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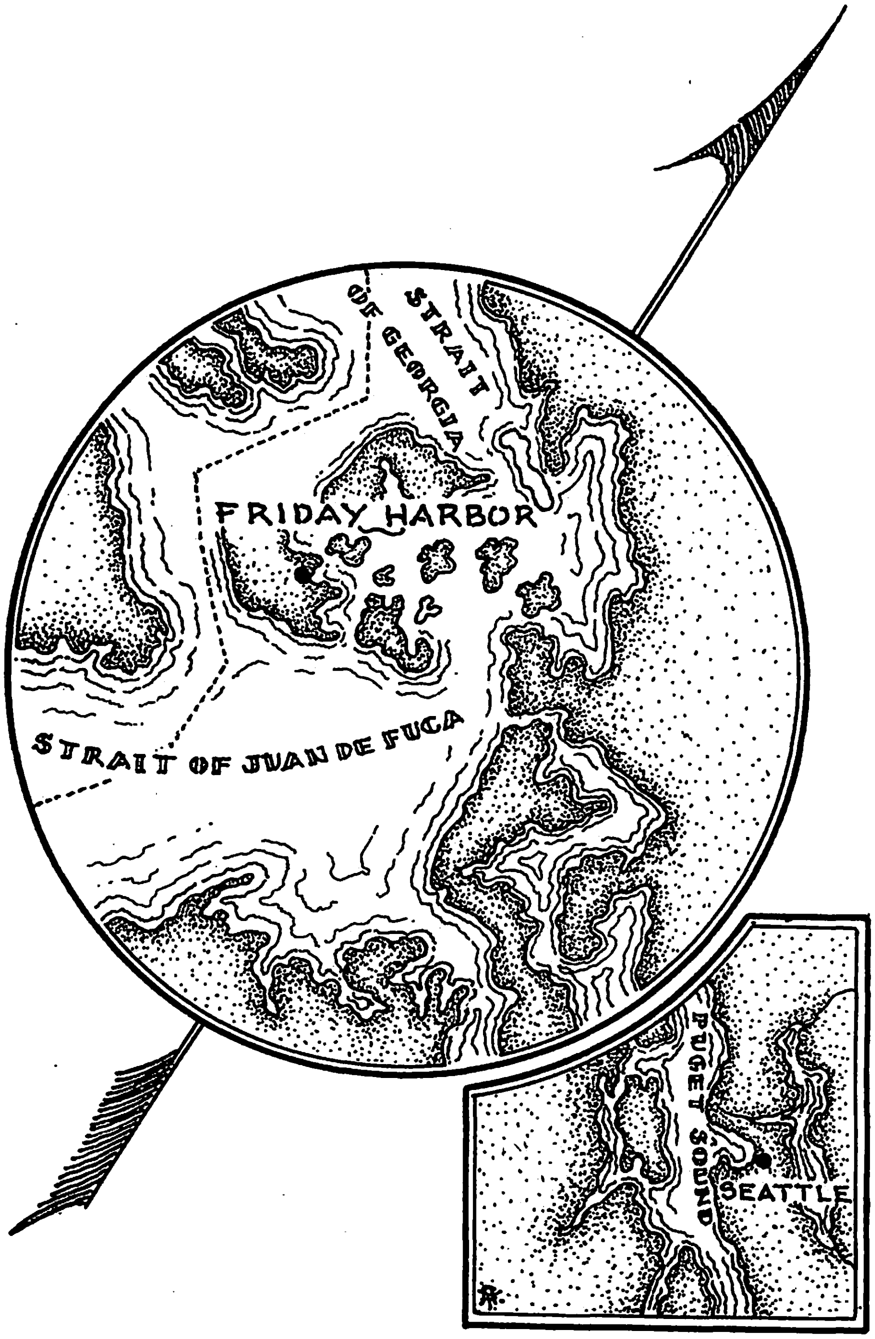
MEASUREMENT OF TIDAL CURRENTS IN PUGET SOUND

Technical Report No. 6



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by

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Thomas G. Thompson
Director

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MEASUREMENT OF TIDAL CURRENTS IN PUGET SOUND

SUMMARY

During the past year tidal currents have been measured at two or more depths simultaneously and continuously for periods up to 38 hours at 22 stations in Puget Sound. Measurements were made from an anchored vessel using Price current meters and recording the electrical pulses on a chronograph. Lately an integrator has been developed to convert the current meter pulses into a continuous line trace reading directly in knots and the technique of transmitting meter pulses up the single bare suspension cable employed. The resulting current measurements show the following features:

1. Currents at 5 meters depth in tideways 60 to 100 meters deep are stronger on ebb and weaker on flood than those at two-thirds the bottom depth. This is attributed to a prevailing seaward flow of low salinity water which exists as a mixed layer of considerable thickness. This admixture is fed by fresh water from precipitation and runoff which locally exceeds evaporation, and by a net influx of coastal sea water at depth sufficient to maintain the salt and water balance.

2. Currents of strengths up to 4 knots show primary fluctuations in velocity of the order of ± 0.1 knot from the average, with

variations in period of 15 to 45 minutes. Smaller second order fluctuations with approximately a 2-minute period and still others of a third order also occur. These higher order fluctuations are apparently associated with eddies and turbulence on corresponding scales.

3. The maximum velocities in water at two-thirds the bottom depth normally occur on flood and do not exceed the maximum surface velocities on the faster of the two chronologically adjacent ebb flows.

MEASUREMENT OF TIDAL CURRENTS IN PUGET SOUND

I. INTRODUCTION

The surface currents in Puget Sound have been well studied during many years by the Coast and Geodetic Survey and are summarized in their publications (1), (2), (3). These measurements, designed to be aids to navigation, have been largely confined to the upper 15 feet with only a few isolated observations made at depths as great as 60 feet. As the water at depth behaves differently from that at the surface, a detailed knowledge of the currents at all depths is needed for a number of purposes. In particular the understanding of the hydrodynamics of water motion and the mechanism of water exchange in the Sound, the predicting of the boundary conditions for the hydraulic model of Puget Sound under construction, and the estimating of the force of the currents acting upon equipment operating at the bottom or intermediate depths require this knowledge.

Detailed measurements in a body of water the size of Puget Sound is a task of some magnitude. The first objective, therefore, was to investigate surface and deeper currents to establish any relationship that might permit predicting the currents at depth from existing surface data. Figure 1 shows Puget Sound and the locations at which current observations were made. Initially, locations of relatively high current velocity were selected in the belief that the differences between the shallow and deep layers would there be more distinct. Observations were commenced near Bush Point where the surface velocities reach 3 to 4 knots. These were extended to a locality of relatively high current velocities in the Strait of Juan de Fuca at the mouth of Admiralty Inlet.

II. EQUIPMENT

1. Vessel. The vessel used is of modified commercial fishing boat superstructure mounted on a 50-foot Navy Launch hull and powered by diesel. It is equipped with a winch and gear for handling two 3/8-inch cables over the stern, and two additional winches for handling lighter lines. The boat is ordinarily anchored by the stern using one of the 3/8-inch cables and a 75-pound Danforth anchor. Three hundred fathoms of cable permit satisfactory anchoring in 60 fathoms of water.

Anchored by the stern the boat yaws less than might be expected, except when a strong wind is blowing counter to or across a weak current. In stronger currents no regular yaw pattern has been observed in frequently repeated three-point sextant fixes. A motion similar to yaw is caused by large eddy structures flowing with the current. At current velocities less than 1 knot, yaw quite possibly occurs. Anchoring requires a scope of 5:1 which at an average depth of 45 fathoms means 225 fathoms of cable out, permitting the boat to swing in a circle of 0.22 miles radius. The positions shown in Figure 1 are the positions of the anchor. The long scope of anchor cable results in low observed velocities at shift in current direction as the boat then drifts with the current for a period of the order of 30 minutes. During current shifts, it has been necessary to raise the deep current meter gear to avoid fouling the anchor cable. The small size of the vessel prevents successful anchoring in exposed tideways in the Sound when winds exceed about 16 knots for any length of time, a frequent occurrence. It has been difficult therefore to obtain continuous records for periods as great as 25 hours, particularly in the Strait of Juan de Fuca near the mouth of Admiralty Inlet.

2. Drift Poles. A few early measurements were made with drift poles and floats attached to drags at appropriate depths. These gave averages over a considerable range with respect to position, time, and depth confusing the interpretation of the data. Additional measurements were made, therefore, with recording instruments from an anchored vessel and only these are reported herein.

3. Current Meters. Continuously recording direction indicating current meters are considered nearly indispensable for measuring simultaneously the currents at two or more depths, and insuring that the peak velocities are recorded. Oscillations in velocity superimposed upon the more or less regular variation in the current cycle may introduce considerable doubt into the interpretation of single short-period measurements. Lacking suitable direction indicating and recording meters the measurements were carried out in part with non-directional meters of the Price type, modified for salt water use by the W. and L. E. Gurley

Company. A few recent measurements have been made with the Roberts current meter. The Price meter is designed to close an electrical contact every ten revolutions of the bucket wheel, or every revolution as desired. It is provided with a stainless steel shaft and a water-tight gland into the contact chamber. The pivots are carbon steel, and corrode very easily.

A number of modifications were made in these meters to adapt them to continuous operation at depth in salt water. The carbon steel pivots were replaced by a sapphire V-cup and a burnished stainless steel pivot. The packing gland was replaced by one of metal with a rubber bushing compressed by a nut. The meter as furnished for contacting every tenth revolution is very susceptible to short-circuiting of the contacts by salt water, owing to the close proximity of the insulated lead to the floor of the contact chamber and a slight but persistent leakage of water. Leakage probably results from the mixing action of the shaft, or from oil escaping around the shaft as the meter is being lowered toward the water. After the instrument is submerged the compressing of the resulting air bubbles permits water to enter under hydrostatic pressure. The difficulty has been overcome by shifting the packing gland from bottom to top of the contact chamber thereby raising the electrical parts. A small silver contact mounted on the end of a spring reaches down to the contractor and provides the necessary electrical connection. As a further precaution, the chamber is filled with an oil compounded from chassis lubricant and medium lubricating oil, more viscous than that commonly used. This modified equipment has operated satisfactorily at depths up to 100 meters, the depth being limited by the excessive wire angles which develop when long electric cables are used at high current velocities.

The Price current meter gives no indication of the direction of the water flow. This is not too serious for strong currents in narrow channels, where the gross current flow follows the channel. For other situations, the direction of flow has been determined periodically with the Ekman current meter. The Ekman meter, however, ceases to function properly at velocities exceeding about 2.0 knots since the shutters fail to open against the force of the current. At somewhat lower currents the indicated velocities become less accurate and the compass unreliable due to instrument tilt.

The electrical pulses from the Price current meters have been recorded on a two-pen chronograph. This has been made from a Friez anemometer recorder by increasing the rate of rotation of the drum to one revolution per hour, adding a second writing element, and replacing the lead screw by one with a finer thread. Measurements can be recorded for a sixteen-hour period before replacing charts. A photograph of the chronograph is presented in Figure 2. A weight-loaded spiral spring helper designed to exert a torque on the shaft and reduce the load on the clock motor occasioned by the increased gear ratio appears at the left end of the shaft. A four-pin socket is provided at the front for the electrical inputs.

A typical chronograph record is shown in Figure 3. As the original chart paper is used, the time scale is expanded by a factor of six from the printed markings. Accordingly one division on the chart corresponds to 50 seconds. The outputs of two meters are recorded simultaneously. The upper record shown is from an instrument at 5 meters depth and the lower from one at 66 and 55 meters.

Except at very low velocities the calibration curve on the Price meter is essentially linear permitting velocities to be readily determined by counting the number of pips within a selected interval. In this instance if the interval is 0.88 inches, the number of pips divided by 20 gives the velocity in knots, averaged over about 4-1/2 minutes. When the pens are writing properly it is possible to resolve pulses at 3-second intervals, which corresponds to about 4.5 knots. Average conditions place the practical limit at about 4 knots. Velocities determined from the chart records for 10-minute intervals are plotted on graph paper.

As several characteristics of the meter circuits required modification before the pulses could be used to actuate the chronograph, a control box was constructed incorporating the following features:

1. Relays to provide current amplification and protect the meter contacts.

2. Adjustable shunts across the relay coils to be used when electrical leakage in the meter cable caused the relay to freeze closed.

3. An adjustable time-delay circuit consisting of a parallel resistance and capacitance interposed between the relay

and recorder, to eliminate spurious pulses. This was necessary at moderate current velocities when the contacts were moving slowly and occasional imperfections caused multiple operations of the pen with consequent over-inking and impairment of resolution. This circuit also very effectively reduced sparking at the relay contacts.

4. Provision for by-passing the relays and operating the recorders directly by the current meter contacts in case of emergency.

5. Provision for insertion of a test ammeter in series in the current meter circuit.

Suspension Gear and Electrical Cables.

At depths greater than a few meters the current meter was initially suspended by 5/32-inch stainless steel line weighted by a 100-pound hemispherical iron weight. The steel line formed one side of the electrical circuit which was completed by a small insulated wire bound thereto at intervals with friction tape. The insulated wire failed to pass through the sheaves properly and had to be stripped from the line each time the meter was raised. Danco nylon-coated cable was tried as a combined supporting line and insulated lead, using water as the circuit return. This worked well until a myriad of cracks developed in the nylon to give severe electrical leakage. A current meter and accessory equipment were lost when the line was inadvertently made positive with respect to the water, and the resulting electrolysis being concentrated at a crack, caused the line to fail. It was finally necessary to return to the use of a separate wire bound to the suspension line. Belden No. 20 vinyl-coated flexible wire when properly bound to the line, passes through the sheaves, and its coating appears nearly impervious and quite tough. An effort is being made to obtain armored oil-well logging cable which may offer a possible solution to the problem.

The Roberts current meter (4) is designed to be used with a radio transmitter operated from a buoy and tended by a ship or shore station which can sample the signals from a number of meters consecutively. In the present work one meter has been operated directly from the boat without radio.

The Roberts meter generates a series of pulses in a two-conductor system which permit both velocity and direction of the current to be obtained. There are two systems of pulses, the velocity pulses which occur in regular sequence with the rotation of the propeller, and the direction pulses which are spaced in between the velocity pulses in such a way that the position in time of a direction pulse with respect to two adjacent velocity pulses gives the direction of the current.

No automatic recording system for direction has been devised. Several are possible but all have been considered too complex for reliable field use. A chronograph operating at a writing speed of about one inch per second appears to be the only simple method of recording. Continuous recording with conventional chronographs at this rate would use prohibitive lengths of tape. Consideration is being given the Alden recorder, which writes in successive closely spaced lines across the paper using reasonable lengths of tape.

III. MORE RECENT DEVELOPMENTS IN CURRENT MEASURING TECHNIQUES

Some recent modifications in current measuring techniques not as yet extensively used in the present field program are:

1. Conversion of the current meter pulses to a continuous line trace.
2. Transmission of the pulses up a single uninsulated suspension cable.

1. Conversion of Pulses to a Continuous Line Trace. The principle involved in this operation has been used in the past and was suggested by the work of S. W. Grinnell (5) on anemometer recorders. If a current meter pulse may be made to trigger a circuit which will create a pulse containing a constant quantity of electricity, the continual repetition of these pulses constitutes the generation of an electric current whose average value is directly proportional to the pulse rate. If the current meter has a sufficiently linear characteristic, the electric current is also proportional to the water velocity. When the pulsating current is smoothed, it may be introduced into a recording milliammeter calibrated directly in knots and a continuous line record obtained of water velocity as a function of time.

In this system the pulses operate a relay which discharges a small capacitor charged to a fixed voltage into a larger smoothing capacitor in a circuit such as that diagrammed in Figure 4. This circuit would give an output proportional to the pulse rate if it were not for

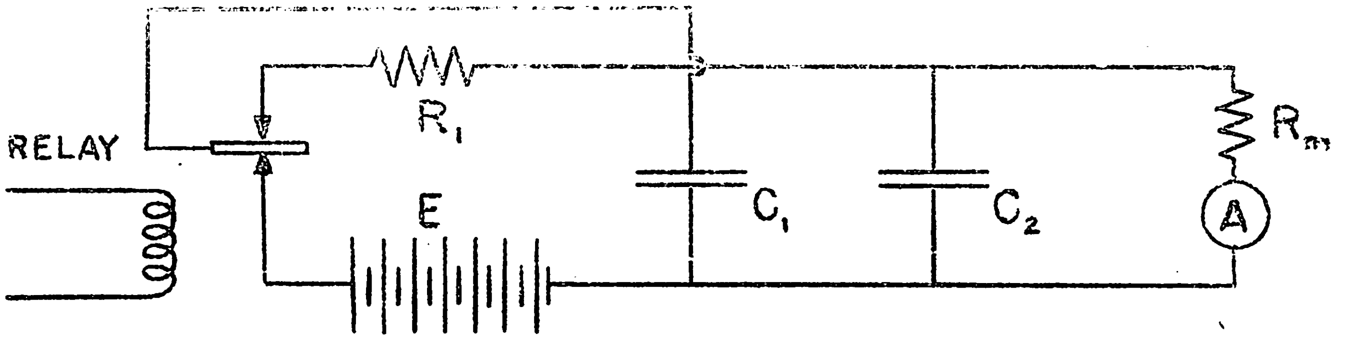

Figure 4
Circuit of the Grinnell Recorder

the fact that the smoothing capacitor C_2 becomes charged to higher voltages at higher pulse rates, and, if this voltage is an appreciable fraction of the battery voltage, the capacitor C_1 no longer transfers its full charge to C_2. This error will be smaller the lower the meter resistance Rm and the higher the battery voltage E. The degree to which the pulsating current is smoothed is determined by the time constant RmC_2 as compared to the pulse frequency F.

Grinnell shows that the average current registered by the meter, I, is given by

$$I = \frac{C_1 FE}{1 + C_1 FRm}$$

Thus, with a one-milliampere Esterline-Angus recorder where $Rm = 1400$ ohms, $E = 90$, and $C_1 = 4\ \mu f$

$$I = \frac{0.00036\ F}{1 + 0.0056\ F}$$

For $F = 3$/sec, which corresponds to about 4 knots water velocity with the Price meter, the current is about 1 milliampere and the deviation from linearity 1.7 per cent or 0.07 knots. If the recorder is set correctly at a mid-scale value of 2 knots, the deviation is ± 0.8 per cent at the two extremes.

In order to obtain reasonably good damping the time constant R_mC_2 must be about the same as the pulse interval. Thus 500 µf is a suitable smoothing capacitor down to about 1 contact per second. For such values, electrolytic capacitors must be used with consequent disadvantages of high and variable leakage and a considerable tendency to soak up charge due to dielectric imperfection. These difficulties would become more marked if effective damping were attempted at low pulse rates by using larger capacitors.

These difficulties were eliminated by carrying on the integration at the input of a simple D.C. amplifier. Since the input resistance of the amplifier is very high and its current requirement correspondingly small, the capacitors may be made very much smaller.

The integrator circuit in its present form is diagrammed in Figure 5. Here C_1 and C_2 have the values 0.03 and 3.0 µf. The charging voltage is 150 volts which is held constant by a voltage regulator tube. The grid resistor, which corresponds to Rm, is normally the parallel combination of R_2 and R_3. When S_1 and S_2 are open, the scale change appropriate to the Roberts current meter is made. S_2 is operated by a cam on a motor-driven sampling switch to be described in the next section. Further adjustable damping is provided by a simple resistance-capacitance filter formed from R_4 and the three capacitors C_3, C_4 and C_5, controlled by the three-position switch S_3. The time for 63.2 per cent of full response is 2, 7, and 22.5 seconds respectively on the three settings. This includes the damping which occurs in the recording meter.

The D.C. amplifier is a common bridge circuit using two 6J5 tubes, with adjustable zero and scale controls. The 12SN7, presumably the equivalent of two 6J5's, was found less stable. The filaments are supplied by a 32-volt battery and the high voltage by a dynamotor. Since the supply voltage may vary from 28 volts to nearly 40 volts, adjustment must be provided by means of a rheostat. Small drifts in the supply voltage when not compensated affect the zero and scale factor of the bridge. Two volts change the zero by 0.05 knots and the scale by about one per cent. The latter effect is due to a change in plate voltage which is not completely compensated by the voltage regulator tube. Provision is made for applying filament power before the plate supply is turned on. This precaution has been shown to be very effective in preventing long term drift in other types of tubes. Aside from the drifts due to change in the supply voltage, the amplifier is surprisingly stable after running about half an hour, and zeroing and calibration need be made only about once an hour, when the zero may be expected to have shifted less than 0.05 knots and the scale factor less than one per cent. For calibration a motor-driven contactor operating at very nearly two pulses per second is used. The driving motor is an Amglo reed-synchronous D.C. motor which retains a relatively constant small deviation from nominal speed. At two closures per second, the calibration value is 2.63 knots for the Price meter.

The recording milliammeter is an Esterline-Angus, one milliampere full scale. The scale is numbered to read 4 knots at full scale.

The integrating system used with the Price meters is capable of operating with the Roberts meter only if the direction pulse is eliminated. The plan therefore was to introduce sufficient resistance in the direction pulse circuit so that the pulse could be screened out at will by increasing the attenuation in the amplifier and brought in periodically for determination of direction by use of a stopwatch or chronograph.

2. Transmission of Pulses Up a Single Uninsulated Cable. In connection with other measurements John D. Isaacs (6) has done considerable work (yet unpublished) on the transmission of electrical pulses up a single bare cable using silicone oils to increase the electrical resistance of the cable-water interface.

Consider a long cable immersed in sea water and a mechanism which applies a voltage between the lower end of the cable and an electrode at some distance from it. The greater portion of the voltage is dissipated in any resistances in the circuit greater than a few ohms, since the sea water forms a shunt path of low resistance. However, an electrical field is set up in the water which penetrates in some degree to the surface. If the cable is run through insulated sheaves and another electrode is trailed in the water at the surface, the applied voltage may be detected, though greatly reduced in magnitude, by means of a suitable amplifier.

This system has been applied to current meters. In order to avoid the use of batteries, which would require water-tight cases, the voltage source used in these investigations is a zinc-copper couple in the sea water. At the lower end of the cable an insulated wire about 30 feet long connects the ungrounded current meter contact to a sheet of zinc about 4" x 12" trailing behind in the current. The other meter contact leads to the frame of the meter and thence to the suspension cable. At the surface, a sheet of copper is also trailed downstream. Trials have been made with and without silicone, and although the resistance of perfectly clean cable is considerably increased thereby, it is not certain that silicone functions any better than ordinary oil, although it may adhere for a longer time.

With this arrangement using Dow-Corning Silicone Fluid DC-200, the following pulse voltages were developed across 15,000 ohms:

Depth, meters	Couple only	10	20	40
Pulse, millivolts	900	82	72	52

Insulation on the cable, such as nylon, greatly increases the voltage, but any cracks in the insulation introduce spurious voltage pulses due to erratic intrusion of sea water. For this reason the Danco nylon-coated cable could not be used. With bare cable the system is relatively noise-free.

Detection of pulses of the above magnitude is a relatively simple matter. The amplifier constructed for the purpose is diagrammed in Figure 6. Three stages of voltage amplification and one of power amplification are provided. The relay will close with pulses as small as 3 millivolts, the extra sensitivity being provided for work at greater depths and to allow for miscellaneous unpredictable attenuations such as might occur if the electrical systems become spray coated or contacts deteriorate. The principal difference between this amplifier and the more common pulse amplifiers is the necessity of providing for very low-frequency response. It was not possible to provide for low-frequency response by increasing the time constants of the coupling circuits, since prohibitively large capacitors would be required. Instead, a short time constant was introduced between the first and second stages and the occurrence of overshoots was postponed by one stage by direct-coupling the first stage. The overshoot occurring between the second and third stages was practically eliminated by means of a diode so that only the primary overshoot appeared in the output of the fourth stage where it could do no harm. Actually, with very strong pulses, an overshoot does occur when the meter contacts open, which results in a second closure of the relay. However there is a wide range of adjustment of the attenuators over which satisfactory operation can be attained.

As a result of shortening the pulse after the second stage, it must be lengthened again to operate the relay satisfactorily. This lengthening is provided by the diode and parallel variable resistor in the grid circuit of the fourth stage. This lengthening also serves the purpose of screening out secondary spurious pulses which sometimes occur at very low contacting rates due to scratching of the contacts. For this reason the time constant of the circuit is made adjustable so that undesired pulses may be screened but the desired pulses retained.

The amplifier is designed with three separate input channels with separate attenuators and a motor-driven sampling switch so that the outputs of three current meters at different depths may be recorded automatically in sequence. One channel is provided with a contact which will automatically change the scale of the integrator to that required for the Roberts current meter, if desired. The Roberts meter has a pulse rate almost exactly one-third that of the Price meter at the same current velocity. The scale factor is suitably increased, but the damping factor is not changed so the trace produced by the Roberts meter is not so well smoothed as the others, but adequately so for the necessary accuracy. This broadening of the trace in Channel 1 is convenient for identification purposes.

With the batteries in the input leads as shown, the system may be operated also in the conventional way with one insulated and one uninsulated conductor and no voltage source at the meter. This practice is usually followed with meters placed near the surface.

With the sampling switch in the position shown, an extra pulse is occasionally produced when switching occurs. This causes a pip to appear on the record trace which aids in identification of the three records. Between the opening of the third channel and closing of the first, there are several seconds during which the amplifier is not connected to the meter leads and the pen drops toward zero. This also is an aid to identification. A better procedure eventually will be to have three separate amplifiers and integrators and do the switching from one integrator output to another. Possibly switching could be carried out in the input of the D. C. amplifier which would require only one of the latter and one set of controls.

The present system has not been tested at great depths. At an earlier stage in the development when the sensitivity was about 1/7 as great, satisfactory signals were obtained at a depth of 160 meters. With the improvements, operation at any depth in Puget Sound should be well within the sensitivity limits.

It must be noted that the potentialities of this system are by no means exhausted in the present apparatus. Much greater sensitivity can be attained by using higher voltage, high-capacity dry cells for a voltage source, by improving the insulating coating on the cable and by increasing the sensitivity of the amplifier. The latter step, however, requires more elaborate shielding of leads to avoid noise pick-up.

IV. MEASUREMENTS

Figure 1 shows most of the current stations which have been occupied and Table 1 summarizes the observations made at each. Data from ten stations selected for detailed analysis are plotted in Figures 7 to 16. Data were selected for plotting which showed reasonable fractions of adjacent flood and ebb half-cycles and at the same time exhibited moderate to high velocities. The latter requirement was established since currents at low velocities were very confused, apparently degenerating into large eddies with frequent and radical changes in direction. Furthermore, velocity data are less accurate and frequently lacking because of the necessity of raising the deep meter to avoid fouling.

The curves have of necessity smoothed some of the short-period variations. Typical variations which do occur are shown in Figure 17 which portrays a section of continuous record obtained from Station 21 in Tacoma Narrows. At other stations somewhat less violent fluctuations could be expected.

V. DISCUSSION OF RESULTS

1. Relation Between Shallow and Deep Velocities. The data have been analyzed first with respect to the relation between shallow and deep velocities. (The shallow water was usually found to move more rapidly on the ebb and more slowly on the flood.) These differences are shown in numerical form in Table II. The results are expressed in terms of an average velocity which has been obtained by mechanical integration of the curves. Since complete half-cycles of water motion were not always available for measurement, the available portions of the curves were used for integration and the resulting average velocity corrected to a common basis for comparison. The basis chosen was the peak velocity, the quantity of greatest interest with respect to the maximum force of the current on objects. The correction was made as follows: Both the shallow and deep currents in a given half-cycle of current flow were integrated over the same limits of time angle θ_1 and

θ_2, estimated from the shallow current curve, and the resulting integrated flows divided by the time interval to give the average velocity $\bar{V}$. To obtain the average peak value V_o, the average velocity was multiplied by a quantity K given by:

$$K = \frac{\theta_2 - \theta_1}{\int_{\theta_1}^{\theta_2} \sin \theta d\theta}$$

Peak velocities calculated using this correction are probably low as the measured currents do not average out a true sine curve, but appear to have lower velocity ordinates in general than consistent with the observed peak values. The deviation from a true sine curve is attributed in part to the drift of the boat with the stream during changes of current near slack water periods. Considerable inaccuracies may arise if the sections of curve measured are too short to have averaged out the statistical fluctuations. A few data of the latter type are included for their qualitative value but should be given little weight for quantitative purposes.

It appears likely that the differences in velocities of shallow and deep layers must be greater with greater velocities of current and, to bring the data to a common basis for comparison, some compensation must be made for this factor. The use of velocities for compensation is complicated by the fact that the latter contain the effect being measured and the basis will be different on flood and ebb. Therefore, in place of velocities, the tidal range for the current flow under consideration has been used. The flow on any tide must transfer the volume of water associated with the tidal prism in the inner Puget Sound basin. As a first approximation the difference between successive tide heights at Seattle is assumed proportional to this volume and to the net flow rate. Accordingly the differences between shallow and deep currents (S-D) have been divided by the corresponding predicted tidal range at Seattle and the results have been tabulated in Table III.

With only two exceptions, stations 10 and 11, the quantity (S-D) divided by the tidal range, ϕ, is more positive on ebb than on flood, and in most cases it is actually positive on ebb and negative on flood. The exceptions occur in the two cases in which ϕ is unusually small, permitting the effect to be more easily obscured by complicating phenomena. Thus it is demonstrated in general that there is a net outflow of surficial water and usually a net inflow of subsurface water. The existence of the net outflow of the upper layers of water has been evident from an inspection of the current tables, but a direct quantitative demonstration of the net flow of the deeper layers into Puget Sound has not previously been accomplished.

The net outflow near the surface is primarily due to the run-off of fresh water from streams emptying into the Sound. Since this fresh water has become mixed with sea water to form a surface layer of considerable depth, salt is transported with it to the sea. Salinity analyses over the past twenty years show that Puget Sound is suffering no significant net loss or gain of salt, consequently a compensating net inward flow of more saline water in sub-surface layers is to be expected.

Qualitatively the results may be explained by assuming that there exists a velocity field due to density structure, in this area determined largely by the salinities. This field is directed outward on the top and inward on the bottom, and is superimposed upon the tidal motion. If the field were the same on flood as on ebb, Ø would be expected to have the same absolute value on flood as on ebb, being negative in the former case.

Analysis of the data, excluding Stations 7, 10 and 11, above shows that the ratio Ø (Ebb) to Ø (Flood) averages -1.7. The greater effect of bottom friction on the lower layers may be sufficient to account for this difference. Since the friction force is directed inward on ebb and outward on flood, it increases S-D on ebb. On flood it makes S-D more positive, hence a smaller negative value.

It has been suggested that it might be possible to explain an apparent change in S-D on flood and ebb by some effect associated with the fact that the force of Coriolis acts toward opposite sides of the channel on oppositely directed currents. For instance, in the absence of other effects, a station on the east side of the channel at Bush Point might be expected to observe higher ebb velocities than flood velocities, and vice versa for the west side.

If the surface layers were more strongly affected by this difference the result would be to make S-D more positive on ebb than on flood, on the east side. However there appears to be no mechanism which would account for S-D becoming negative on flood, as it has in most of the data. Moreover, if the effect is general, one would expect stations on the west side to show results exactly opposite to those on the east side. It is believed that the data will not support such a hypothesis.

As another check a number of salinity sections across Admiralty Inlet at various points and times have been examined. Although the patterns are sometimes complex, there seems to be a general tendency for the iso-saline lines to tilt upward toward the west bank on both flood and ebb flows. This is consistent with a more rapid surface flow on ebb and a more rapid deep flow on flood. A centrifugal force acting always toward the west could also account for the tilt of the iso-salines, but this situation cannot exist throughout all parts of Admiralty Inlet.

The actual velocity distribution is undoubtedly a function of the salinity gradient both vertical and along the channel, the flow characteristics of the channel, and topographical effects. Efforts are now being made to estimate the effect of the salinity gradient, using salinity data obtained with the S-T-D. It is evident also that stations which are affected by water from two or more co-oscillating estuaries may show confused results. The same is true in cases where a sizeable fraction of the tidal cycle may be made up of large persistent eddies resulting from a bulk flow in the opposite direction. Preliminary studies of the hydraulic model of Puget Sound constructed in these laboratories suggest that the latter phenomenon tends to occur in the wider expanses of water and near the time of slack water. The anomalous results of Stations 10 and 11 may be due to effects associated with competition of Rosario Straits to the north and Admiralty Inlet to the south for water from the Straits of Juan de Fuca. The partly anomalous results of Station 7 could be due to similar causes.

2. Fluctuations in Current Velocity. It will be apparent from examination of Figures 7 to 16 that there is a fluctuation of velocity superimposed upon the relatively steady change. The period of fluctuation is usually between 15 and 45 minutes and the variation in amplitude of the order of 0.1 knot from the average value. To date no well defined dependence on velocity or depth is apparent. The effect of topography is quite marked. This is especially notable in the data for Tacoma Narrows, Figure 16. Here the narrow channel, high velocities and large bottom irregularities induce violent eddy motions and the average amplitude of oscillations is about twice that for most other stations. At stations not near mid-channel (not shown) the oscillations are much more extreme and the current motion becomes very complex.

The association of irregularities in current with the passing of eddies is at times quite apparent. In the wider and deeper channels, cells of water exhibiting rotary motion in the surface plane can be readily observed to move along with the stream. Pronounced fluctuations of the current meter pen are found to coincide with the passing of the convergences at the edges of these cells. Greater fluctuations occurred in the Tacoma Narrows where occasional cross-channel convergences moved with the stream tending to maintain their identity and configuration. Furthermore these showed little or no evidence of closed rotary motion in the surface plane, suggesting a horizontal axis of motion.! The similarity of the water masses on the two sides of the convergence line indicated that density differences were not the cause of the convergence.

The effect of an eddy upon the velocity registered by the current meter is complex and depends upon the rotational velocity structure within the eddy, the portion of the eddy intersected by the boat's position, and the translational velocity of the water mass. It is therefore possible to say very little with respect to size and velocity of eddies with the data available at present.

Besides these long-period fluctuations, the integrator trace shows a short period fluctuation averaging ±0.05 knots in most places but ±0.2 in mid-channel in Tacoma Narrows (see Figure 17) with a period of about two minutes. There is a smaller fluctuation of still shorter period superimposed, and probably still more rapid and smaller changes which are damped out by the inherent frequency limitations of the measuring system.

It must be noted that data taken under calm conditions have been used for these conclusions. There is unquestionably a fluctuation if swells are present. These can be estimated by watching the records, and in such cases the lower envelope of the fluctuations is used for plotting, which approximately compensates. Under the roughest conditions which the boat can tolerate, swells generate a spurious velocity contribution averaging about 0.2 knots on the Price meters.

3. Velocity Structure Near the Surface. In Figures 14 and 15 data are presented for stations 12 and 14 respectively showing velocities at 2 meters depth based on indicator records, and at 5 meters and deeper as interpreted from concurrent chronograph records. At station 12 on 15 May there was little wind and at station 14 on 29 June winds rose steadily from 10 to 16 knots during the afternoon in the flood direction. The density of the water mass at station 12 increased 0.4 in σ_t in the upmost 5 meters, thence more gradually to give a total change of 1.5 in σ_t from the surface to 50 meters depth. In the second case the density increased rather uniformly, changing 2.0 in σ_t from the surface to 50 meters depth. The 2- and 5- meter curves agree closely in both cases, excepting possibly at low velocities where measurements are less accurate, demonstrating no significant velocity structure over

that depth range. In the rather complicated tidal and topographic situation no definite effect is evident from a wind of 5 hours' duration, blowing at 12-1/2 knots. Such differences as occur in the upper levels could arise from the method of taking average velocities from the chronograph record. The generally good correspondence is evidence for the proper operation and calibration of both chronograph and indicator systems. Since velocity gradients are dependent upon many variables including wind effects, tides and the density stratification of the water, considerably more information obtained over a wide range of conditions is necessary to establish the separate effect of each or to make valid generalizations.

4. *Prediction of Maximum Velocity of Deep Currents.* From the data examined to date, with minor exceptions the only case in which the deep current is faster than the surface current is on flood, and the surface current on flood averages considerably weaker than on ebb. For example, the Current Tables for the month of June show for Admiralty Inlet an average ebb velocity of 2.54 knots and an average flood velocity 1.45, a ratio of 1.74. It may be stated in general that the maximum velocity in the deep layers will not exceed the largest surface ebb velocity for the same day. Using the Current Tables as a guide to estimate the maximum ebb current when it does not appear in the data, it is found that there are no exceptions to this rule in the data.

Usually the maximum deep current will lie intermediate between the maximum ebb and the maximum flood for the same day.

The possibility of unusual topographical conditions which would greatly exaggerate the deep currents cannot be completely excluded. For example, a deeply furrowed bottom which would channel the deep water into a fast moving jet might provide an exception to the rule. However, it is felt that such conditions are unusual and fairly easy to recognize.

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3. Tidal Current Charts, Puget Sound Southern Part, U. S. Government Printing Office, 1948.
4. Roberts Radio Current Meter Operating Manual, Lt. Cmdr. Elliott B. Roberts, USCGS, U. S. Department of Commerce, Coast and Geodetic Survey, Washington, D. C., 1947.
5. S. W. Grinnell, Some Instruments Used By Division 10, NDRC at Dugway Proving Ground for the Continuous Recording of Micro-meteorological Conditions, OSRD 6088 (1945).
6. Unpublished paper presented at Symposium on New Methods of High-speed Oceanographic Research, American Society of Limnology and Oceanography, meeting of June 16, 1949, Vancouver, B. C.

TABLES I - III

and

FIGURES 1 - 3 and 5 - 17

TABLE I
DETAILS OF CURRENT STATIONS

Sta No.	Date	Area *	Av. Anchor Pos. Lat. 47°N + Mins	Av. Anchor Pos. Long. 122° W + Mins	Depth, Meters	Measurements Made **	Wind from, kts	Ekman Meas'ts
1	12/8-9/49	BP	59.5	36.0	99	5PC20, 74PC11	S12-20	22
2	1/11/50	BP	59.8	35.7	110	5PC9, 80PC11	S12-20	14
3	2/8/50	BP	60.4	36.3	100	5PC9, 75PC11	S3-20	11
4	2/9/50	BP	58.9	38.6	64	5PC11, 40PC8	SSW5-13	43
5	3/1/50	BP	59.1	38.4	66	5PC9, 40PC9	S21-3-18	18
6	3/28-29/50	HC	56.0	38.1	95	5PC24, 60PC24	N10-S3-N10	40
7	3/29-30/50	BP	59.0	37.2	101-80	5PC23, 66-55, PC23	calm	26
8	3/30-31/50	BP	59.8	35.4	68	36PC	0 - NNW4	4
9	4/26/50	ST	71.8	48.5	76	5PC5, 50PC5	W12-24	4
10	5/1/50	ST	72.2	47.4	81	5PC6, 52PC6	SE10 - W10	
11	5/2/50	ST	72.4	47.5	71	5PC9, 48PC8	NW6-10	
12	5/15-16/50	ST	70.4	49.3	51	2PI11, 5PC24, 34PC10	SW10, E4, W6	15
13	6/28/50	ST	71.6	50.2	76	2PI3, 5PC7, 48PI3, 48PC7	W12-18	
14	6/29/50	ST	71.9	50.2	73	2PI9, 5PC9, 50PC9	W4-17	
15	7/7/50	SJ	108.0	59.6	160	2PC4, 10PA4, 50PC3	SW12	
16	7/11/50	SJ	94.6	54.4	54	2PA4, 5PC4, 29PC4	SW7	
17	10/9/50	CP	30.6	28.9	100	4PA8, 66RA8	S14-3	
18	10/19-20/50	CP	20.4	33.3	65	5RA15, 44PA15	N4	6
19	11/6, 7, 8/50	TN	13.2	34.9	75	5PA38, 25PA3, 50RA34	S4-N10	
20	11/8/50	TN	13.0	34.7	70	5PA2, 47RA2	N16	
21	11/9/50	TN	13.1	35.2	75	5PA4, 50RA4, 25RA1	N14	
22	11/9-10/50	TN	13.4	34.4	61	5PA16, 40RA16	N10-3-10	

* BP, Bush Point; HC, Hood Canal; ST, Straits at North end of Admiralty Inlet; CP, Colvos Passage; TN, Tacoma Narrows; SJ, San Juan Islands.

** Symbol indicates depth in meters, type meter (P, Price; R, Roberts), type recorder (C, chronograph; I, integrator; A, integrator-amplifier), and number of hours data with each meter.

TABLE II

RELATION BETWEEN SHALLOW AND DEEP CURRENTS

Station Number	Date	Shallow or Deep	Flood or Ebb	Time Interval	θ_1 and θ_2 x $1/\pi$	K	Miles of Water Passing	Avg. Peak Velocity Knots	Shallow - Deep Knots
2	1/11/50	S	E	1400 - 1820	0.5 - 1.0	1.57	7.06	2.56	
		D		4.33 hrs.			1.40	0.51	2.05
		S	F	1820 - 2017	0 - 0.45	1.40	0.82	0.59	
		D		1.95 hrs.			1.40	1.01	-0.42
3	2/8/50	S	E	1130 - 1530	0.38 - 0.88	1.25	11.36	3.55	
		D		4.0 hrs.			5.55	1.74	1.81
		S	F	1750 - 2020	0.27 - 0.72	1.07	2.72	1.16	
		D		2.5 hrs.			4.48	1.92	-0.76
4	2/9/50	S	E	1030 - 1735	0.16 - 1.0	1.42	8.28	1.66	
		D		7.1 hrs.			4.80	0.96	0.70
		S	F	1735 - 1845	0 - 0.2	3.28	0.13	0.36	
		D		1.17 hrs.			0.48	1.35	-0.99
5	3/1/50	S	F	1530 - 2200	0.24 - 1.0	1.41	8.32	1.80	
		D		6.5 hrs.			4.64	1.01	0.79
		S	F	2200 - 2330	0 - 0.24	2.4	0.95	1.5	
		D		1.5 hrs.			1.77	2.8	-1.3
7	3/29-30/50	S	F	2055 - 0335	0 - 1	1.57	7.62	1.79	0.60
		D		6.67 hrs.			5.06	1.19	

TABLE II (Continued)

RELATION BETWEEN SHALLOW AND DEEP CURRENTS

Station Number	Date	Shallow or Deep	Flood or Ebb	Time Interval	θ_1 and θ_2 x $1/\pi$	K	Miles of Water Passing	Avg. Peak Velocity Knots	Shallow - Deep Knots
7	(continued)	S	E	0430 - 1100	0.2 - 1.0	1.39	6.59	1.41	
		D		6.5 hrs.			3.69	0.79	0.62
		S	F	1100 - 1220	0 - 0.36	1.95	0.54	0.79	
		D		1.33 hrs.			0.54	0.79	0
		S	E	1430 - 1900	0.1 - 0.69	1.23	7.17	1.96	
		D		4.5 hrs.			4.84	1.32	0.64
10	5/1/50	S	F	1430 - 1735	0.19 - 1.0	1.39	4.27	1.91	
		D		3.1 hrs.			3.80	1.70	0.21
		S	E	1735 - 2040	0 - 0.56	1.47	3.30	1.57	
		D		3.1 hrs.			3.59	1.70	-0.13
11	5/2/50	S	F	1245 - 1830	0.18 - 0.93	1.25	10.93	2.38	
		D		5.8 hrs.			12.33	2.68	-0.50
		S	E	1905 - 2200	0 - 0.7	1.39	3.91	1.88	
		D		2.9 hrs.			4.30	2.06	-0.18
12	5/15-16/50	S	E	1735 - 2230	0 - 1.0	1.57	5.81	1.86	
		D		4.9 hrs.			4.16	1.33	0.53
		S	F	2230 - 0230	0 - 0.8	1.39	3.01	1.05	
		D		4.0 hrs.			3.44	1.20	-0.15

TABLE II (Continued)

RELATION BETWEEN SHALLOW AND DEEP CURRENTS

Station Number	Date	Shallow or Deep	Flood or Ebb	Time Interval	θ_1 and θ_2 x $1/\pi$	K	Miles of Water Passing	Avg. Peak Velocity Knots	Shallow - Deep Knots
14	6/29/50	S	E	0930 - 1200	0.75 - 1.0	2.6	3.80	3.80	
		D		2.5 hrs.			2.40	2.40	1.40
		S	F	1200 - 1730	0 - 1.0	1.57	7.20	2.06	
		D		5.5 hrs.			10.57	3.02	-0.96
19	11/6-7/50	S	F	2242 - 0250	0.1 - 0.9	1.32	6.80	2.18	
		D		4.13 hrs.			7.34	2.35	-0.17
		S	E	0350 - 0820	0.1 - 0.8	1.25	5.48	1.52	
		D		4.5 hrs.			4.05	1.12	0.40
		S	F	1130 - 1500	0.5 - 1.0	1.57	6.66	2.98	
		D		3.5 hrs.			7.52	3.37	-0.39

TABLE III

Velocity Differences Compensated For Tidal Range

Station Number	Flood or Ebb	S-D Knots	Seattle Tide Range - feet	S-D ÷ Range = ∅	∅ Ebb ÷ ∅ Flood
2	E	2.05	10.8	0.19	
	F	-0.42	6.8	-0.16	-1.2
3	E	1.81	11.2	0.16	
	F	-0.76	8.0	-0.095	-1.7
4	E	0.70	11.6	0.060	
	F	-0.99	9.0	-0.11	-0.5
5	E	0.79	10.1	0.078	
	F	-1.3	12.4	-0.10	-0.8
7	F	0.60	10.9	0.055	
	E	0.62	5.6	0.11	2.0
	F	0	3.2	0	
	E	0.64	8.5	0.075	
10	F	0.21	12.8	0.016	
	E	-0.13	6.5	-0.02	-1.2
11	F	-0.50	14.6	-0.034	
	E	-0.18	6.2	-0.034	1.0
12	E	0.53	4.3	0.12	
	F	-0.15	3.9	-0.038	-3.2
14	E	1.40	15.2	0.092	
	F	-0.96	16.2	-0.059	-1.6
19	F	-0.17	7.1	-0.024	
	E	0.40	5.4	0.074	-3.1
	F	-0.39	7.8	-0.050	-1.5
					-1.7

FIGURE I
CURRENT STATIONS OCCUPIED
IN PUGET SOUND
BASE CHART — USC AND GS
NO. 6400

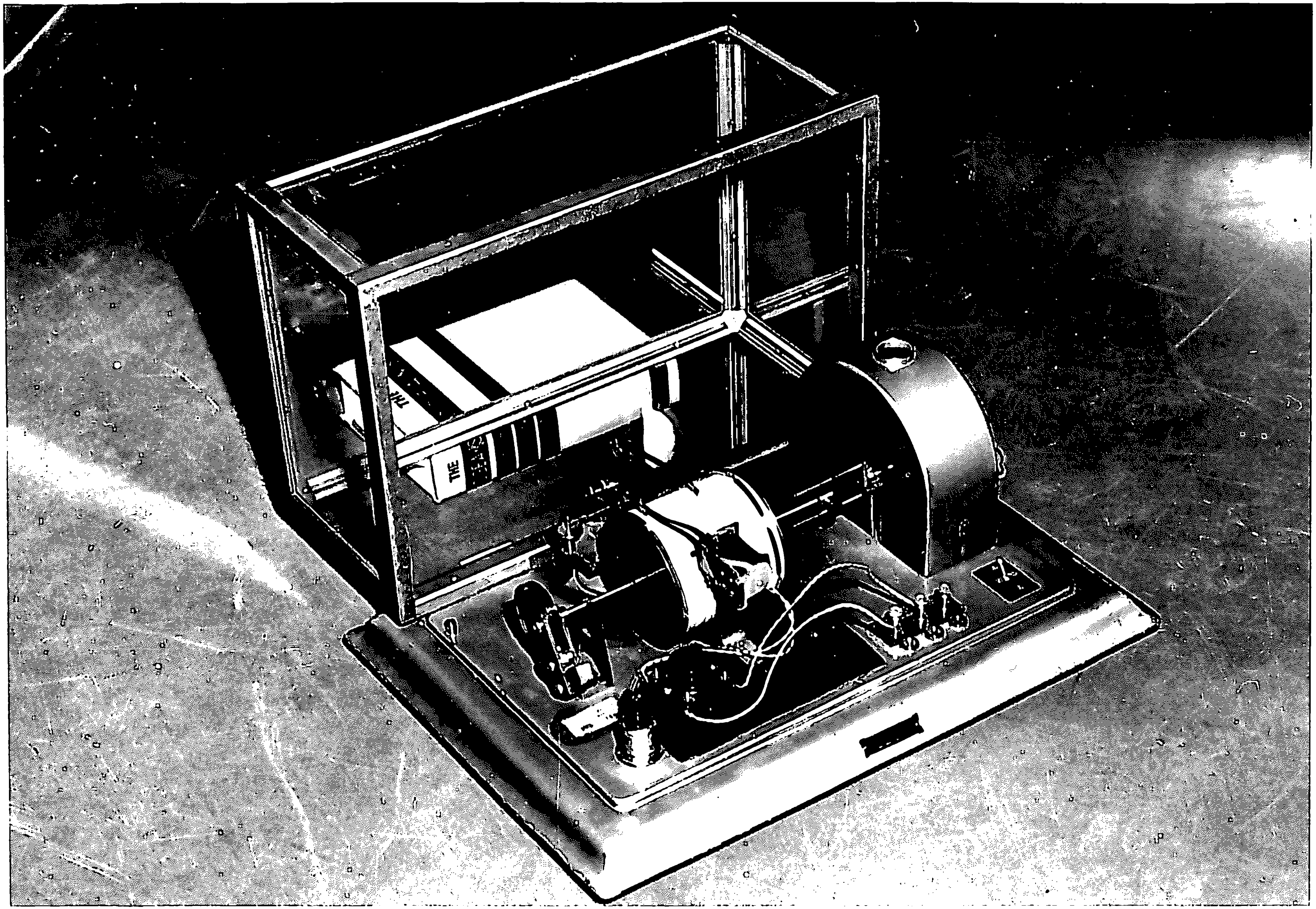


FIGURE 2. Chronograph Used With Current Meters

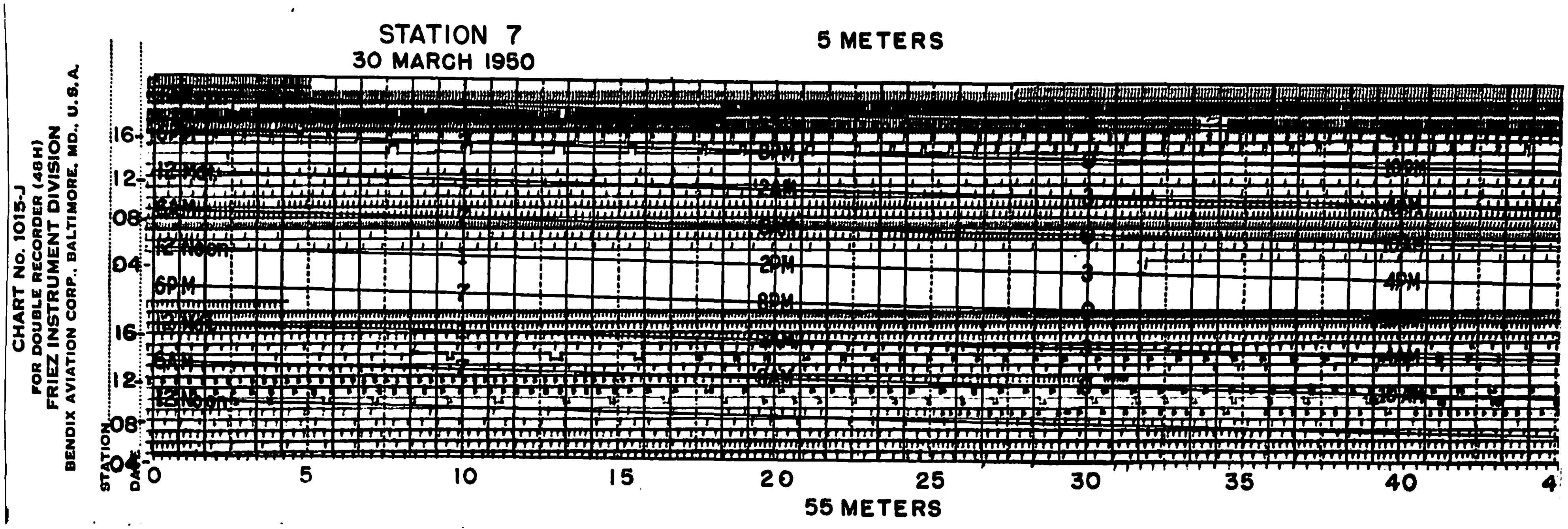
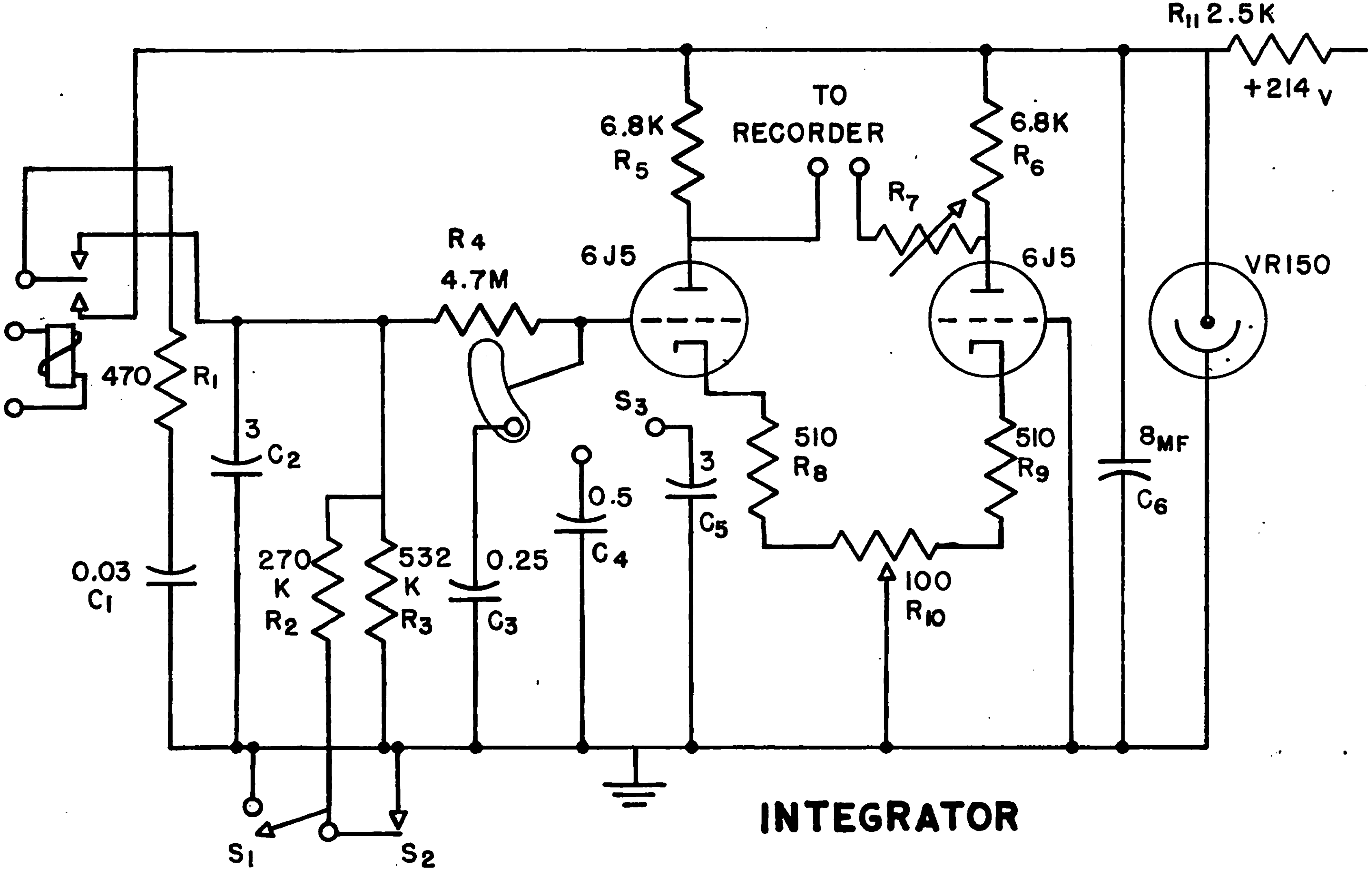


FIGURE 3. Section of Chronograph Record for Station 7. Hours are marked on the left.



INTEGRATOR

FIGURE 5

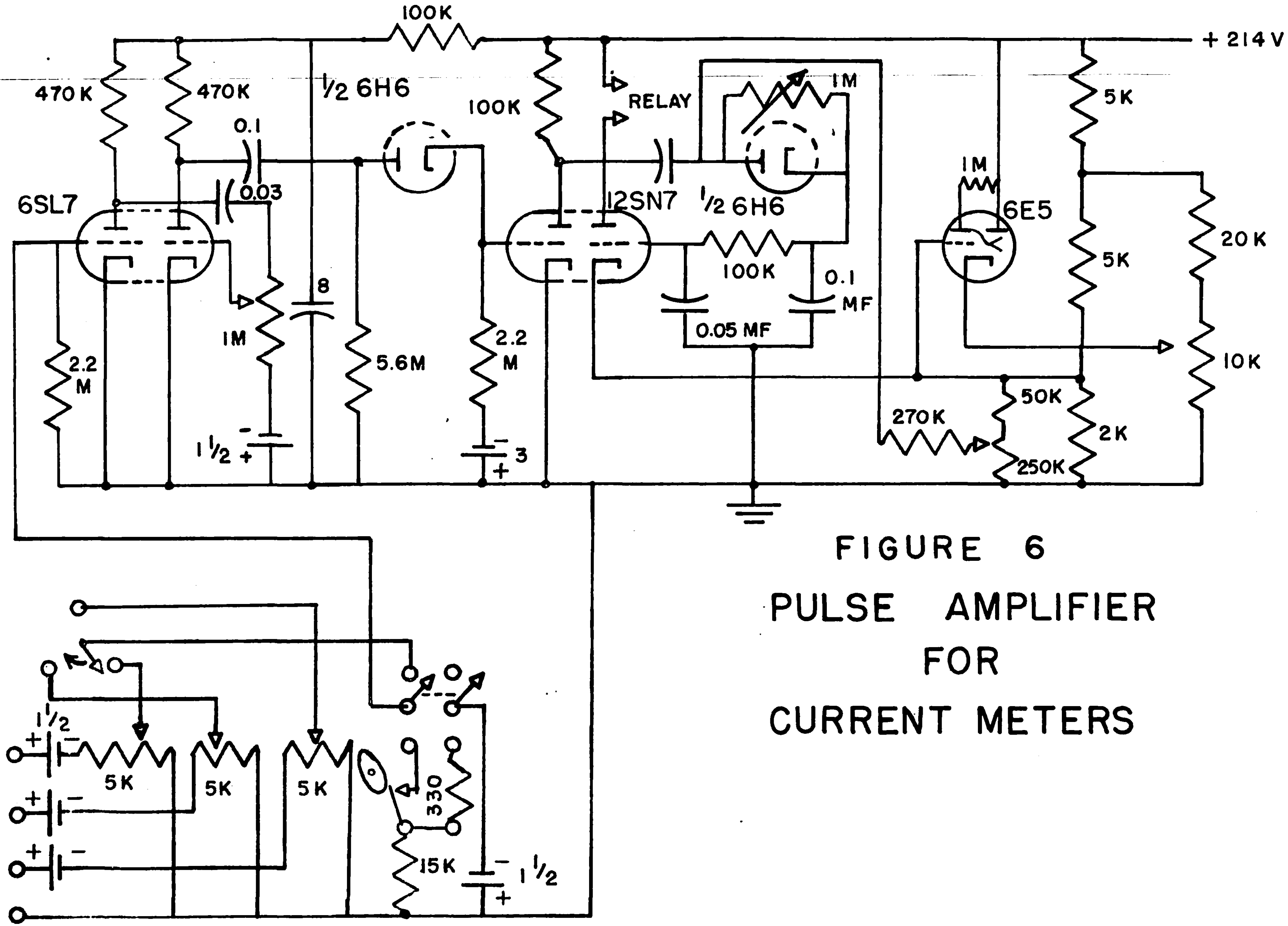


FIGURE 6

PULSE AMPLIFIER FOR CURRENT METERS

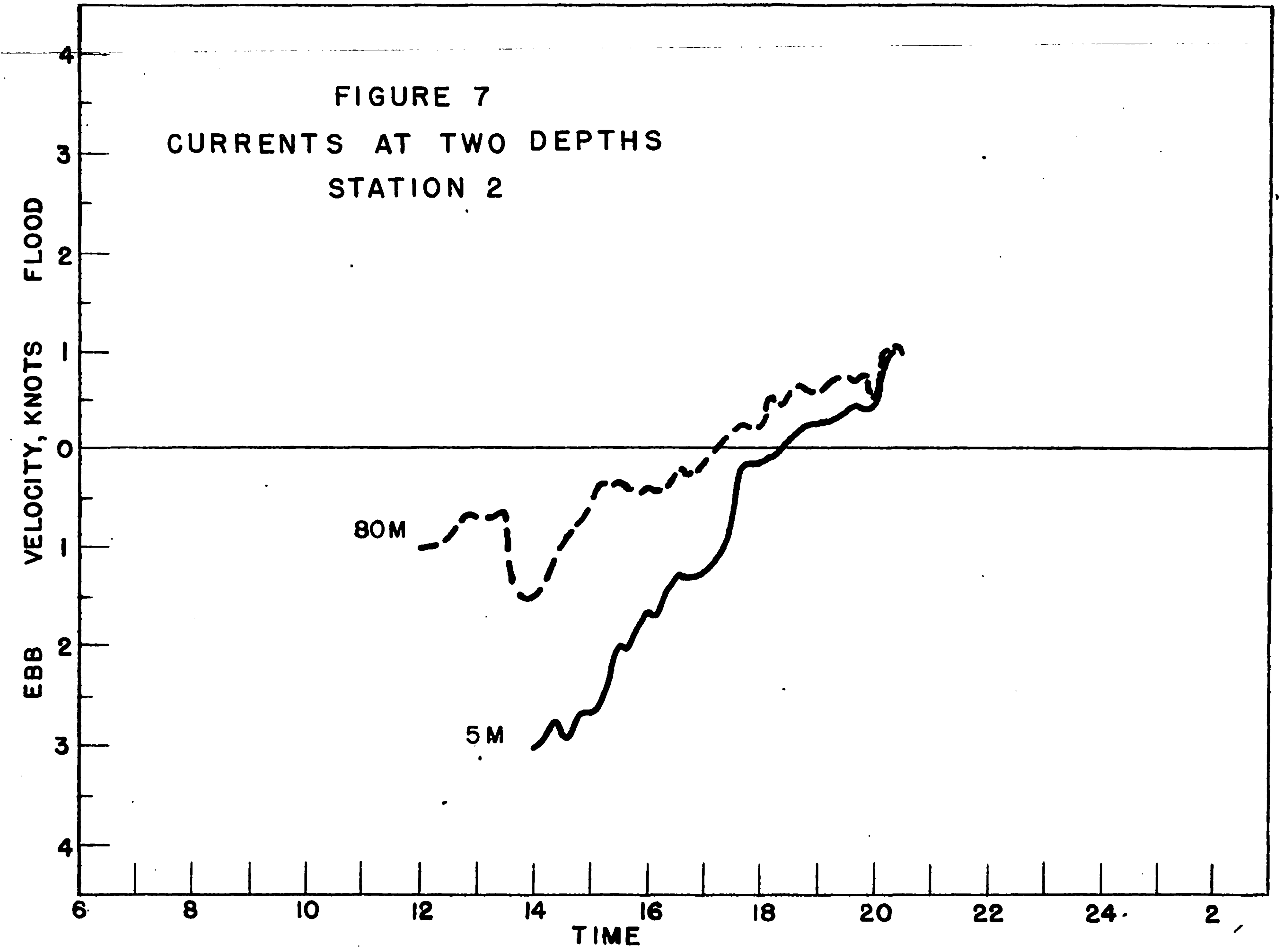


FIGURE 7
CURRENTS AT TWO DEPTHS
STATION 2

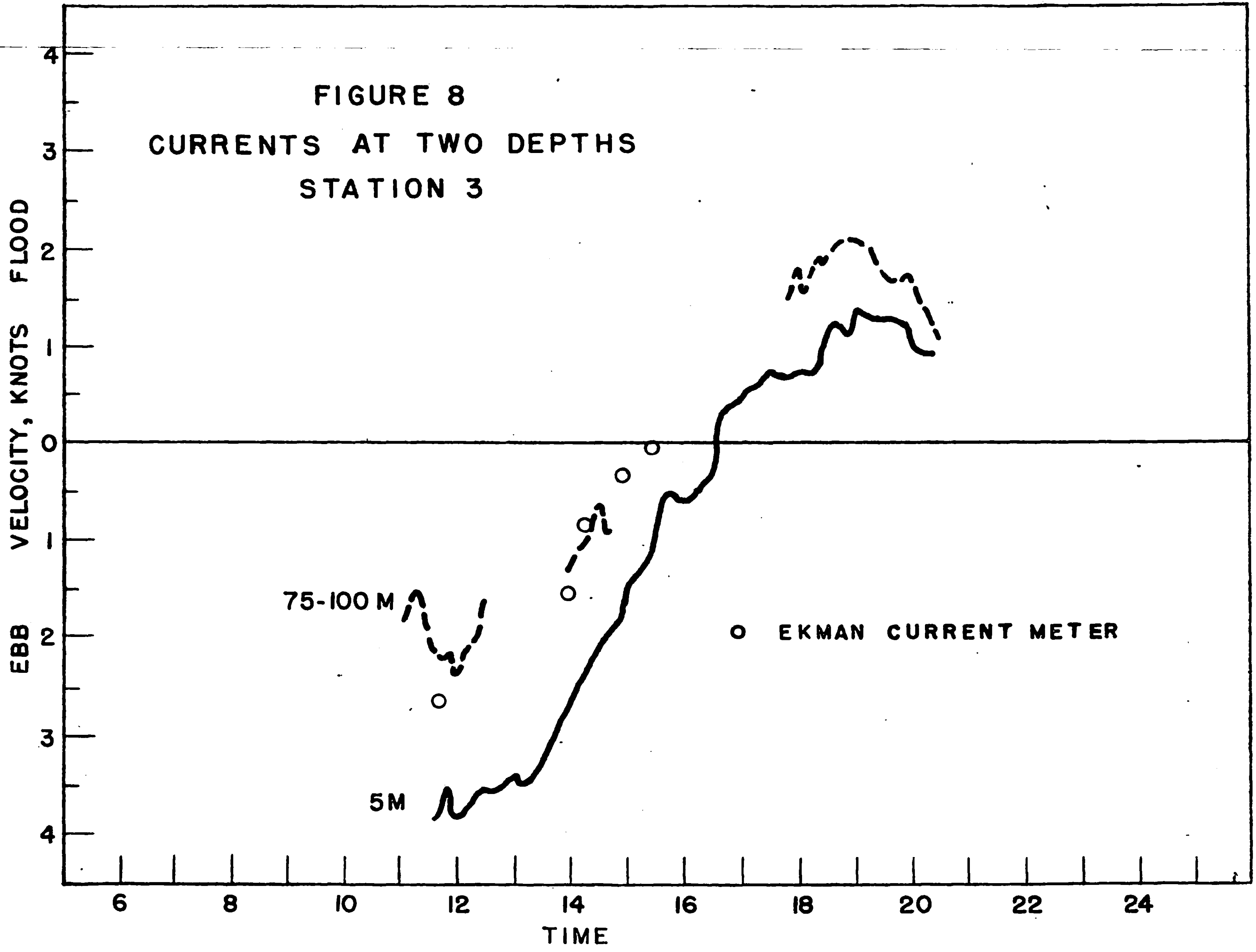


FIGURE 8
CURRENTS AT TWO DEPTHS
STATION 3

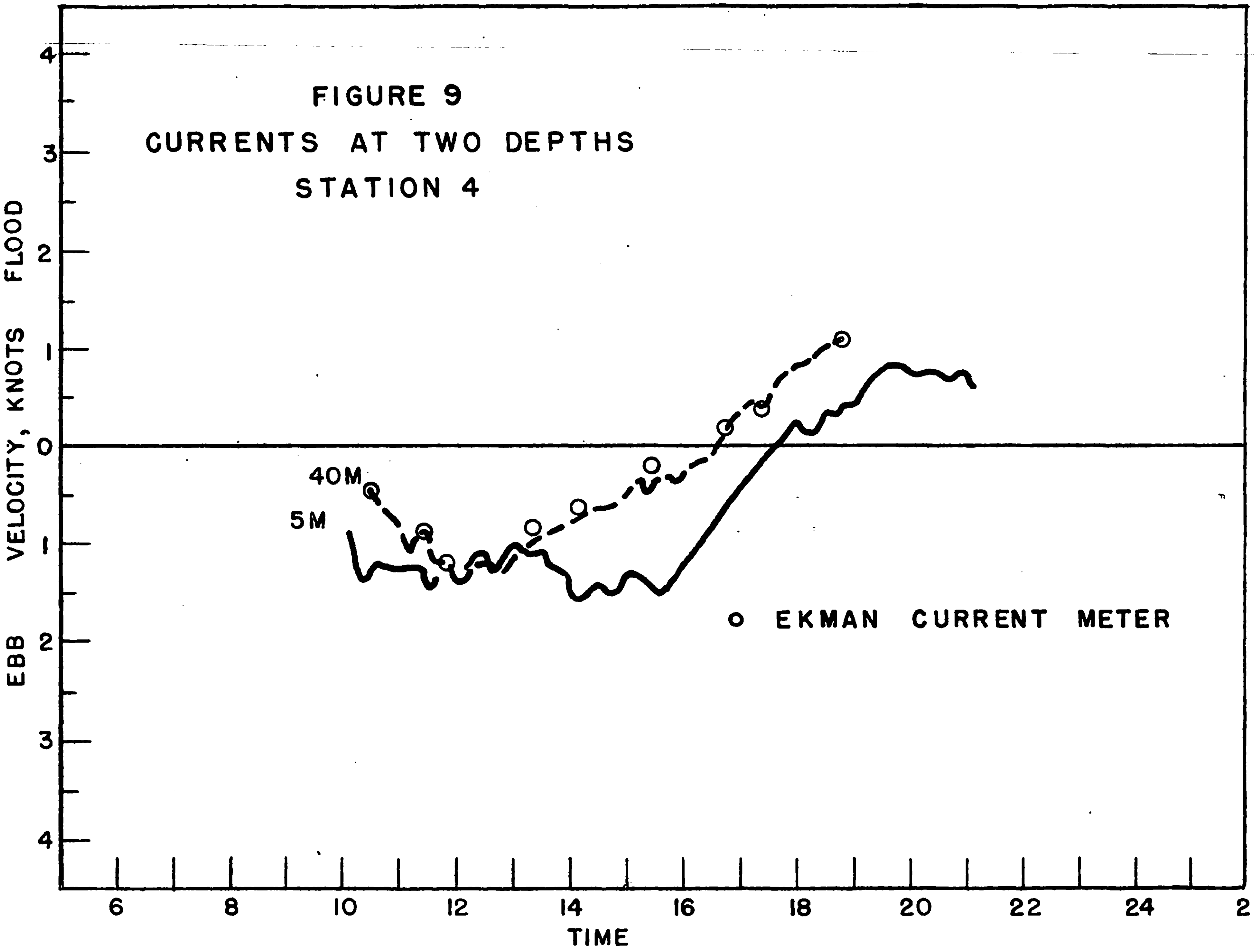


FIGURE 9
CURRENTS AT TWO DEPTHS
STATION 4

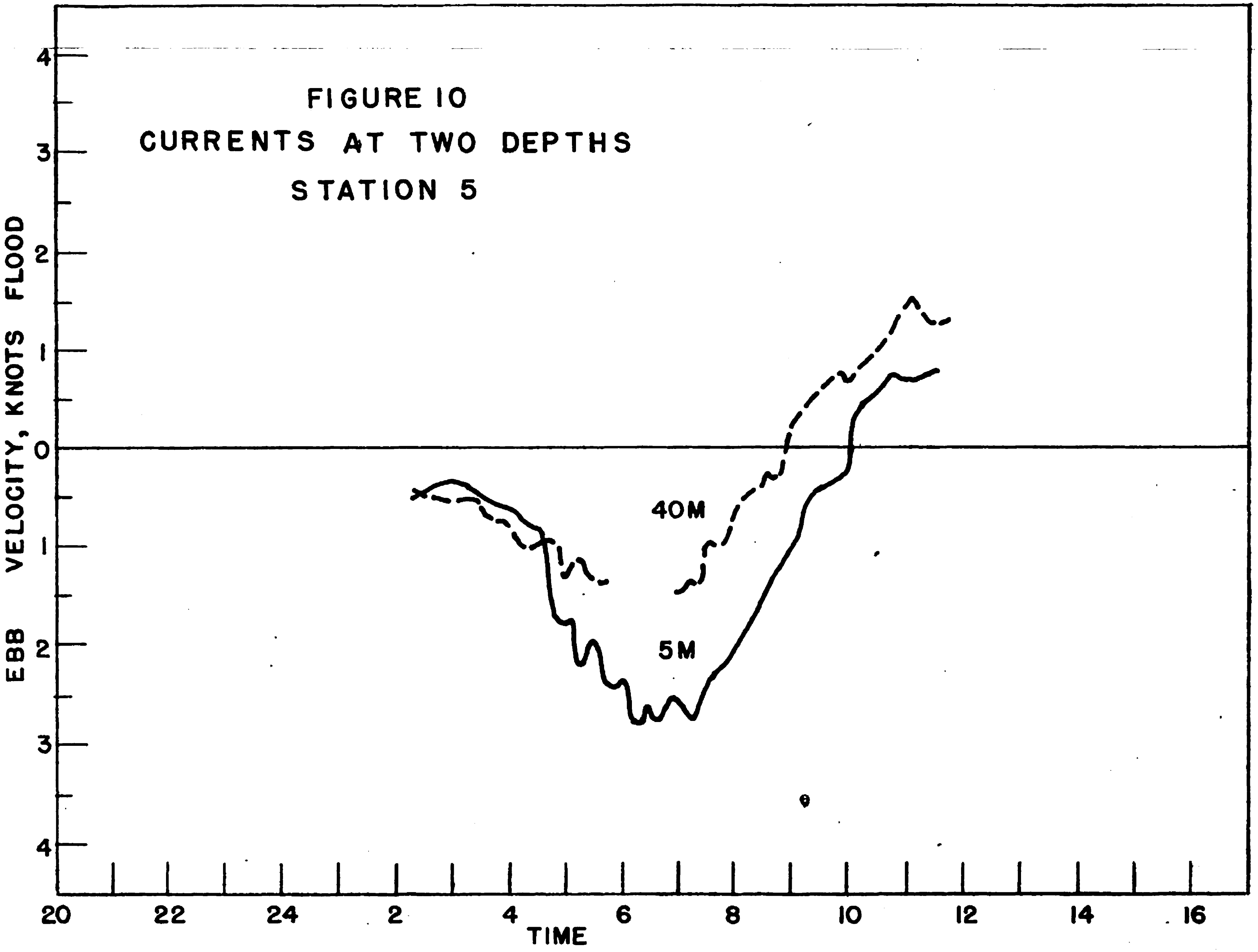


FIGURE 10
CURRENTS AT TWO DEPTHS
STATION 5

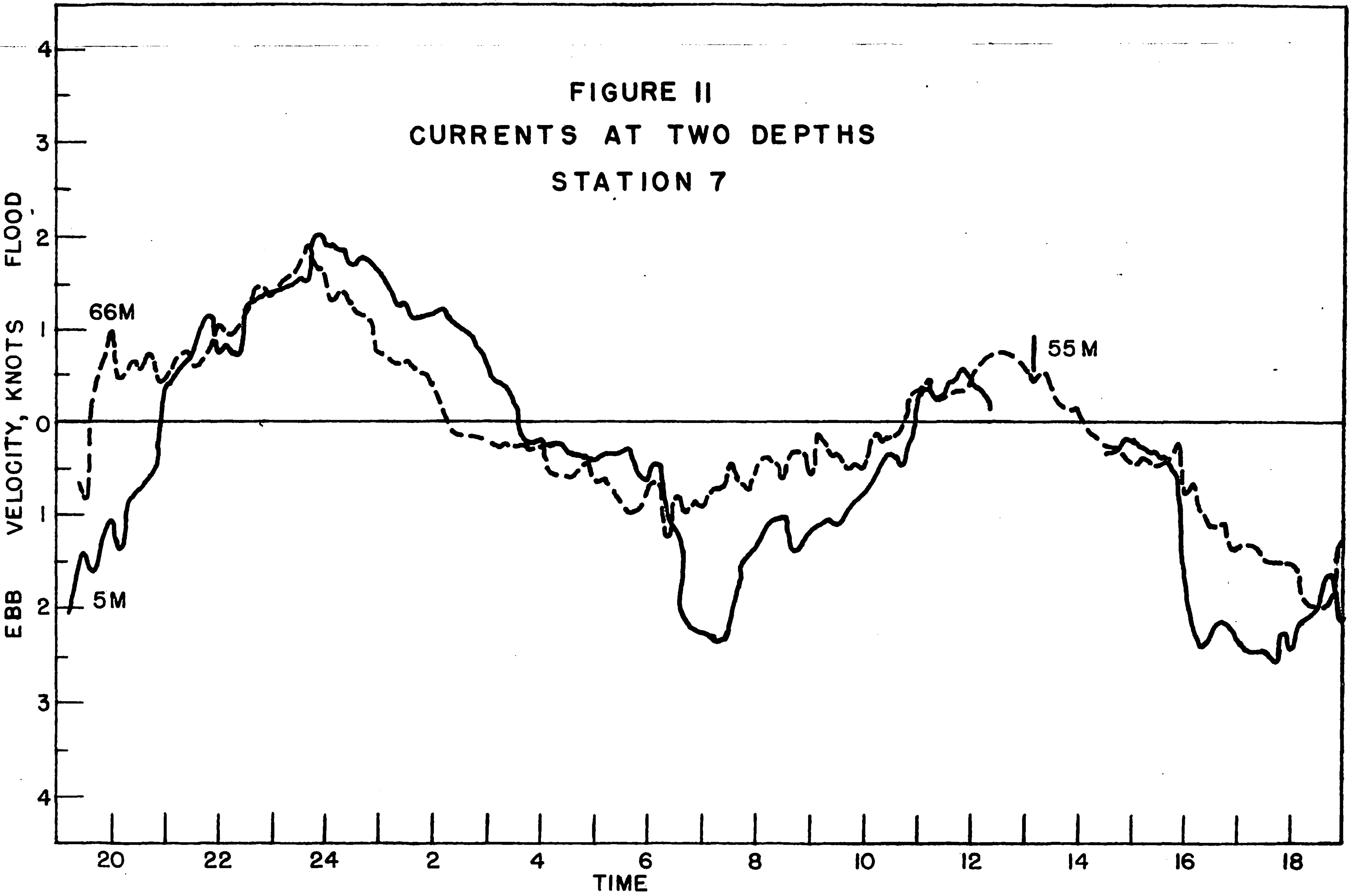


FIGURE 11
CURRENTS AT TWO DEPTHS
STATION 7

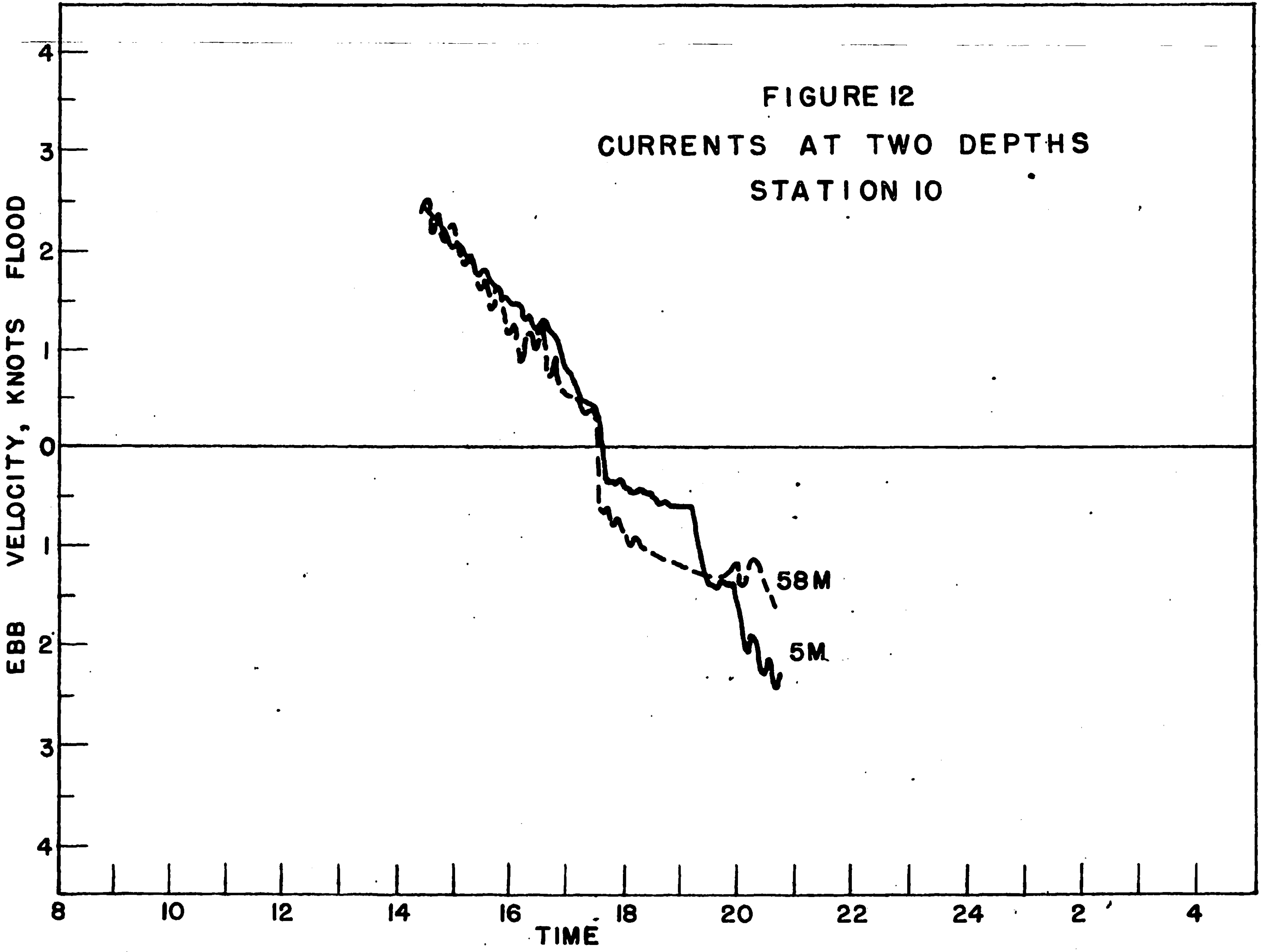


FIGURE 12
CURRENTS AT TWO DEPTHS
STATION 10

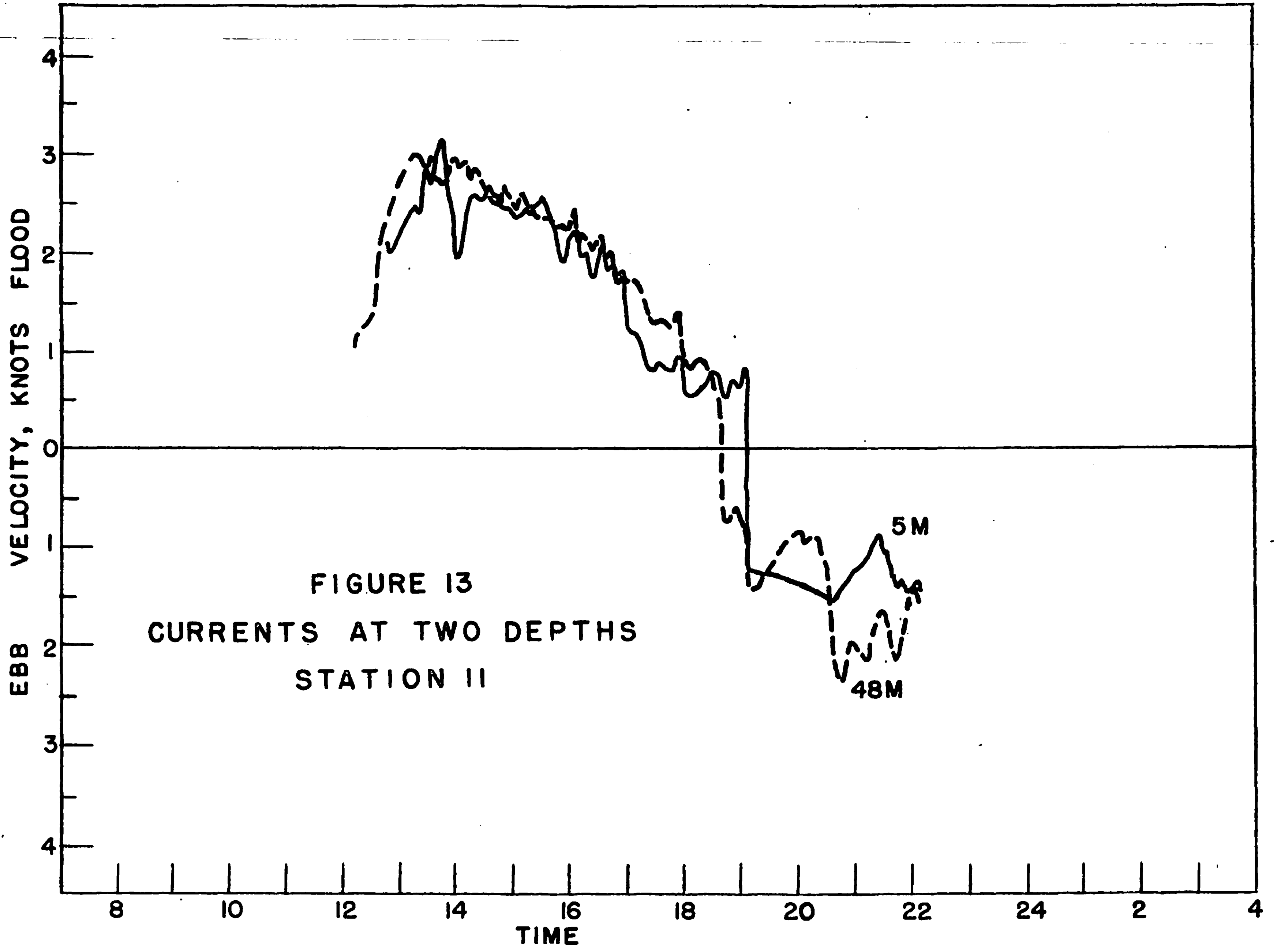


FIGURE 13
CURRENTS AT TWO DEPTHS
STATION 11

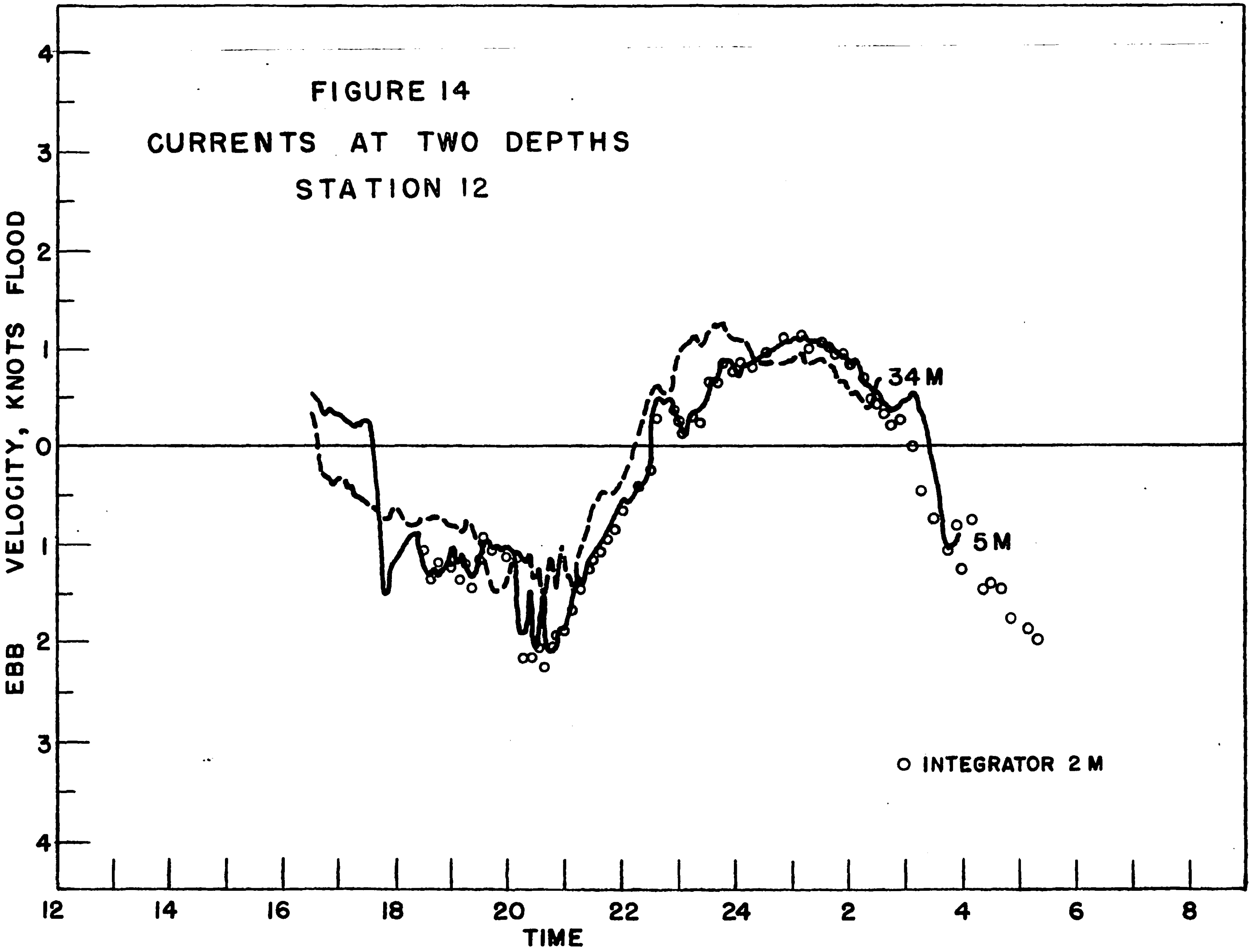


FIGURE 14
CURRENTS AT TWO DEPTHS
STATION 12

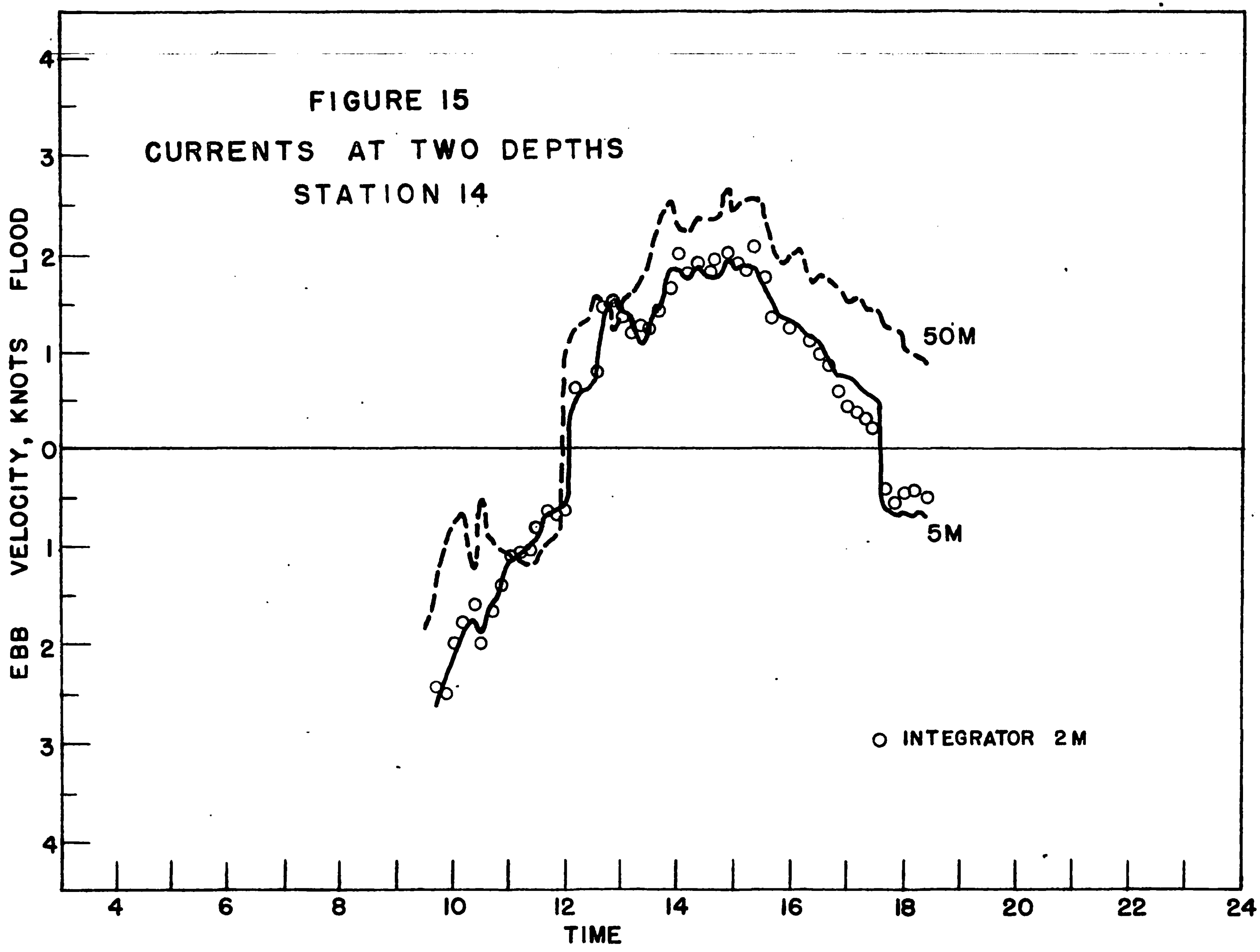


FIGURE 15

CURRENTS AT TWO DEPTHS

STATION 14

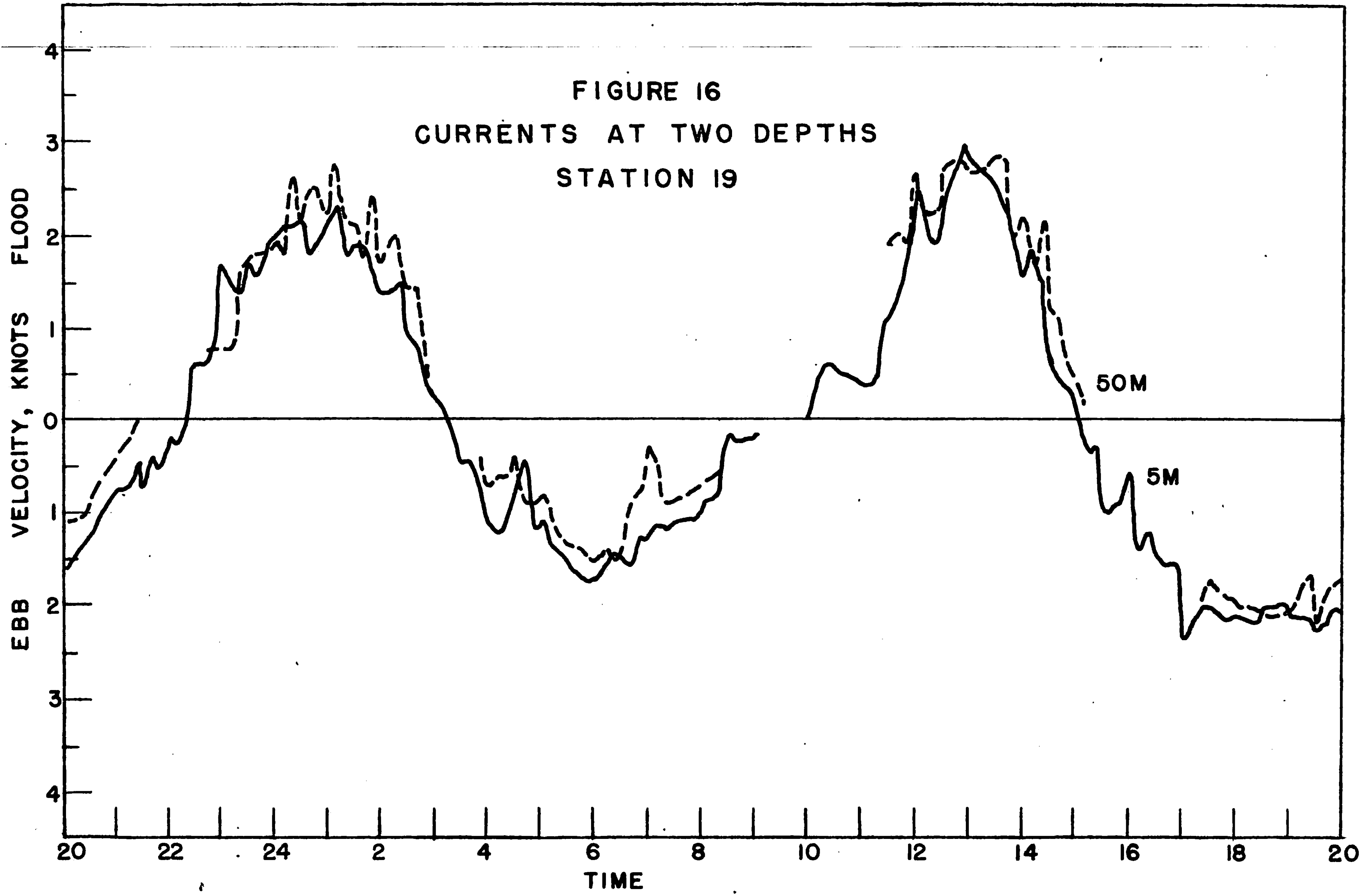


FIGURE 16
CURRENTS AT TWO DEPTHS
STATION 19

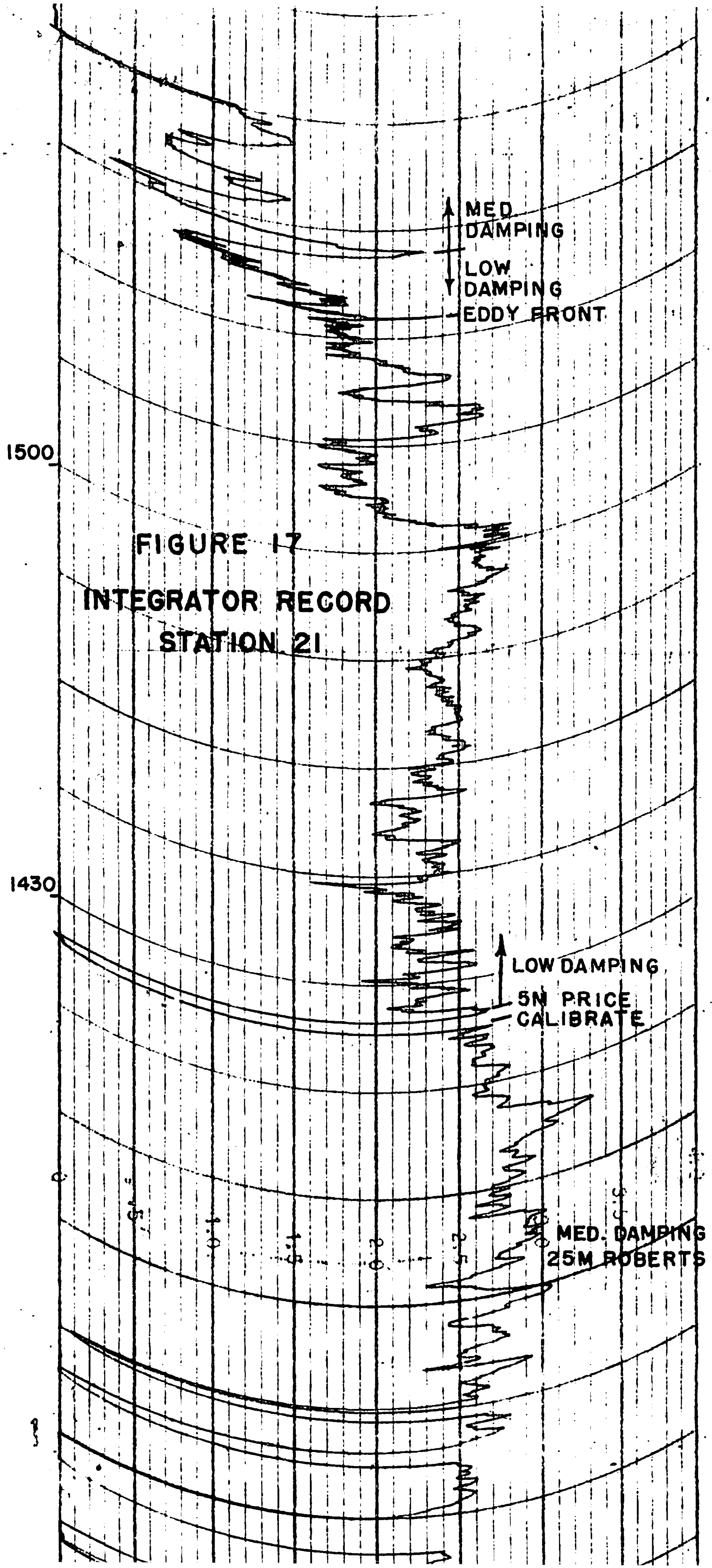


FIGURE 17

INTEGRATOR RECORD

STATION 21

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