivity should be 5 mv/div.
5. Connect the scope to pin 9 and adjust R22 so the base of the signal is at zero volts. Scope sensitivity should be 5 mv/div.
6. Connect the scope to pin 8 and adjust R12 so the points of slope reversal are at zero volts. The rectified signal is negative at this point in the circuit.
7. Turn the instrument off, disconnect the scope and generator, and install the source-sensor and high-pass filter card.

E. Composite Calibration

1. Turn the instrument off, and connect the probe cable and probe. Immerse the probe in clear water and brush the probe to remove any air bubbles.
2. Turn the instrument on and set the panel ZERO control to 100.
3. Adjust R4 on the source-sensor and high-pass filter card until the panel meter deflection is zero.

An instrument evaluation is possible without the probe to check for proper operation. This is accomplished by setting the switch located on the source-sensor high-pass filter card to the CAL position and connecting the special adapter to the cable instead of the probe. When this is done, use the ZERO control to reduce the meter deflection to zero and monitor the output with a scope set for a sensitivity of 10 mv/div, dc. The signal should have no drift and the noise should be less than 10 mv. Be sure to return the switch on the card to the normal position before connecting the probe.

F. Zero Indicator and Voltage-to-Frequency Card.

1. Connect a shielded twisted-pair cable to the INTEGRATOR INPUT jack and short all three wires together.
2. Connect the counter to the INTEGRATOR OUTPUT connector. The frequency indicated should be approximately 10 kHz.
3. Adjust R5 until the frequency is 10,000 Hz.
4. Connect the dc voltage reference to the INTEGRATOR INPUT jack using the shielded twisted-pair cable and adjust R3 until the frequency indicated corresponds to 1000 Hz/volt.
5. Repeat steps 3 and 4 until no additional adjustment is necessary.
6. Remove the dc reference voltage from the INTEGRATOR INPUT jack and connect the oscillator using the shielded twisted-pair cable. Set the oscillator voltage for a voltage of 60-80 mv peak at 100 Hz.
7. Connect one trace of the oscilloscope to the input signal and the second trace to pin 11 on the card. Trigger the scope on the input signal.
8. Adjust R7 so the voltage on pin 11 switches from zero to positive when the input voltage crosses +20 mv with a negative slope.
9. Move the scope probe on pin 11 to pin 10.
10. Adjust R12 so the voltage on pin 10 switches from zero to positive when the input voltage crosses -20 mv with a negative slope.
11. Remove all leads. Instrument calibration is completed. The chassis should be installed in the cabinet.

II. INSTRUMENT OPERATION

A. Connect the probe to the cable and the cable to the connector located on the back of the instrument.

B. Immerse the probe in clear water.

C. Turn the instrument on. The probe is not damaged if it is removed from the water while the instrument is on.

D. Adjust the ZERO control until only the upper LED is on.

E. The instrument is now ready either for calibration or for making sediment concentration measurements.

A counter can be used for obtaining indications of the mean voltage displayed by the meter. If a counter is to be used, connect it to the INTEGRATOR OUTPUT connector. The frequency indicated when the probe is in clear water and when the ZERO control is adjusted as indicated above is 10,000 Hz, ± 20 Hz. The calibration coefficient for the converter is 1000 Hz/volt.

A separate input to the converter is available through the transfer jack labled INTEGRATOR INPUT. If desired, a bi-polar input in the range of ± 10 volts can be connected to the converter for integration by a 3-pin plug.

To calibrate the system, the probe must be located in known concentrations of suspended sediment and the mean output voltage recorded for each concentration. The dependence of signal on particle size and position in the probe field makes it absolutely necessary to use the same sediment for calibration as used in the study. Once the calibration curve is obtained, the system is ready for measurement. The instrument should be calibrated for each probe before a system calibration is made.

Oscillator and AGC Card

List of Components

Item	Description	Value
R1	Resistor	10K Ω
R2	"	2K
R3	"	20K
R4	"	1.05K
R5	"	2.49K
R6	"	selected
R7	"	2.49K
R8	"	selected
R9	"	24.9K
R10	"	2K
R11	"	2K
R12	"	20K
R13	"	20K
R14	"	20K
R15	"	10K
R16	"	10K
R17	Potentiometer	1K
C1	Capacitor	0.033 µf
C2	"	1000 pf
C3	"	1000 pf
C4	"	0.01 µf
C5	"	0.1 µf
T1	Transistor	2N5486
T2	"	2N5486
D1	Diode	1N914
D2	"	1N914
D3	"	1N914
A1	Operational amplifier	1024 T-P
A2	" "	1024 T-P
A3	" "	3505 B-B
A4	" "	3140 RCA

Source-Driver High-Pass Filter Card

List of Components

Item	Description	Value
R1	Potentiometer	10K
R2	Resistor	49.9K
R3	"	20K
R4	Potentiometer	10K
R5	Resistor	10K
R6	"	2K
R7	"	2K
R8	"	221
R9	"	2K
R10	"	249
R11	"	750
R12	"	1K
R13	"	4.99K
R14	"	4.99K
R15	Potentiometer	5K
R16	Resistor	10K
R17	"	49.9K
R18	"	18.2K
R19	"	6.34K
R20	"	6.34K
R21	"	3.16K
R22	"	12.7K
C_1	Capacitor	680 pf
T1	Transistor	2N3767
T2	Voltage regulator	LM317
A1	Operational amplifier	1024 T-P
A2	" "	1024 T-P
A3	Active filter	UAF21 B-B

Detector and Low-Pass Filter Card

List of Components

Item	Description	Value
R1	Resistor	1K Ω
R2	"	2K
R3	"	2K
R4	"	--
R5	"	selected
R6	"	499
R7	"	1K
R8	"	1K
R9	"	1K
R10	"	1K
R11	"	2.5K
R12	Potentiometer	10K
R13	Resistor	15K
R14	"	4.99K
R15	"	10K
R16	"	4.99K
R17	"	49.9K
R18	"	44.2K
R19	"	44.2K
R20	"	48.7K
R21	"	46.4K
R22	Potentiometer	10K
R23	"	100K
R24	"	499
C1	Capacitor	100 pf
C2	"	1000 pf
C3	"	0.002 µf
D1	Diode	1N914
D2	"	1N914
A1	Operational amplifier	1025 T-P
A2	" "	1024 T-P
A3	" "	1024 T-P
A4	" "	3140 RCA
F1	Active Filter	UAF41 B-B

Zero Indicator and Voltage-to Frequency Card

List of Components

Item	Description	Value
R1	Resistor	243 Ω
R2	"	1690
R3	Potentiometer	500
R4	Resistor	selected
R5	Potentiometer	5K
R6	Resistor	4.99K
R7	Potentiometer	50
R8	Resistor	10K
R9	"	4.99K
R10	"	499
R11	"	4.99K
R12	Potentiometer	50
R13	Resistor	10K
R14	"	4.99K
R15	"	499
D1	Diode	1N914
D2	LED	5082-4887, H-P
D3	Diode	1N914
D4	LED	5082-4887, H-P
C1	Capacitor	0.01 μf
A1	Operational amplifier	3140 RCA
A2	" "	3140 RCA
T1	Voltage Regulator	LM317
VF1	Voltage-to-Frequency	VFC15 B-B