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Iowa University
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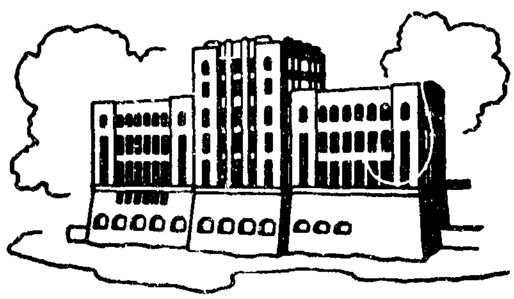

IIHR Report No. 120

Iowa Institute of Hydraulic Research
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ABSTRACT

A new electro-optical system has been developed for *in situ* measurement of suspended sediment concentration in alluvial channel flows, estuaries, and shoaling waves. The transducer for the system consists of a gallium arsenide diode as a light source and a silicon planer diode as a light sensor. The source light detected by the sensor is modulated by the suspended-sediment in the gap between the source and sensor. The amplifier for the sensor output has been combined on one chassis with signal analyzing circuitry, which includes an analog-to-frequency converter and multiplier circuits. The resulting system is capable of measuring suspended sediment concentrations down to 100 ppm, and can compute the mean concentration, the mean square of the concentration fluctuations, and the correlation between sediment concentration and another signal supplied to the system. Exploratory experiments were undertaken in a recirculating laboratory flume and a laboratory wave basin to evaluate the practical usefulness of the system.

KEY WORDS

suspended sediment, sediment transport, multi-phase flow, electronic instrumentation, beach erosion, optical transducer, mean-product computer

An Electro-Optical System for Measurement of
Mean and Statistical Properties
Of Sediment Suspensions

I. INTRODUCTION

There has been for many years a conspicuous need, in laboratory investigations as well as in field data-collection operations, for an improved method of measuring concentrations of suspended sediment in turbulent flows. Practically all methods used heretofore involve withdrawing from the flow by one means or another a sample of the fluid-sediment mixture, separating the two phases, and measuring the weight or volume of sediment contained in a known quantity of the mixture. Such techniques have several obvious shortcomings. First, they are slow and inefficient, and hence expensive. Second, the devices used to withdraw the samples have some effect, generally of unknown significance, on the local flow field and hence also on the measured sediment concentration. Moreover, the relatively large size of most samplers has generally precluded measurement of concentrations very close to the bed, often the region of greatest interest. Finally, devices which withdraw samples can determine only the time-average concentration at a point and cannot, for obvious reasons, yield information on the statistical character of turbulent fluctuations of concentration or on the temporal distribution of concentration in unsteady flows (e.g., in water waves).

These shortcomings of available instruments prompted development at the Iowa Institute of Hydraulic Research of an electro-optical transducer and appurtenant circuitry capable of measuring *in situ* point sediment concentrations. The design requirements included: a linear concentration-voltage relation; sufficiently high-frequency response that the system could be used to measure concentration fluctuations, both random and periodic; a transducer small enough and adequately streamlined to permit measurement of concentrations very close to erodible beds without causing extensive local scour; and incorporation into the instrument chassis of analog circuits for computation of time integrals, mean-squares, and products of input signals. The instrument has been designed for laboratory application, but can be used in the field under ideal conditions. The foregoing objectives have been realized in the Model Old Gold Iowa Sediment Concentration Measuring System (ISCMS), which consists of the Iowa Sediment Concentration Probe (ISCP) and the Iowa Sediment Concentration Analyzer (ISCA).

Section II presents a complete description of the design and construction of the ISCMS, and in Section III some laboratory data obtained with it are presented and briefly discussed. Section IV consists of concluding remarks.

II. DESIGN AND CONSTRUCTION OF THE ISCMS

The Model Old Gold Iowa Sediment Concentration Measuring System is a complete system for measuring mean and statistical properties of particle concentration in sediment suspensions. It consists of two subsystems: the sediment transducer and associated electronics for generating an electrical signal proportional to the instantaneous sediment concentrations; and the signal analyzing circuits which generate signals representing certain statistical properties of point concentrations in the suspension. The circuitry is incorporated into the instrument shown in figure 1a. Description of these subsystems is best accomplished by considering each in terms of the functions performed by the corresponding components in the instrument. This approach will aid in understanding the instrument, and also illustrate its flexibility.

Transducer and Associated Electronics

Transducer. The transducer consists of a pin photodiode (type 4204) and a gallium arsenide electroluminescent diode (type 4107), both manufacfactured by Hewlett-Packard, Inc. The emission spectrum of the light source is concentrated at 0.9 microns whereas the spectral response of the light sensor is much wider, although it peaks at approximately 0.9 microns. A typical transducer configuration is shown in figure 1b. The diodes are soldered to spring-tempered support wires which are passed through 13 gauge stainless steel support rods. An epoxy paint is applied for insulating the exposed conducting surfaces.

The radiant power output of the source diode varies linearly with forward current, and hence the sinusoidal diode current used provides a sinusoidal light output. Sinusoidal excitation was selected because it reduces cross-talk between the source and sensor via the common cable used to inter-connect the transducer and chassis. This is especially important because the sensor operates with a reverse bias and hence has a very high output impedance. The radiant power is temperature sensitive, decreasing with increasing temperature when driven by a constant-current source, and increasing with increasing temperature when driven by a constant voltage source.

The light sensor photocurrent response to radiant power is also linear, and hence nonlinear amplification of the detected signal is not necessary. Temperature influence on the light sensor is evident by changes in the dark current (photocurrent when the source light is cut off) that occur when the temperature of the surrounding water is varied. However, since an alternating light source is used, changes in dark current due to temperature changes are not detected, and temperature has little influence on the light sensitivity of the sensor when detecting light from an alternating light source.

Light-source excitation circuitry (card 1). Figure 2 is a schematic of the light-source excitation circuitry; it represents a straightforward technique for supplying the diode with a current linearly related to the excitation voltage. To offset decreasing radiant power output with increasing temperature, the diode is driven by a constant voltage source having an output impedance, of 2 to 10 ohms, which is selected for each individual probe to provide optimum compensation. The diode is biased by observing the collector voltage of the driving transistor, T_1. Resistors R_3 and R_5 are adjusted so that the driving current is sinusoidal and does not exceed the 100 milliampere maximum current rating of the light source.

To eliminate another source of drift, a crystal oscillator with one-percent amplitude stability is used as the voltage generator. The variable gain network provides the proper impedance match for the oscillator while also supplying the power gain for driving the diode.

Light sensor circuitry (cards 2 and 3). Elimination of spurious signals (primarily 60 Hz signals) is the main function of the circuitry on card 2, although it also provides some voltage gain. The optimum bias voltage of the sensor is -20 to -5 volts, and thus it has a very large output impedance which causes signal attentuation by the cable connecting the transducer to the instrument. As can be seen in figure 3, the sensor bias is supplied through a balanced network which is connected to a differential-to-single-ended amplifier. The amplifier has a dual-amplifier-balanced differential input stage with a common-mode signal gain of unity independent of the differential gain determined by the two feedback resistors (R_6 and R_8) and the cross-coupling resistor (R_7). Optimization of the common-mode-rejection ratio is obtained by making the gain of the first stage as high as possible. The dynamic characteristics degrade, of course, with increasing gain, making it necessary to adjust the gain so that the frequency response covers the required bandwidth (10 kHz for this application). The gain is given approximately by

$$\text{Gain} \cong 1 + \frac{R_6}{R_7} + \frac{R_8}{R_7}$$

and is set at 41.

Amplifier A3 is the differential-to-single-ended interface between the balanced dual-amplifier input stage and the remaining amplification, detection, and filtering circuits. The circuitry mounted on card 3 is depicted in figure 4. The gain provided by amplifier A1 and associated circuitry is adjusted as a function of the transducer sensitivity and is controlled by the zero control. The non-inverting configuration was selected because of its higher input impedance, which is independent of the gain-adjusting resistor (R_3). Since zero sediment concentration produces the maximum detected light signal, the output signal, which is zero at zero concentration and 10 volts when no source light is detected, is a function of gain. Hence, even though the source diode is temperature sensitive, concentration sensitivity can be corrected simply by adjusting the gain until zero output voltage is obtained when the transducer is in sediment-free water.

Amplifiers A2 and A3 constitute the detector and filter to provide a signal proportional to the instantaneous value of the sediment concentration. Amplifier A2 is a half-wave rectifier with a gain of minus two; its output is added to the signal from amplifier A1 to produce full-wave rectification. However, instead of using an amplifier for the addition operation and then a second amplifier for the active filtering required, addition and filtering are both performed by amplifier A3 and associated circuitry.

The filter for suppressing the carrier signal is an active third-order Butterworth filter with two input networks, one for the output of amplifier A1 and the other for the output of amplifier A2. The network has a gain of 10 over the frequency spectrum of dc to 100 Hz. Attenuation is -3 db at 1000 Hz and -60 db at 10,000 Hz, the carrier frequency.

Signal Analyzing Circuits

Analog-to-frequency converter (card 4). This card contains a bi-polar analog-to-frequency-converter which eliminates the need to read a fluctuating meter. Its input is connected in parallel with the monitor, and one or the other of its outputs (depending on the polarity of the input signal) is connected to an electronic counter for displaying the frequency. A complete analysis and circuit diagram for this component are given by Glover (1), and a block diagram and functional description are presented in figure 5.

The conversion is based on the principle of integration using an operational amplifier. Rather than permitting the total integral to accumulate on the feedback capacitor during the period of integration, the integral is divided into n equal parts which are removed from the feedback capacitor as they are accumulated. The accumulation rate of the equal parts is, of course, proportional to the input signal. In terms of capacitor charge, which is proportional to the integral of voltage, equal quantities of charge are removed at a rate necessary to keep the charge on the capacitor below a fixed level. The removal rate is constant or varies according as the input voltage is constant or variable. Because the op-amp integration configuration is capable of real-time addition, fixed quantities of charge can be removed while integration of the input voltage continues undisturbed. Hence, linearity

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(1) Glover, John R., "Old Gold Model, Type 4-2H Hot-Wire Anemometer and Type 2 Mean-Product Computer," *IIHR Report No. 105*, Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City, July 1967.

over the operating range (10 millivolts to 10 volts with a coefficient of 1000 Hz per volt) is excellent.

A symmetrical network is required to accommodate the integration of bi-polar voltages (i.e., for determining a mean product). Therefore, in order to determine the mean value of a product, the two frequency outputs must be subtracted.

Range card (card 5). Amplification prior to multiplication of the signal representing the instantaneous deviation is provided by card 5, schematized in figure 6. To facilitate the handling of the intensities of the various mean products, a selectable signal amplification feature is included. A unity-gain amplifier with high input impedance provides the isolation needed between the blocking capacitor and the gain selection switch. The time constant of the input stage is 12 seconds, and the high-frequency response is flat to beyond 10 kHz.

Multiplier (card 6). Multiplication of any two signals selected by the function switch and amplified by the range card is accomplished in the circuitry of card 6, shown in figure 7, by a Burr-Brown Model 4030/25 multiplier. The unit is connected to give -0.1 of the product which is then inverted to obtain the correct sign. Frequency response for a 1 percent absolute error is dc to 5 kHz, and the -3 db small-signal response is 1 MHz. The multiplier is of the quarter-square type containing two precision diode-squaring circuits and three wide-band operational amplifiers.

Switches

The FUNCTION switch selects the product to be computed by the multiplier. In position 11, the instantaneous square of the deviations of signal 1 is computed. Position 12 causes the product of signals 1 and 2 to be computed. and in position 22, the square of signal 2 is computed. To display these products the MONITOR switch should be in position PO (product output); full-scale meter deflection then corresponds to one volt. The integrator input is also connected to the output of the multiplier when these computations are being made. Position M on the FUNCTION switch connects the integrator in parallel with the MONITOR, and thereby permits the integration of signal 1 (the sediment concentration signal). This feature is particularly useful when the instantaneous concentration has large deviations from the mean. When monitoring signal 1, full-scale meter deflection corresponds to 10 volts.

Computations

The expression giving the relation between the output voltage of the multiplier and the input signals is

$$Fe_0 = e_i e_j$$

where F is the position of the RANGE Switch, e_0 is the analog output voltage, and i and j indicate the position of the FUNCTION switch. The relation between concentration, C, and voltage e_i is

$$C = A\ e_i$$

where A is a constant determined by calibration, and e_i is the voltage at AUXILIARY OUTPUT 1 and corresponds to the sediment concentration. The mean square of the concentration fluctuations is given by

$$\overline{(c')^2} = A^2 Fe_0$$

with i = j = 1. Similar relations exist for the other products.

Auxiliary Inputs

The AUXILIARY INPUT jacks are transfer jacks. When a plug is not inserted, the signal from the transducer circuitry, e_1, is connected to the Mean-Product Computer. Inserting a plug disconnects e_1 and connects the signal carried by the plug to the computer.

Operating Procedure

1. Connect the power cord to any standard 117 volt ac outlet. If a three-pin outlet is not available and an adapter is used, be sure the ground wire of the adapter is securely grounded. If the instrument is being

used jointly with associated equipment and ground loops are a problem, an ungrounded adapter is recommended provided at least one of the associated instruments is properly grounded.

2. Connect the probe cable to the transducer and to the back of the instrument. The transducer and the instrument may be connected or disconnected without harm to either.

3. Rotate the MONITOR switch to position 1, the RANGE switch to position 10, and the FUNCTION switch to position 11.

4. Turn the instrument on and check the pilot light. Failure of the pilot light to illuminate can be due either to a defective bulb or a blown fuse. After the meter returns to an on-scale reading, position the needle to zero with the zero control. Failure to be able to do so indicates a defective transducer. Calibrate the transducer as described in the following section.

5. For mean-square measurements of concentration fluctuations turn the MONITOR switch to position 11. Rotate the RANGE switch counter-clockwise until a deflection approaching full scale is obtained.

To utilize the analog-to-frequency converter in the instrument, a counter must be connected to the appropriate BNC output jack located on the back of the instrument. The converter monitors the output of the Mean Product Computer when the FUNCTION switch is in position 11, 12, or 22. When the FUNCTION switch is in position M the converter monitors the voltage displayed by the panel meter.

Voltages at the AUXILIARY OUTPUTS M and 1 are for signal processing by auxiliary equipment, such as an oscilloscope. The AUXILIARY INPUT jacks permit processing by the Mean Product Computer of signals other than those generated by the instrument.

Calibration

Calibration of the system to obtain the relation between output voltage and concentration of suspended sediment between the two arms of the transducer is required for each different transducer, suspending liquid, and suspended material. Calibrations of the instrument have been realized in a three-inch diameter recirculating fluidized bed apparatus containing small quantities of the materials for which calibrations were sought. In the case of non-cohesive materials the sediment concentration at the elevation of the probe was varied by changing the water discharge through the fluidized bed, and was measured by withdrawing small samples of the suspension through the side of the vertical fluidized bed column and weighing the dry weight of the material contained in the measured volume of the sample. In the case of clay the concentration was varied by changing the amount of material present in the flow circuit.

Figure 8 shows the results of a calibration obtained for quartz sand using the sieve fractions retained between successive sieves in a square-root-of-two series. It is seen that the output is linear with concentration over the range evaluated: about 1,000 ppm to 30,000 ppm (by weight). However, a different calibration curve is obtained for each different sand size. The output was also found to be dependent, as might be expected, on the opacity of the suspending fluid. It was found that if the incremental voltage,

$$\Delta V = V(C) - V(0)$$

is normalized by V_0, the output voltage when the sensor is shielded from the light source (by simply inserting a card between the sources and sensor), and plotted versus C/D, where C is the concentration and D the particle diameter, all points fall on a straight line, as shown in figure 9. Note that one can set $V(0) = 0$. using the zero control as described in the previous section. That $\Delta V/V_0$ is the appropriate output-voltage variable can be deduced straightaway from dimensional considerations. Consider now the role of particle size. For a unit volume of sediment, the number of particles present varies as D^{-3} and the surface area per particle is proportional to D^2. Hence the particle surface area per unit volume of sediment is proportional to D^{-1}. Therefore, the linearity of $\Delta V/V_0$ as a function of D^{-1}, revealed in figure 9, indicates that the light attenuation is proportional to the sediment surface area per unit volume of suspended material and hence results almost exclusively from light scattering at the particle surfaces.

Light absorbtion by the particles would be expected to be negligible since quartz is virtually transparent to 0.9-micron wavelength light (2).

Figure 10 shows the calibration curve obtained for 0.1 mm glass beads, while figure 11 portrays the results of a calibration for bentonite clay with particles smaller than 0.02 mm. Both curves are seen to be linear, and $\Delta V/V_0$ is found to be sufficiently sensitive to C for practical application of the instrument.

III. SOME REPRESENTATIVE RESULTS OBTAINED WITH THE ISCMS

Several experiments were conducted to evaluate the practical usefulness of the ISCMS. In the first group of tests the vertical distribution of suspended sediment concentration was measured in steady, uniform flows over flat sand beds in the 3-foot wide, 90-foot long recirculating flume located in the Institute Annex. The bed sand particles had a geometric mean diameter of D_g = 0.21 mm and a geometric standard deviation of σ_g = 1.32. The calibration shown in figure 9 was used with $D = D_g$. Velocity profiles were measured with a 0.125-inch Prandtl tube. Suspended sediment concentrations were measured at various elevations with the ISCMS and by withdrawing samples through a 0.118-inch high, 0.434-inch wide rectangular sampling tube oriented parallel to the flow. In keeping with accepted practice, the samples taken at each elevation were withdrawn at a velocity equal to the measured flow velocity at that elevation. The sediment concentration in each sample was measured by filtering and weighing the sand. An averaging period of 100 seconds was used in measuring the mean concentration and mean-square of the concentration fluctuations with the ISCMS. The slope of the energy gradient, mean depth, discharge, etc., were measured using techniques similar to those employed by Laursen (3). Typical results are summarized in figures 12, 13, and 14. The quantities z and z_1 are, respectively,

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(2) Weast, Robert C. (editor-in-chief), *Handbook of Chemistry and Physics*, 50th Edition, Chemical Rubber Co., Cleveland, Ohio, 1969-1970.

(3) Laursen, E. M., "The Total Sediment Load of Streams, *Proc. ASCE, J. Hyd. Div.*, Vol. 94, No. HY1, February 1968.

the calculated and measured values of the exponent in the suspended load equation, $z = \frac{w}{\kappa U_*}$, where w is the mean fall velocity of the particles, κ is Kármán's constant, and U_* is the shear velocity. In determining z, use was made of w corresponding to D_g, the value of U_* obtained from the measured depth and slope, and κ obtained from the measured velocity profiles. The quantity z_1 was obtained from the slopes of the data curves in figures 12 and 13. The measured concentration obtained from the two different methods are seen to be in excellent agreement. It should be noted that concentrations as small as 100 ppm were measured without difficulty. It is also noteworthy that measurement of each concentration profile required less than 15 minutes with the ISCMS, but more than three hours with the sampler tube.

Figure 13 summarizes results of measurements of the RMS of the concentration fluctuations for a flat-bed flow, and also shows $\sqrt{\overline{c'^2}}$ normalized by the mean concentration at each elevation. The quantity $\sqrt{\overline{c'^2}}/C$ is seen to be nearly constant and equal to about 0.05 over the lower half of the flow, but to become somewhat larger near the surface. The quantity $\sqrt{\overline{c'^2}}$ is greatest near the bed and decreases toward the free surface. The form of its variation is similar to that of velocity fluctuations in turbulent flows in conduits (4).

In figure 14 are summarized the results of another experiment performed in the course of evaluating the ISCMS. Waves with a period of 1.5 seconds were generated on water with an undisturbed depth of 0.83 ft. in the Institute's 28-foot long wave tank. The sand used was identical to that employed in the flume experiments described above. The sand beach was exposed to the waves for several hours before measurements were initiated, to allow an equilibrium beach profile to develop. The water surface elevation was measured with a capacitance type wave gauge connected to a recording oscillograph. Figure 15 depicts the measured beach profile, wave envelope, undisturbed water surface, and mean point sand concentrations averaged over 100 second periods. The mean concentrations seem to be greater in the breaker region, and to decrease with increasing distance from the bed. These data

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(4) Hinze, J. O., *Turbulence*, McGraw-Hill, New York, 1959.

were obtained with the ISCMS in only a few hours and with minimal difficulty, whereas, using the conventional concentration measuring techniques employed heretofore, they would have been impractical if not impossible to acquire.

IV. CONCLUDING REMARKS

One of the major stumbling blocks to further progress in the field of sediment transport mechanics has been an inadequate understanding and formulation of the entrainment and suspension phenomena. These processes are inherently random in character, and hence detailed data on them have been difficult, if not impossible, to obtain. The ISCMS would appear to open a new avenue to achieving more complete measurements of the mean, periodic, and random components of suspended sediment concentrations. The ease with which concentration data can now be obtained in unsteady as well as in steady flows and the possibilities which the ISCMS opens for measuring turbulent fluctuations of sediment concentration should lead to collection of more complete data, better data interpretation, and improved understanding of the mechanics of sediment transport in rivers, through estuaries, and on beaches.

The field of electronic instrumentation is ever changing and rapidly evolving. Hence, modifications and improvements will no doubt be incorporated into the ISCMS as new electronic components and techniques become available. But even in its present form it is a very usable and useful research tool.

V. ACKNOWLEDGMENTS

Grateful acknowledgment is extended to Mr. Ernest E. Schwab of the Institute Electronics Staff for instrument construction. Financial support for design and construction of this unit was provided by the Corps of Engineers, Coastal Engineering Research Center, under contract DACW72-68-C-0009-X-01.

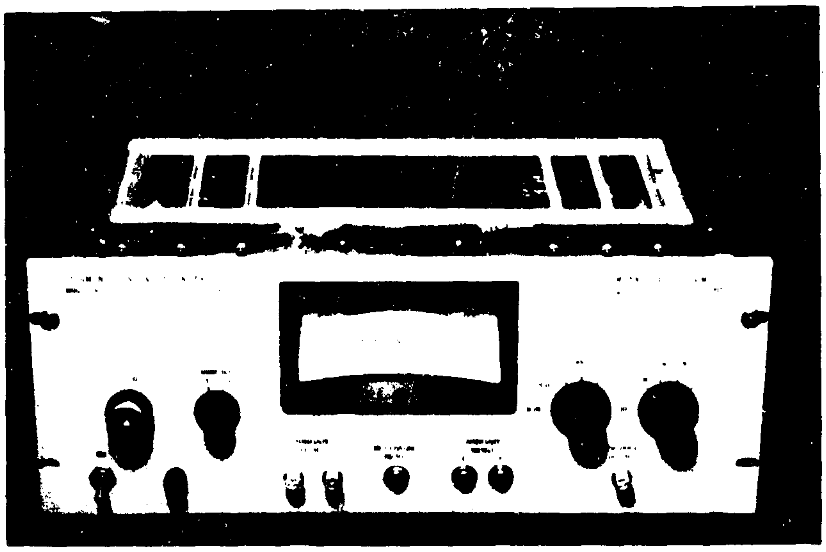

Figure 1a. Instrument chassis incorporating the signal amplifying and signal analyzing circuits.

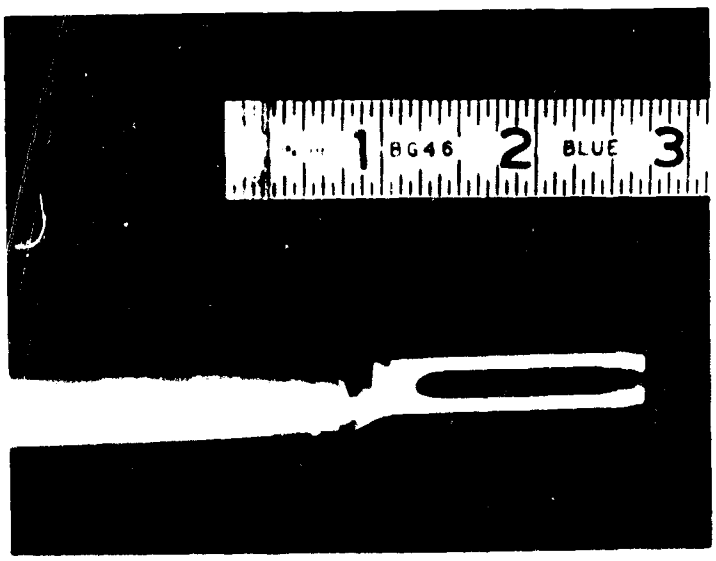

Figure 1b. Typical transducer configuration with photo diodes mounted with optical axes coaligned.

Figure 1. The Model [illegible] Measuring System ([illegible]).

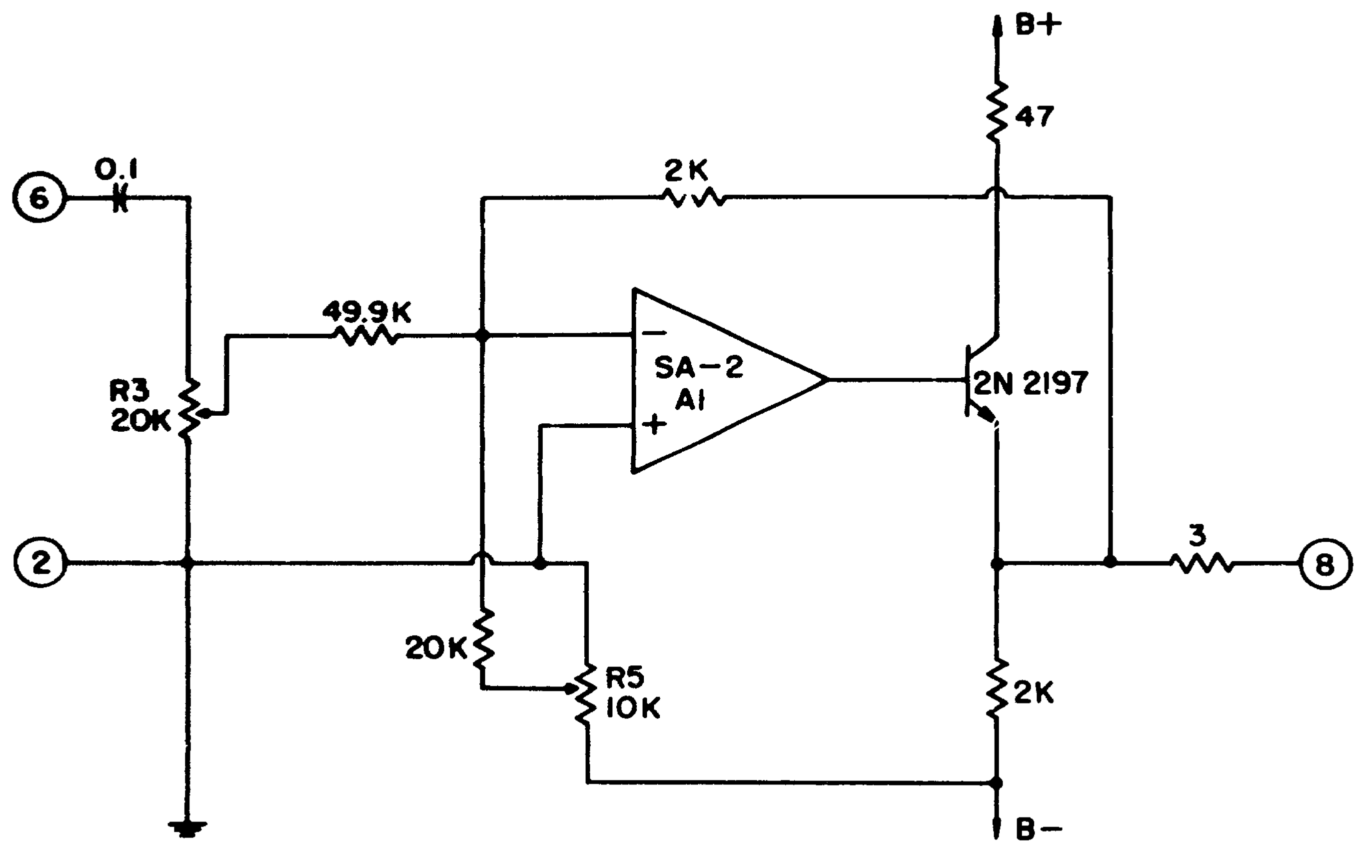

Figure 2. Light-source excitation circuitry mounted on card 1.

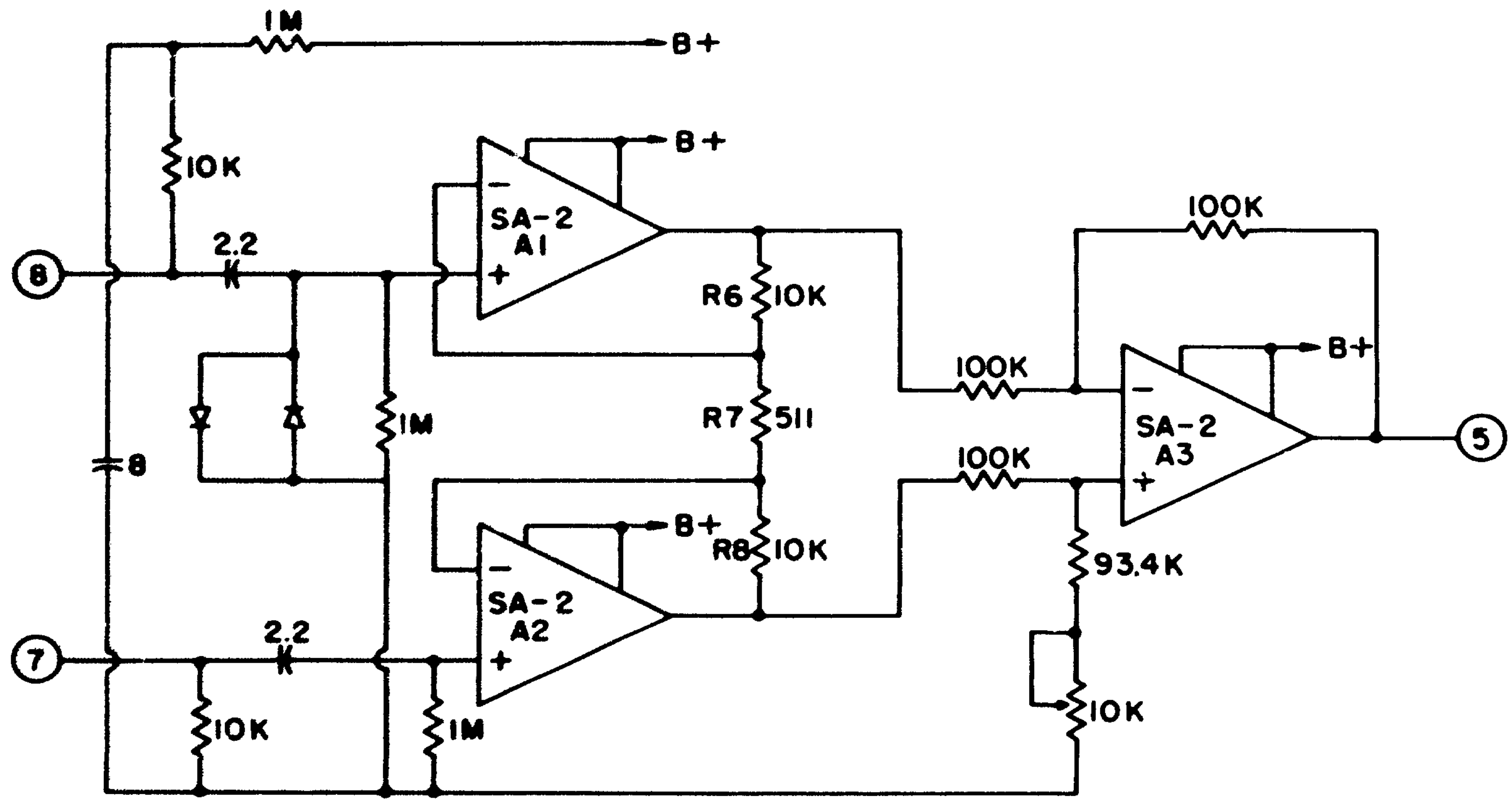

Figure 3. Sensor diode output amplifying circuitry mounted on card 2.

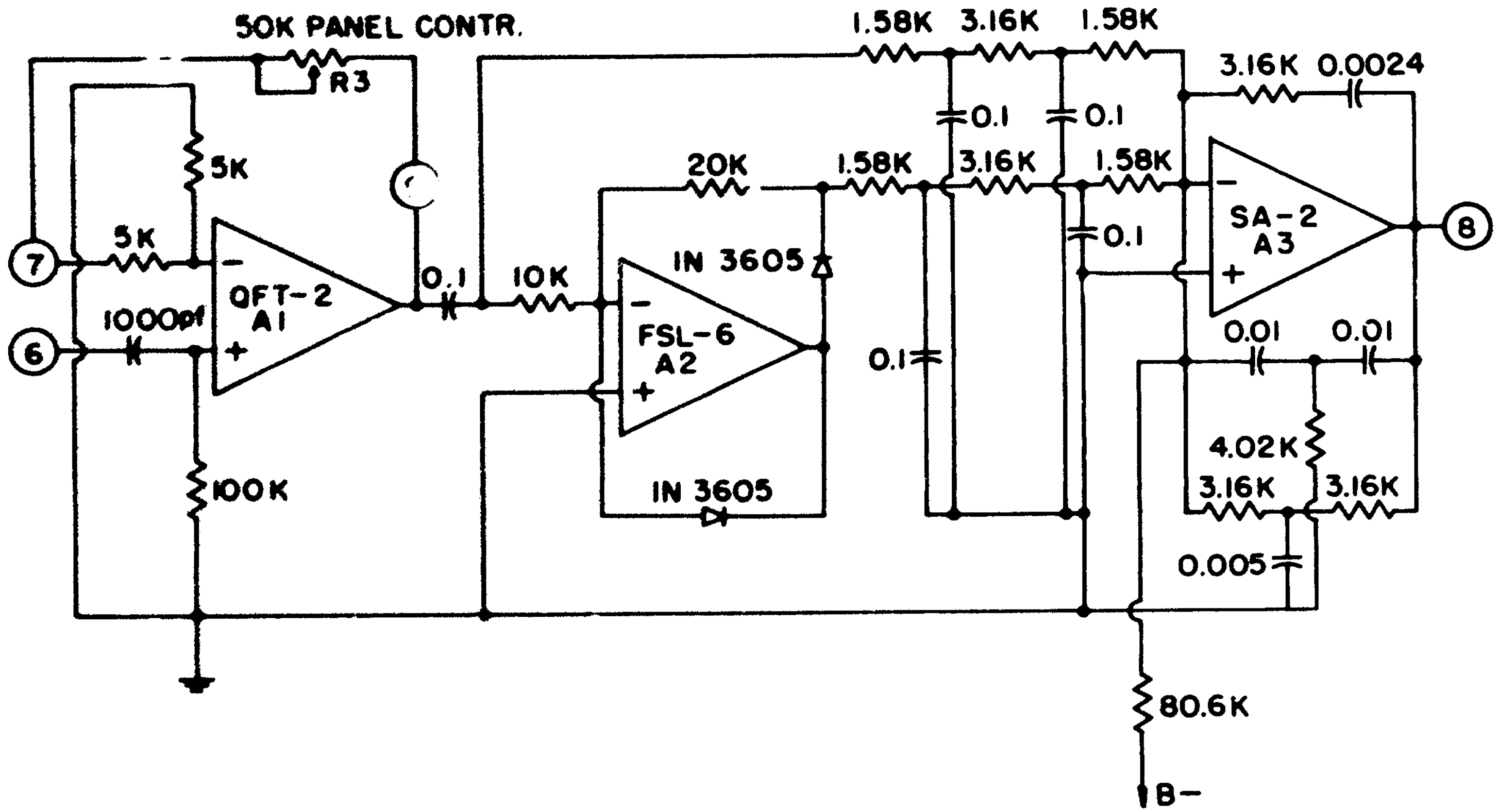

Figure 4. Gain, detector and filtering circuitry mounted on card 3.

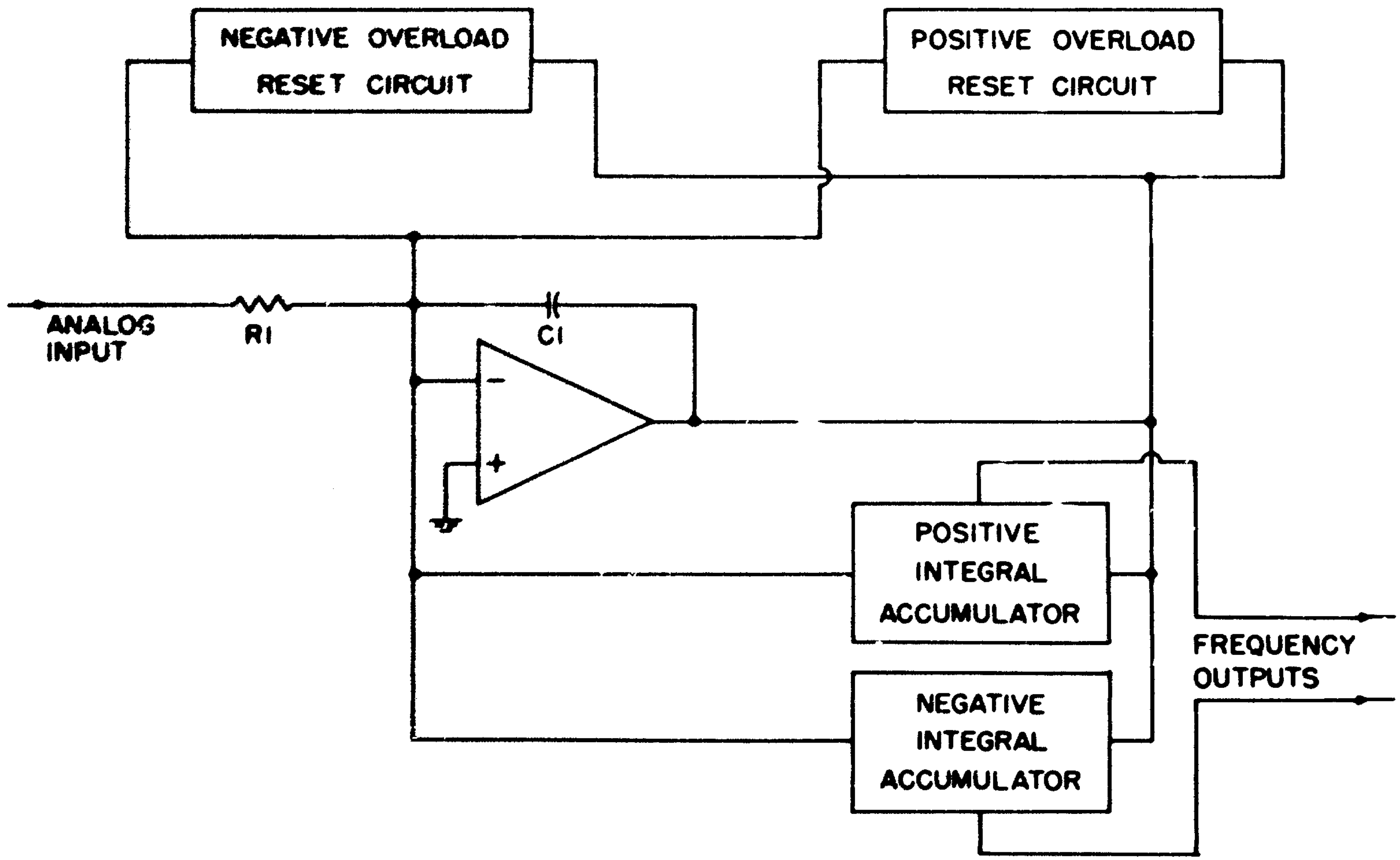

Figure 5. Analog-to-frequency converter; card 4.

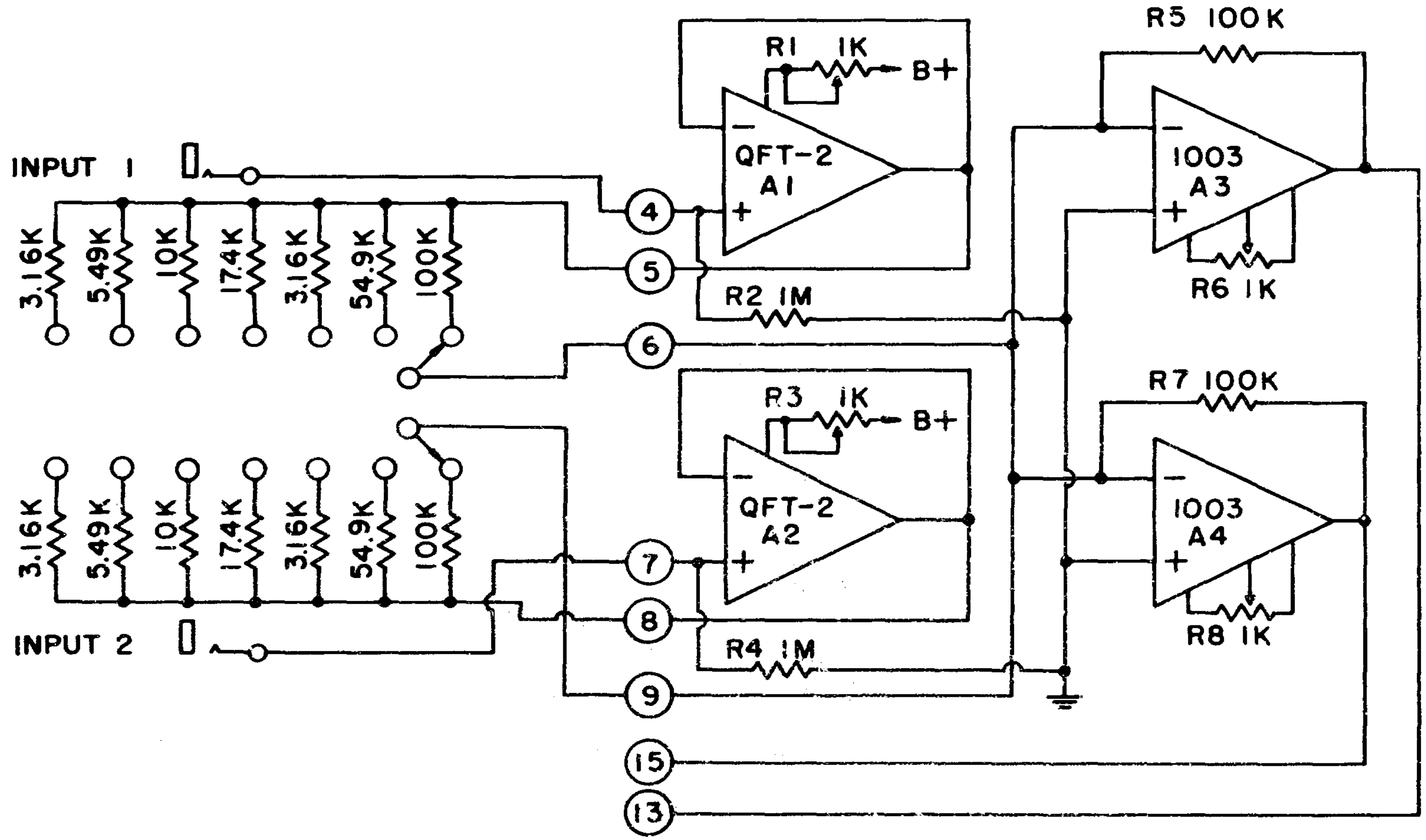

Figure 6. Range network mounted on card 5.

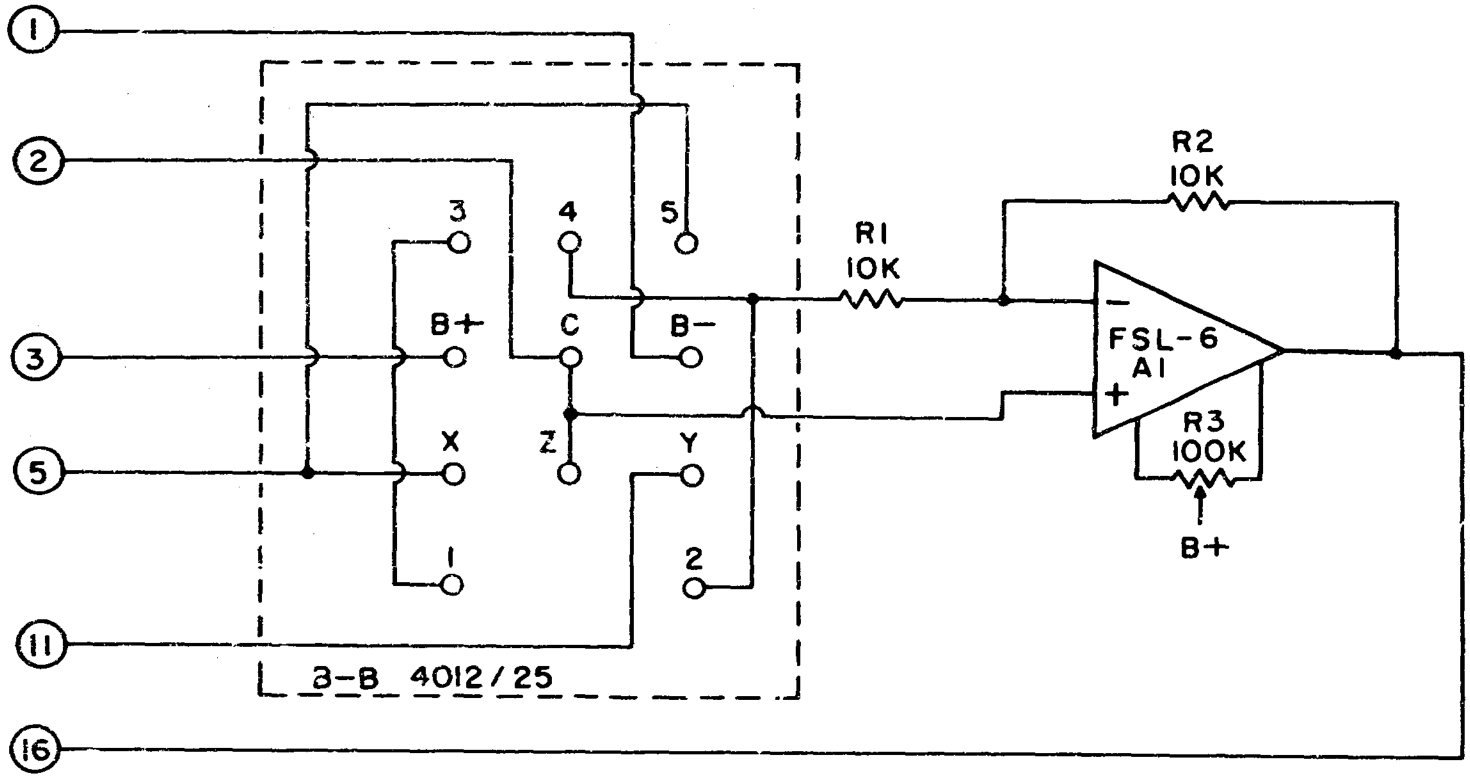

Figure 7. Mean-product multiplier; card 6.

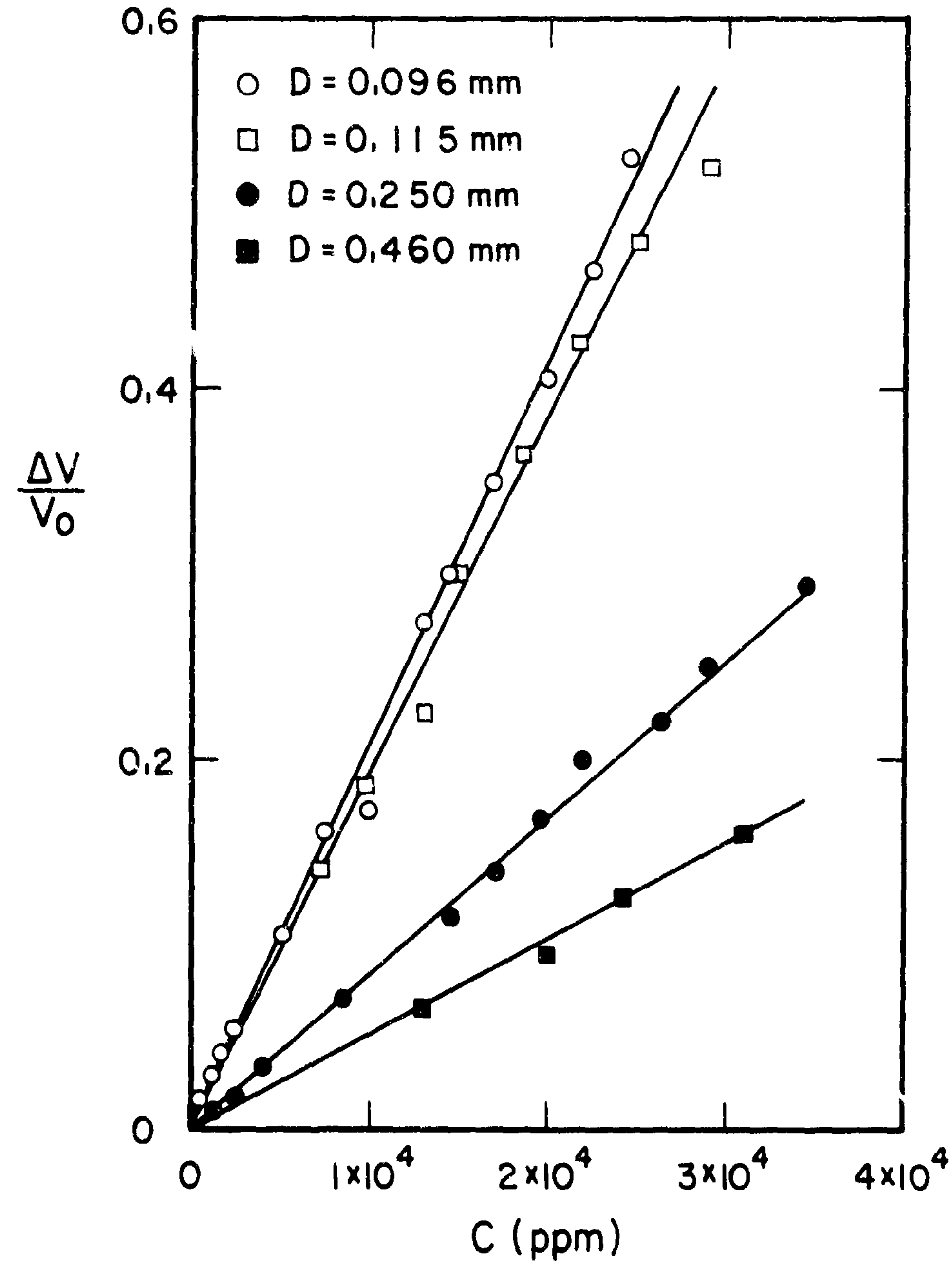

Figure 8. Calibration curves obtained for four different sand sizes.

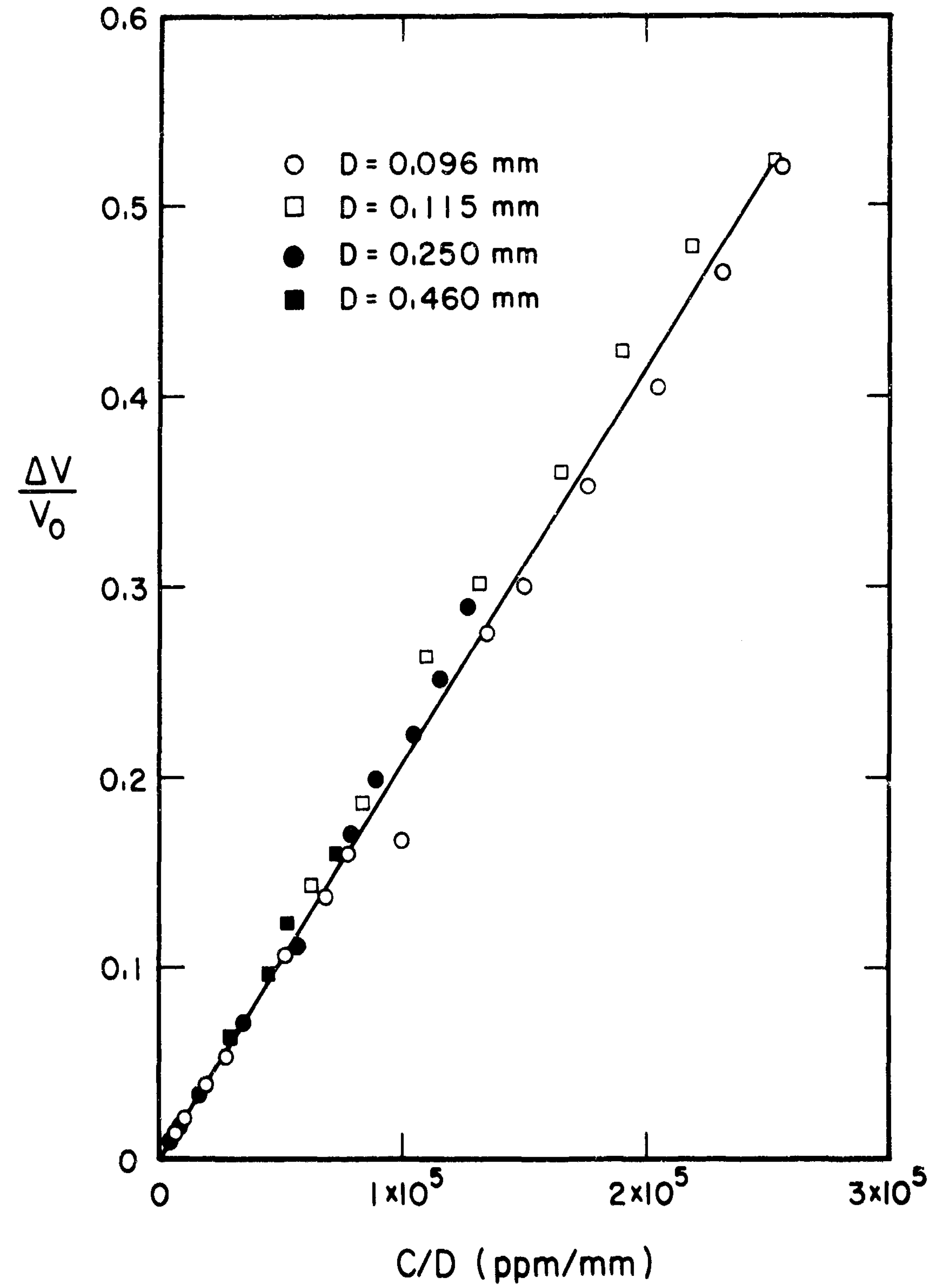

Figure 9. Unified calibration curve expressing $\Delta V/V_0$ as a function of C/D for quartz sand.

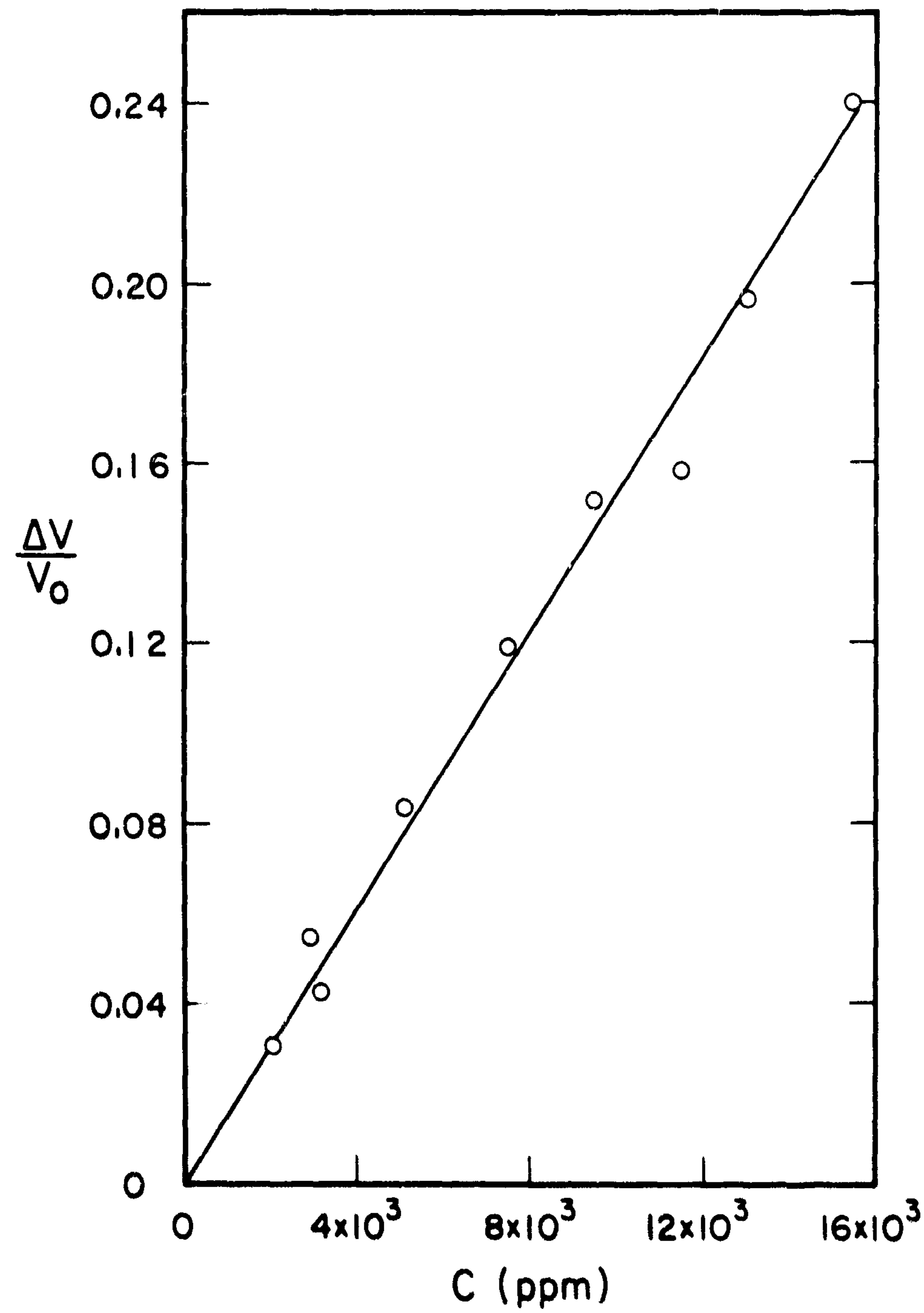

Figure 10. Calibration curve for 0.1 mm glass beads.

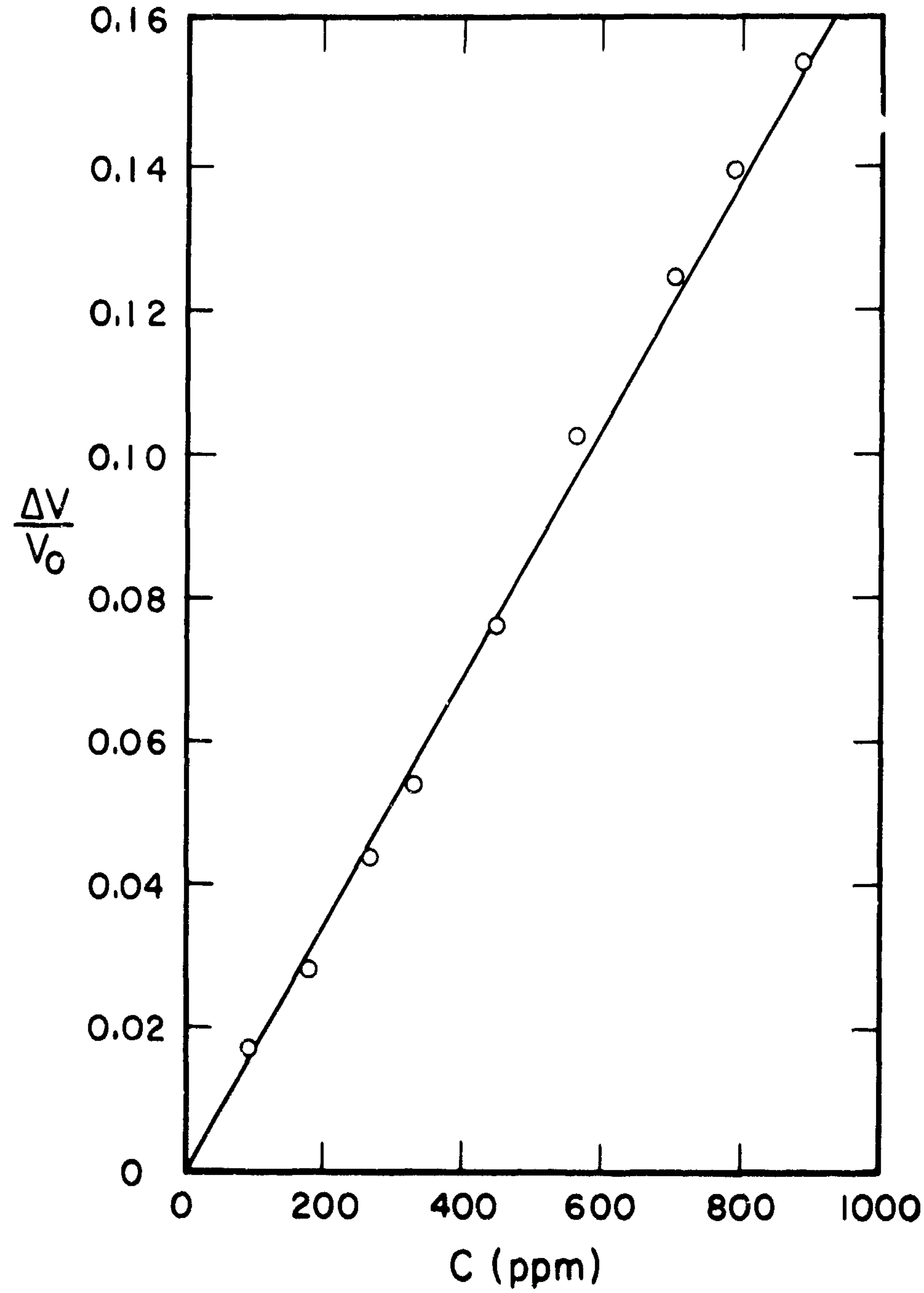

Figure 11. Calibration curve for bentoni e clay with particle sizes less than 0.02 mm.

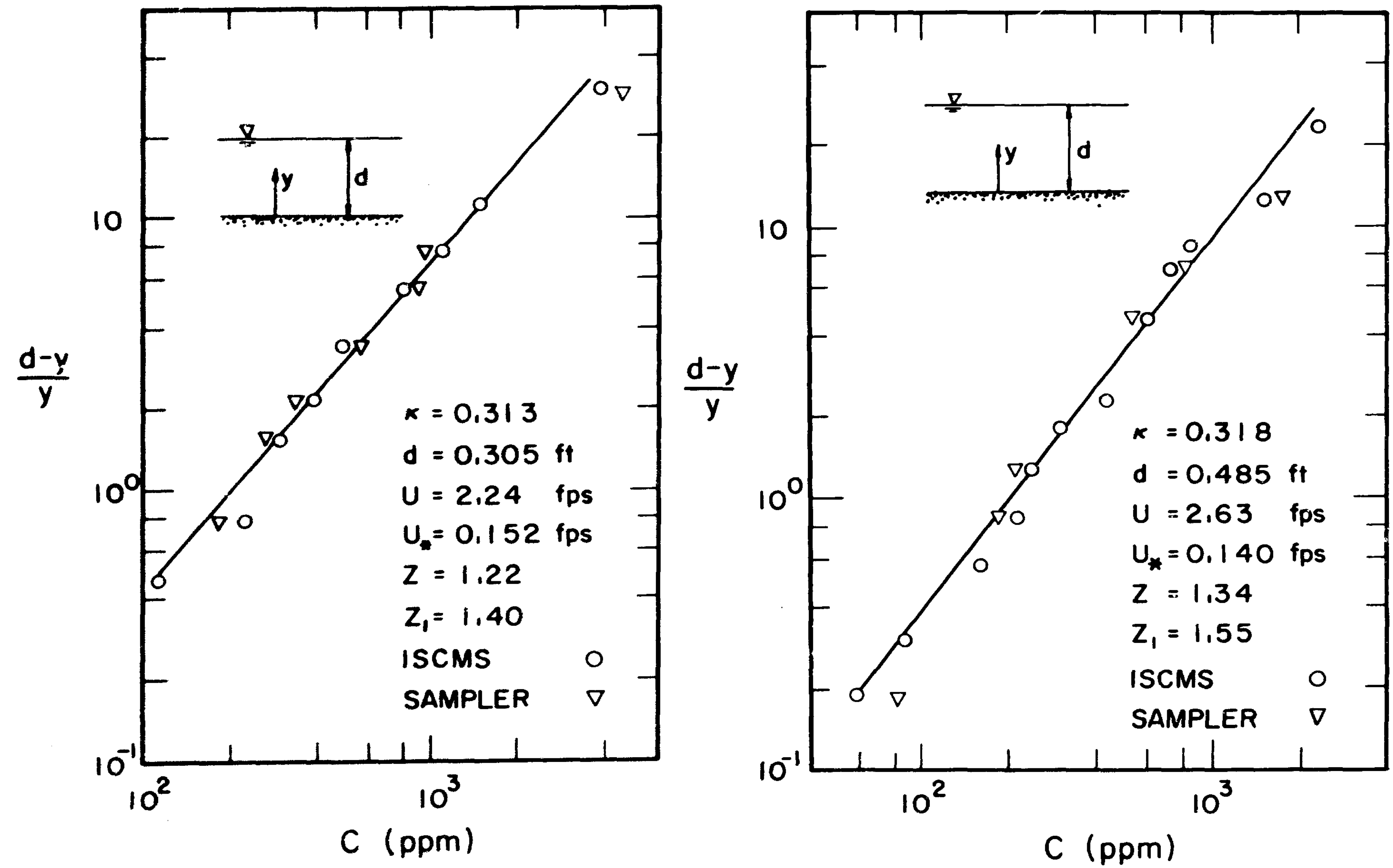

Figure 1?. Suspended-sediment concentration profiles in steady, uniform flows over flat sand beds, measured with the ISCMS and a withdrawal sampler.

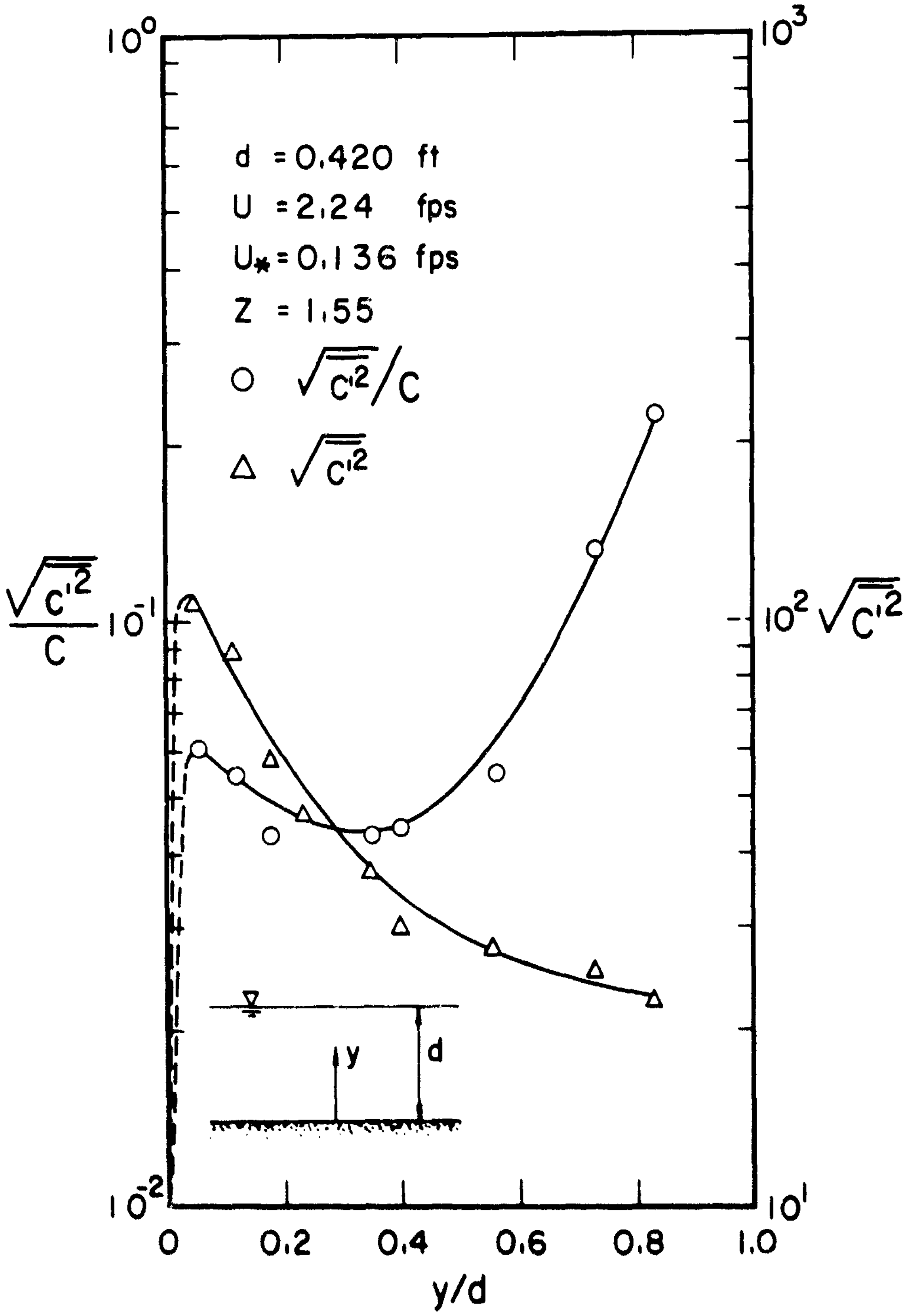

Figure 13. Vertical distribution of RMS of concentration fluctuations in a steady, uniform flow over a flat sand bed.

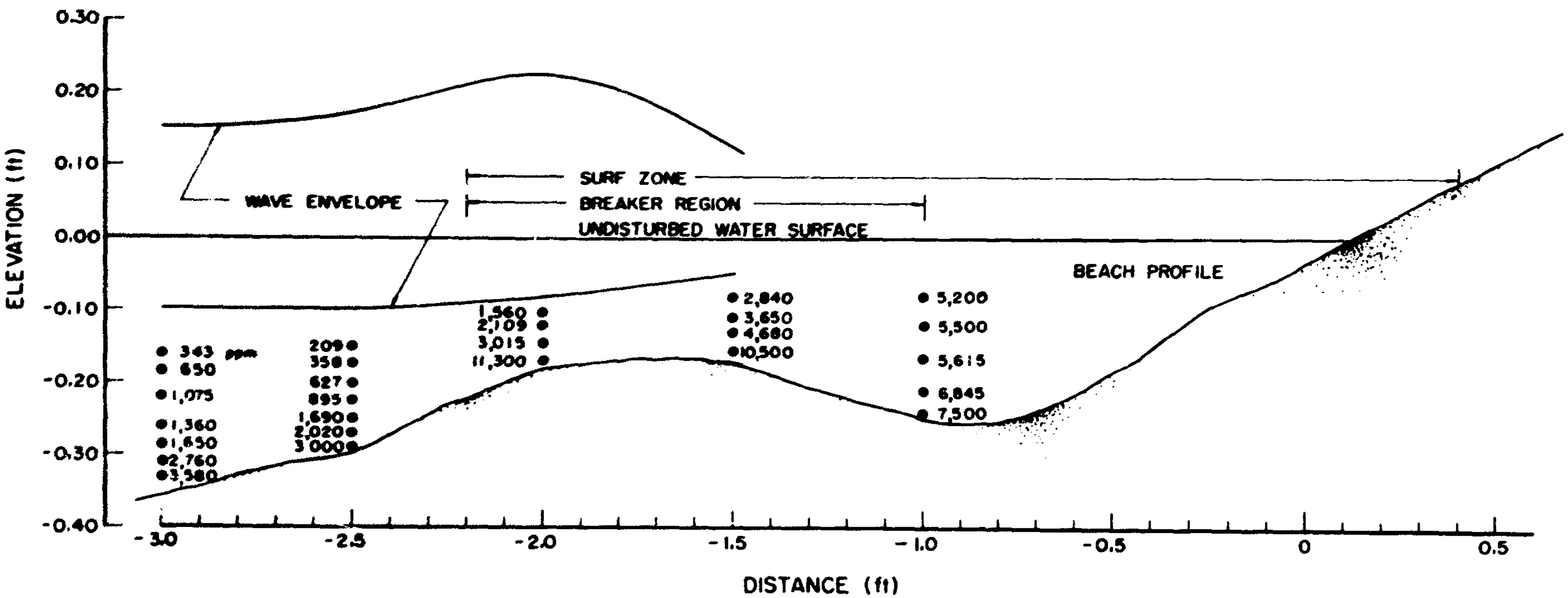

Figure 14. Mean concentrations of suspended sediment measured in shoaling waves in a laboratory tank. (Number by each point is the mean concentration in ppm.)

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Abstract

A new electro-optical system has been developed for *in situ* measurement of suspended sediment concentration in alluvial channel flows, estuaries, and shoaling waves. The transducer for the system consists of a gallium arsenide diode as a light source and a silicon planer diode as a light sensor. The source light detected by the sensor is modulated by the suspended-sediment in the gap between the source and sensor. The amplifier for the sensor output has been combined on one chassis with signal analyzing circuitry, which includes an analog-to-frequency converter and multiplier circuits. The resulting system is capable of measuring suspended sediment concentrations down to 100 ppm, and can compute the mean concentration, the mean square of the concentration fluctuations, and the correlation between sediment concentration and another signal supplied to the system. Exploratory experiments were undertaken in a recirculating laboratory flume and a laboratory wave basin to evaluate the practical usefulness of the system.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
suspended sediment						
sediment transport						
multi-phase flow						
electronic instrumentation						
beach erosion						
optical transducer						
mean-product computer						

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