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ELECTROMAGNETIC FLOW SENSORS

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ABSTRACT

Flow sensors based on the principle of electromagnetic induction were investigated as alternatives to commonly used mechanical devices utilizing rotors and propellers. Prototype sensors were constructed showing considerable promise. Measurement accuracy in excess of .01 knot seems feasible with devices suited to long term battery operation. The inertial effects and many of the reliability problems inherent in moving part devices would be overcome by use of an electromagnetic sensor.

Table of Contents

LIST OF FIGURES

ELECTROMAGNETIC FLOW SENSORS

Introduction

Ocean currents have been routinely measured by differences in potential caused by the electrically conductive seawater moving through the vertical component of the Earth's magnetic field (von Arx). Blood flow in animals is also determined by electromagnetic induction. In this case the magnetic field is produced by a coil placed next to the blood vessel. But this latter method of using a locally generated field has found only occasional use in oceanography. The continually disappointing performance of mechanical current meters has motivated us to take a new look at the possibilities of electromagnetic flow sensors. We will describe first the theory involved in the design of such a sensor. Then we will show what results one can get in an actual device. Finally we will discuss potential uses (such as current meters) to which this kind of flow sensor can be applied.

Theory

The flow sensor (Fig. 1) contains a coil to produce a magnetic field. A set of electrodes measures the voltage gradient across the face of the coil which is induced in the water when it flows through the field. The principle of induction states that the voltage field induced is the vector product of the velocity and the magnetic field ($E = V \times H$). The magnetic field produced by a coil depends on the current and the number of turns (ampere turns). Because of the I^2R relation with power and the NI determination of the field, magnetic field varies with the square of the power. Thus, if the sensitivity is to be increased 10 fold the coil power must go up 100 times. Coils of 10 cm diameter and 1 cm^2 cross section are convenient. They require about 250 grams of copper. With a d.c. powered 100 mw coil, the resulting field reacts with a flow of 1 knot to produce a potential difference of 10-15 microvolts at the electrodes. A flow sensor for .01 knot would require measurement of electrode potentials of about .1 microvolt.

Because of chemical uncertainty at the electrode surface it is impossible to get 2 electrodes to remain within a few microvolts of potential difference. They can easily have a static offset 1000 times this large. If, however, the magnetic field is periodically reversed, the polarity of the electrode potential due to water flow will change, while the static offset remains constant. The electrode voltages can be detected in synchrony with the field reversals. The magnitude of the change is a function of the velocity of the flow. Electrode errors caused by electrochemical effects and input amplifier d.c. offset and drift do not matter. It is necessary only that these offsets do not change during the field cycle. Further, measuring the change in electrode potential can utilize a.c. amplifiers. Large gains are possible without risk of saturation, because d.c. effects are excluded. This detection technique is critical to the operation of an e.m. flow sensor.

Although field reversal overcomes many problems, it introduces some new ones. When the voltage applied to the coil is reversed, the resulting magnetic field builds up with the increasing electrical current. Because this current follows the relationship $i = I_{final}(1-E^{-t})$ it never reaches a stable value. After 10 time constants $(t = 10)$, however, the current is within .01% of final value. Each time the field is reversed, the measurement of the electrode voltage is therefore delayed until the field is essentially stable.

In a perfectly symmetrical coil, voltages induced by this changing field would be nulled. In real coils, some imbalance is inevtiable. An error voltage, indistinguishable from water flow, always exists as the product of residual field change and asymmetry. With good design this error can be kept below .01 knots. It tends to be constant and may therefore be balanced out along with other offsets in the d.c. amplifier. Operation at low frequencies minimizes these effects.

Electrical noise, which tends to mask the signal, is contributed by the input amplifier, the chemical uncertainties at the electrode surface, and the resistance of the water path. The first of these is by far the most important. Noise increases disproportionately at low frequencies. Since a full cycle of field reversal is needed for determination of water velocity, measurement of rapid changes may require a faster switching rate than asymmetry considerations might dictate.

Electromagnetic sensor

The flow sensor contains a coil of wire and a set of electrodes. The coil was wound on a bobbin made up from Lucite tubing and flat stock. In the prototype the contents of a 1/2 pound spool of copper wire (Beldon #8055 no. 30) were used. This gave a winding length of about 490 m and a resistance of 162 ohms. Average turn length was 36 cm so that the coil contained approximately 1370 turns. After winding, the coil was vacuum impregnated with epoxy resin (Hysol #R9-2039 resin, #H2-3561 hardener). The bobbin was then machined to a diameter of 14 cm and the outside edges rounded.

The bottom of the sensor (electrode surface) is a flat disc of Lucite.

Recesses for the electrodes were machined in this disc to a depth of 3 mm. Small holes (drill #57) were angled from the recesses into the center well of the bobbin. The electrodes were small (6 mm x 20 mm) rectangular pieces of Ag/AgCl mesh. A single strand of wire was isolated from the mesh and led through the hole to the bobbin center well. The electrode recesses were stuffed with glass wool. This buffers the electrode from rapid changes in water chemistry and attendant effects on static offset. The glass wool was retained by cover plates of fiberglass-epoxy laminate. Three holes of 1 mm diameter were drilled in each cover to serve as the electrical contact points for the sensor. A center reference electrode was similarly constructed. The cables were run straight down to the disc, with the electrode wire laid out on a diameter, and the cable shield connected to the center reference electrode. The coil leads were twisted as they lead out from the coil, assuring cancellation of stray magnetic field effects. The center well was then cast with epoxy resin, thus insuring heavy insulation of the electrical terminations.

The electronics used with the prototype sensor provide a ± 6 volt drive to the field coil. This results in a ± .037 ampere field current for a magnetizing force of 50 ampere-turns. The integration of the field over the seawater length for this sensor results in a voltage at the electrodes calculated to be 36 microvolts per meter per second, or about 18 microvolts per knot. Coil power consumption in the prototype was .22 watt ($I^2R = .037^2 \times 162$).

Electronics

The electronics provides a reversing field, an electrode amplifier capable of responding to sub-microvolt signals, and a detector which demodulates the signals to produce a voltage level which is a function of flow velocity only. These will be described in turn. A functional block diagram is shown in Fig. 2. Fig. 3 is the schematic diagram for the complete prototype electronics.

Field drive

Coil geometry determines the time required to produce an arbitrarily unchanging field. We take 7 time constants to be minimum for a device capable of cm/sec accuracy. A coil 10 cm in diameter exhibits a time constant of about 1.3 ms so that a stabilization period of 10 ms is indicated. Since this is 1/4 of a complete field cycle, maximum frequency will be 25 Hz. Because fast response was not an important factor, we operated this device at 10 Hz. This provided even more freedom from changing field effects. The field coil is driven by a DPDT switch arrangement made up of transistors Q1-4. An ocillator at 40 Hz followed by two binary dividers activates the switch. The field current is the 'field supply voltage' divided by the resistance of the coil, in this case, 6 volts and 162 ohms, respectively, for a coil current of 0.037 ampere. For a given coil geometry, the field intensity is proportional to field current. Collector saturation voltage of the transistors and temperature effects on coil resistance affect coil current and scale factor of the device to a small extent, and will be discussed further on. The operation of the binary dividers and the NOR gates (G_1 and G_2) provide switching signals synchronized to the field drive which are used to control the rectifier.

Electrode Amplifier

The input resistance of the 'follower-with-gain' configuration used is 10^7 ohms or more. This is so large compared to the nominal 50 ohm resistance of the electrodes that salinity effects and aging produce negligible change in sensitivity. Use of feedback with operational amplifiers assures large, stable, and predictable gain. The circuit shown has a voltage gain of 20,000, sufficient to raise the level of the voltage at the electrodes to the millivolt range. Were the gain much lower, drift in the d.c. amplifier following detection would be troublesome. The electrode amplifier gain is divided between the input cross-coupled pair A1 and A2 and the difference amplifier A3. This arrangement provides very large rejection of any but differential signals from the electrodes. The gain for this difference is

$$\frac{R1 + R2 + R3}{R1} \times \frac{R10}{R8}$$

A4 compares the voltage at the output of A3 with 0 volts. Any difference causes a current to flow which is time-integrated at A4's output. This voltage is used to null and d.c. offsets produced by the electrodes or A1 and A2. With the components shown, offsets up to ± 12 mv can be accommodated. In effect this circuit is an a.c. amplifier with a -3 db frequency of .4 Hz.

The input amplifier used (Fairchild #ua739) has a noise level of 10^{-8} volt per Hz bandwidth at 10 Hz. However, the power consumption of this unit is fairly high at about 50 mw. Amplifiers having lower power consumption generate larger input noise voltages. For example, the Fairchild ua 776 operating at 10 ua quiescent produces 1.7×10^{-7} volts/Hz noise. These noise levels are equivalent to approximately 5×10^{-4} and 10^{-2} knots respectively. The input circuitry uses the operational amplifiers to best advantage in that the series resistance from the sense electrodes is zero and amplifier gain is high.

Detector

The detector uses a cmos bilateral transmission gate (S_1) in a manner analogous to a DPDT center-off switch. The logic signals which control the operation of the switch are obtained from the gated outputs of the binary divider. After each field reversal, the switch is open so that changing field effects are blocked. During positive field half cycles, the switch connects the output of A3 (amplified electrode voltage) to the differential d.c. amplifier made up of A5 and associated components. During negative field half-cycles, the polarity of this connection is reversed. The result of this process is that any signals that are not synchronous with the field drive will produce an output averaging zero.

The ratio of R15 to R13 determines the d.c. gain of the device. Since R13 must be large compared to the series resistance of the transmission gate, and because of bias current requirements in A5, the gain of this stage should be small. R18 and R17 allow connection of a potentiometer for zeroing the d.c. amplifier offset voltage.

Waveforms

The behavior of some circuit voltage and current levels through time gives important clues to the operation of the device. The relevant waveforms are shown in Fig. 4 and described below. All have the same time scale.

No. 1. Field drive voltage. The field voltage alternates between +field supply and -field supply, in this case, 6 volts.

No. 2. Coil current and magnetic field. These have the same shapes. When the field drive voltage changes, coil current begins to change exponentially.

No. 3. Detector control. The multiplying effect of the detector is shown here. While the field is changing, signal does not pass. During the stable portions of the field cycle the detector alternately multiplies the signal by +1 and -1.

No. 4. Detector output with 'd.c.' input. Small voltage offsets may exist at the detector input. This waveform demonstrates the way these errors are eliminated. The d.c. offset is first transferred directly (x1). During the second measuring period, the offset is inverted (x -1). When the result is averaged, the output is zero. Any signal which is not in synchrony with the field is treated in this manner, including noise. The effect of a -offset is shown.

No. 5. Electrode potential with +flow. The difference voltage with time, at the electrodes. The output of A3 is a larger replica of this signal.

No. 6. Rectifier output in response to amplified electrode voltage. The average value is a finite positive d.c. level. If the flow were negative, the signal at A3 would be low first, high second, and the detector output would be negative.

Discussion

In considering the change to an e.m. sensor it is important to see clearly what advantages it has over present mechanical systems. These latter are finally starting to give data after 15 years of effort. In fairness, one must note that roughly the first 8 years were spent finding out how to put an instrument in the ocean and get it back. During that bleak period many of us spent long weeks scanning the horizon for the orange floats that weren't there. Only in the past few years have returns been frequent enough to focus on the operation of the instrument itself. And only in the past year has it been realized how complex the motions on a surface buoyed mooring are. It is now apparent that these motions can lead to several-fold overestimates of the energy in shorter time periods (Mode 0). Having come this far and expended this much time and money on the Savonious rotor, one must have convincing arguments for change. We find that the e.m. sensor offers many advantages and some disadvantages.

1. It has a large linear dynamic range and keeps a constant calibration. Flows over a range of at least 1000 fold can be measured.

2. The sensor is simple and rugged. The electronics required are straightforward and relatively simple; this should help reliability.

3. Almost any flow sensitivity can be had by averaging the signal over a longer time. This follows because the noise is random and centered on zero. We demonstrated the device in a tub with the output connected to a pen recorder such that full scale represented 0.03 knot. If the electrical time constant of the amplifier output is 30 seconds the noise band is about 0.0005 knots. With no flow, the recorder will draw a trace within such limits for many days. No zero drift over this time was detected.

4. The power requirements are reasonable for long term battery operation since one can trade time for sensitivity. Where power is not an important consideration, we see no limitation in increasing electrical current for greater sensitivity, although the heat generated in the coil will eventually cause convection currents.

5. An electromagnetic flow sensor has no moving parts, so it will not have undesirable inertial properties. Bearing problems do not exist so that mechanical limitations for both high and low speed flows are

removed.

6. The electrical output changes sign with the direction of flow. This is convenient in measuring flow along a channel in that displacements along one axis can be summed electrically with an integrator.

7. A second set of electrodes, together with additional amplifier and detector, can be mounted on the sensor and use the same magnetic field. If this electrode set is oriented at a right angle to the first, the outputs of the two detectors will be the rectangular coordinates of the current flow, appropriate sign included. These coordinates contain complete information defining magnitude and direction of flow.

8. A determination of flow is completed for each cycle of field reversal. It is possible to integrate the detector output in synchrony with the field so as to completely eliminate any need to average large numbers of field cycles. The time of integration still sets the bandwidth, however, so that acuity and sensitivity must be balanced. For flows above 0.1 knots one can see velocity detail with an acuity down to at least .04 seconds. This may make the device useful in turbulent studies.

Hydrodynamic Properties

The flow properties of the e.m. sensor may limit its use in some applications. But a number of variations are possible to minimize such restrictions. For instance, to the extent that the water next to the sensor is retarded by skin friction, the indicated flow will be lower than that in the bulk of the water. This can be overcome in part by making the sensor surface concave, or by shaping the sensor as a toroid rather than a disc. The cut out center would allow free passage of the water past the sensor. A toroidal shape would probably be less sensitive to tilt, and to a biased indication of current flow resulting from any vertical pumping motion of the mooring.

Another sensor configuration would involve placing two field coils concentric and about a diameter apart. This would result in fairly uniform distribution of magnetic field within the open 'cylinder' defined by the two toroids. The struts connecting the toroids would support the electrodes. This would give a flow determination of the water mass between the coils; very little disturbance by the sensor of this flow would be anticipated.

Acoustic Flow Sensors

Flow sensors based on various sound propagation techniques (pulse time-of-flight, continuous-wave phase-shift, doppler) have hydrodynamic properties and reliability potentials which make them worthy of study. These systems seem to us conceptually similar to e.m. devices. The choice between e.m. and acoustic flow sensors may rest on a balancing of engineering considerations not yet apparent.

Errors

The device creates the magnetic conditions in water which generate a square-wave voltage potential. This is amplified and detected to provide a d.c. level, the sign and magnitude of which are a function of flow velocity. There are three kinds of errors which affect the accuracy of this process. They are: 1) offset errors or baseline drift, 2) scale errors, i.e., sensitivity changes, and 3) the catastrophic errors which involve dynamic limitation or device malfunction, and which ususally result in wildly inaccurate readings, or no readings. These errors will be discussed below.

Baseline Drift

This device uses an a.c. amplifier to magnify changing voltages to some arbitrarily large level. These relatively large changes are then demodulated to produce a d.c. level equal to the magnitude of the change. Since demodulation must occur at a finite level, the d.c. drift of the output amplifier will affect zero stability. In this instrument, a 1 knot current produced about 360 mv of d.c. output. The stability of the d.c. amplifier is about 5 uv/deg. This implies that temperature effects from this source are less than 2 x 10^{-5} knot/deg. Aging effects with d.c. amplifiers are such that drift is typically 15 uv/month and this contributes further to drift.

Zero drift is also caused by the asymmetry/residual changing field error. Since the absolute value of this offset is on the order of .01 knot, and because changes in this value imply changes in geometry and frequency, the effect on stability from this source is small. If the magnetically induced electrical field is grossly altered, as it is when the sensor is brought up against a non-conductor, the asymmetry effect can be substantial, perhaps .05 knot.

A third source of zero drift exists in long term unidirectional changes in the electrode potentials. If the electrode difference voltage changes at some consistent rate, an output will result which will appear to be signal. For example, if the electrodes change at a 1 microvolt per second rate, the equivalent signal will be 1/(2 field frequency) times this. In the prototype, this would represent an error of .003 knot. We find that the electrodes are within a millivolt of each other over long periods, so the error from this source is apparently very small. If the amplifier is not continuously powered, however, as might be the case in devices intended for intermittent sampling, bias currents from the input operational amplifiers can cause significant errors as the electrodes adjust to a new equilibrium. This effect does not appear to be significant after about 15 seconds.

A fourth source of baseline error arises from electrical leakage between the field coil and the water. If this resistance is not extremely high (or perfectly balanced with respect to the electrodes, which is very unlikely) the field drive voltage will divide across this resistance and the electrode resistance to cause a signal which produces offset. Changes in this resistance are likely, so that the offset cannot be permanently nulled. A leakage of 10^9 ohms will cause an offset on the order of .01 knot. We used good practice in insulating the coil. We did not identify leakage as an error source in the sensor described here, although some earlier and less careful efforts resulted in large errors.

Care must be exercised in wiring of the device, particularly the amplifier input circuitry, so that ground loops do not exist. The electrode ground reference is especially sensitive. It should be connected with the other signal common lines to a single point.

Scale Errors

Constant scale factor depends on stable coil current and geometry and unchanging gain in the sense electronics and detector. In the prototype we used a constant field supply voltage. Coil current is nominally this voltage divided by coil resistance. The actual drive voltage is less than this value by the saturation voltage of the switch transistors

(Q1-4). This is about 200 mv and has a temperature coefficient of approximately 0.2 mv/deg. If the field supply voltage is 6 volts, scale factor will change about .003%/deg. Aging effects should be similarly small.

Variation in coil current is more importantly affected by the temperature coefficient of resistance of the copper wire from which the coil is wound. This is about .4%/deg and causes a similar change in magnetic field and scale factor.

The scale factor effects described above could be essentially eliminated by use of constant current coil drive. This is not difficult to implement. For many applications, the errors with voltage drive are not significant. Most of the sources of baseline drift have some (small) dependence on field drive level, so that care in regard to field stability may be important even though great precision in measurement of magnitude may not be.

The sensor electronics also affect scale factor. The voltage potential at the electrodes divides between the electrode source resistance and the amplifier input resistance. Since the source is much smaller than the input resistance, this effect is negligible in seawater. It might be significant in fresh water where electrode resistance would be orders of magnitude larger. The resistor feedback networks used to set gain with the operational amplifiers are a source of error. Here the resistors are stable to 100 ppm/deg so that scale factor should change by no more than several times this value. The operational amplifiers have sufficient excess gain that the feedback alone accounts for significant changes in gain accuracy. Differential changes in series resistance of the bilateral transmission gate will affect scale. These resistances are about 1000 ohms and changes in this value are significant only when large compared to the 100 k ohm input resistance of A5. In general, it is easy to feel confident in a scale factor accuracy of better than 1% over time and temperature.

Catastrophic Errors

Apart from the obvious failure of critical components, the limits imposed by dynamic range of electrical devices are significant. The internal circuitry as configured can compensate electrode differentials up to about 12 mv. Above this, the device is completely inoperative. The output will be some arbitrary and unchanging d.c. level close to zero. Currents in excess of some limit will cause non-linear amplification of the electrode difference voltage. This will be indicated as a steady d.c. output far in excess of nominal scale.

Single Axis Electronics

We tested the reproducibility of the sensor electronics by reducing the circuit of Fig. 3 to a 5 cm x 15 cm printed circuit board. Component values were the same as those used in the prototype. Fig. 5 is a photograph of the sensor, electronics, power source, and indicator for a working system.

Power for the electrodes and field was derived from a stable ±6 volt supply. The uncorrected baseline error was determined by shorting the input terminals. The output was -3.7 mv and did not change when the field was connected. This represents a flow of .01 knot. This error was trimmed to zero with an external potentiometer. The input terminals were then connected to the electrodes and the sensor was immersed in a tub (55 cm diameter, 32 cm deep) of seawater. With the sensor in the center of the tub and 10 cm below the water surface, the output was +.5 mv. This error apparently represents the effect of residual changing field and sensor asymmetry. Moving the sensor to an edge of the tub caused a more severe imbalance in the symmetry of the electric field sensed by the electrodes. The output in this case was +7 mv.

An RC filter (R = 820 K, C = 3 uf) was used to integrate the output, giving a bandwidth of .065 Hz. The maximum deviation of the output (as observed on a pen recorder) was .5 mv over a period of an hour. Most of the time, however, the output was within .2 mv of zero. This compares well with calculated noise levels for amplifiers of this type. The device showed little variation with time or temperature. The drift with time was such that the recorder trace did not deviate more than 1 mv (.003 knot) over a period of 48 hours. Temperature cycling between 20 deg C and 0 deg C produced a baseline shift of approximately .2 mv (.0006 knot).

Moored Current Meter

The e.m. sensor seems to be an appropriate device for use in a moored current meter. Several configurations are possible, some of which might be adaptations of existing instruments. For example, an e.m. sensor with a single electrode set could substitute for the Savonious rotor in any instrument which lines up with the current. An output consisting of magnitude and direction results because the velocity sensor is always oriented to the flow. The resultant polar form cannot be averaged directly, but the system would be suitable for stable moorings and slowly changing currents. Another approach would involve a two axis e.m. sensor. The rectangular coordinate output of such a device can be directly averaged. Such a device would not cope with mooring movements on a time scale similar to the averaging period. But it would allow vector averaging of rapidly changing water flow. The electronics to do this are straightforward in that they involve only a simple linear integration of the orthogonal components. Each of these components and compass bearing might be stored. By storing three numbers instead of two, the trigonometric computations can be done on shore.

If bearing information is available as sine and cosine of compass angle, (as it would be with a magnetometer compass) the orthogonal components from the e.m. sensor can be multiplied by the bearing information and the result averaged and stored. This might be the most straightforward and reliable approach to a true vacm. However, existing vector averaging electronics can be utilized if the e.m. rectangular components are first converted to polar form. This simulates the output format of the rotor/vane combination.

Magnetometer Compass

Conventional compasses suffer some of the disadvantages inherent in electro-mechanical devices. They have fragile bearings, uncertain dynamic properties, and are difficult to read electrically. These considerations may point to use of magnetometers for directional information. A simple magnetometer uses a high permeability toroidal core on which several sense windings are placed. The Earth's magnetic field produces an imbalance in the magnetic core which can be electrically sensed. The result is an output signal which varies as the sine of heading. A pair of cores mounted at right angles will completely determine bearing. This additional information would allow the orthogonal e.m. sensor outputs to be resolved on a time scale of 1 second or less. The instrument could rotate randomly without affecting the validity of the current data.

A magnetometer of the type described can operate with sufficient accuracy (± 3 deg or better) at power levels compatible with long term measurement problems, i.e., 25 mw or less.

Other Applications

We have tested the sensor by monitoring the flow through the channel leading into Eel Pond here in Woods Hole. We had expected to see a simple tidal movement. The record in Fig. 6 shows otherwise. The tidal flow is obscured by a short period (about 16 min) oscillation which is constantly present. It accounts for 10 times as much flow as the tide. It varies 3 fold in amplitude on a schedule which we cannot correlate. The record shown is full scale ± .5 knots.

The cross section of the channel is well defined (2.5 x 11 meters). The integrated flow during the 8 minutes of a half cycle can be expressed as volume of water moving through the channel. This volume distributed over the known area of the pond (49,000 m^2) tells the change in height. Since the time constant of the pond is short compared to 16 minutes, the same change in height must occur outside the channel. Its periodic movement up and down represents a long slow wave driving the water through the channel. The waves shown in the record have amplitudes of 1.5 to 5 cm.

Vineyard Sound outside the harbor is approximately 6000 meters wide and 15 meters deep. A seich determined by these dimensions (Neuman and Pierson, 1966) has a period of 18 minutes. The constantly oscillating water movement in the Eel Pond Channel is thus probably due to such a seich. The flow sensor (or current meter) makes a useful wave-meter for such long period seiches, and also tides. The record as shown is the differential of wave height and must be integrated if height is to be recorded directly.

The record in Figure 7 shows the inward water movement in the channel when the research boat Asterias passed out to the ocean. It is an average flow of .3 knot for 3.5 seconds which represents a .53 meter displacement in the channel. This means 14.6 m^3 of water moved in to replace the boat which thus must weigh about 15 tons. We present this not as a serious method of weighing boats but as an example of the rapid dynamic response of the sensor.

By the direct approach of more power to the coil one can improve the signal to noise and get a more rapid response from the sensor. We propose it as a means of monitoring the turbulent nature of a flow where the eddies are larger than the sensor. As an example (Fig. 8) we show the decay of circulation in a tub. It was stirred with a single stroke of a paddle on the side opposite the sensor. Such a stroke generates a large single eddy and also imparts rotary motion to all the water in the tub. The eddy maintains itself and rides on this overall circulation.

As the eddy passes the sensor its rotary motion adds on to that of this overall circulation. The sensor therefore sees a greater instantaneous velocity. Many passages of the eddy past the sensor are apparent. With time both the rotation of the eddy and also that of the overall water slow down.

We were surprised to find such a record when we attempted to test the sensor in the laboratory. Our analysis of the mode of this circulation is based on observing particle movement in the water. The analysis of the circulation regime from the record itself would be much more difficult. However we have gradually learned to trust the sensor when it generates such unexpected records.

We plan to use this electromagnetic sensor to monitor flow in the mouth of nets. This will tell the filtering rate and give an idea of the ship's speed. The latter is a needed data not now available on Woods Hole ships. We are also building sensors to do routine monitoring of the flow in salt marsh creeks.

Parts list for single axis e.m. flow sensor

Integrated circuit operational amplifiers

A_1, A_2	uA739C	dual low noise	Fairchild
A_3	uA741C	general purpose	Fairchild
A_4	uA740C	FET input	Fairchild
A_5	uA741C	general purpose	Fairchild

Integrated circuit logic

I_1, I_2, G_1, G_2	CD4001AE	quad NOR gate	RCA
I_3, I_4	SCL4441AE	quad buffer	Solid State Scientific
FF_1, FF_2	CD4013AE	dual flip-flop	RCA
S_1	CD4016AE	quad trans. gate	RCA

Transistors

Q_1, Q_3	2N4400	Motorola
Q_2, Q_4	2N4402	Motorola

Capacitors

C1	10 uf/10v	Components, Inc	#CCm-101-106
C2	.01uf	Erie	#8121-050-651-103M
C3	.01uf	Erie	#8121-050-651-103M
C4	.01uf	Erie	#8121-050-651-103M
C5	10 uf/10v	Components, Inc	#CCM-101-106
C6	.01uf	Erie	#8121-050-651-103M
C7	.01uf	Erie	#8121-050-651-103M
C8	.01uf	Erie	#8121-050-651-103M
C9	10uf	Cornell-Dubilier	#MFP05W1-10
C10	.1uf	Cornell-Dubilier	#MFP05P1-10

Resistors, 1% metal film (Mepco #MR24D)

R1	100	ohm
R2	10	Kohm
R3	10	Kohm
R7	1	Kohm
R8	1	Kohm
R9	100	Kohm
R10	100	Kohm
R11	2	Kohm
R12	2	Kohm
R13	100	Kohm
R14	100	Kohm
R15	200	Kohm
R16	200	Kohm
R17	100	ohm
R18	75	Kohm
R22	100	Kohm

Resistors, 10% carbon

R4	18	Kohm
R5	12	ohm
R6	12	ohm
R19	220	ohm
R21	680	Kohm
R23	2.7	Kohm
R24	2.7	Kohm
R25	2.7	Kohm
R26	2.7	Kohm

Parts list for single axis e.m. flow sensor (cont.)

The electrode cable is a miniature two-conductor shielded type (Belden #8413). The same cable is used for field drive, with the shield unconnected.

Printed circuit artwork is available from the authors.

Sensor materials

Lucite disc	6" diameter, 3/16" thick	electrode surface
Lucite disc	5" diameter, 3/16" thick	upper bobbin side
Lucite tubing	4" o.d. 3/8" long, 1/8" thick	bobbin mandrel
Lucite tubing	6" o.d. 5/8" long, 1/8" thick	dam for potting
Lucite tubing	1" o.d. 3" long, 1/8" thick	mounting collar
Copper wire	Belden #8055 1/2 pound spool	
Vectorbord	#76M38-032	electrode covers
glass wool		

Ag/AgCl electrode cut from GEK electrode

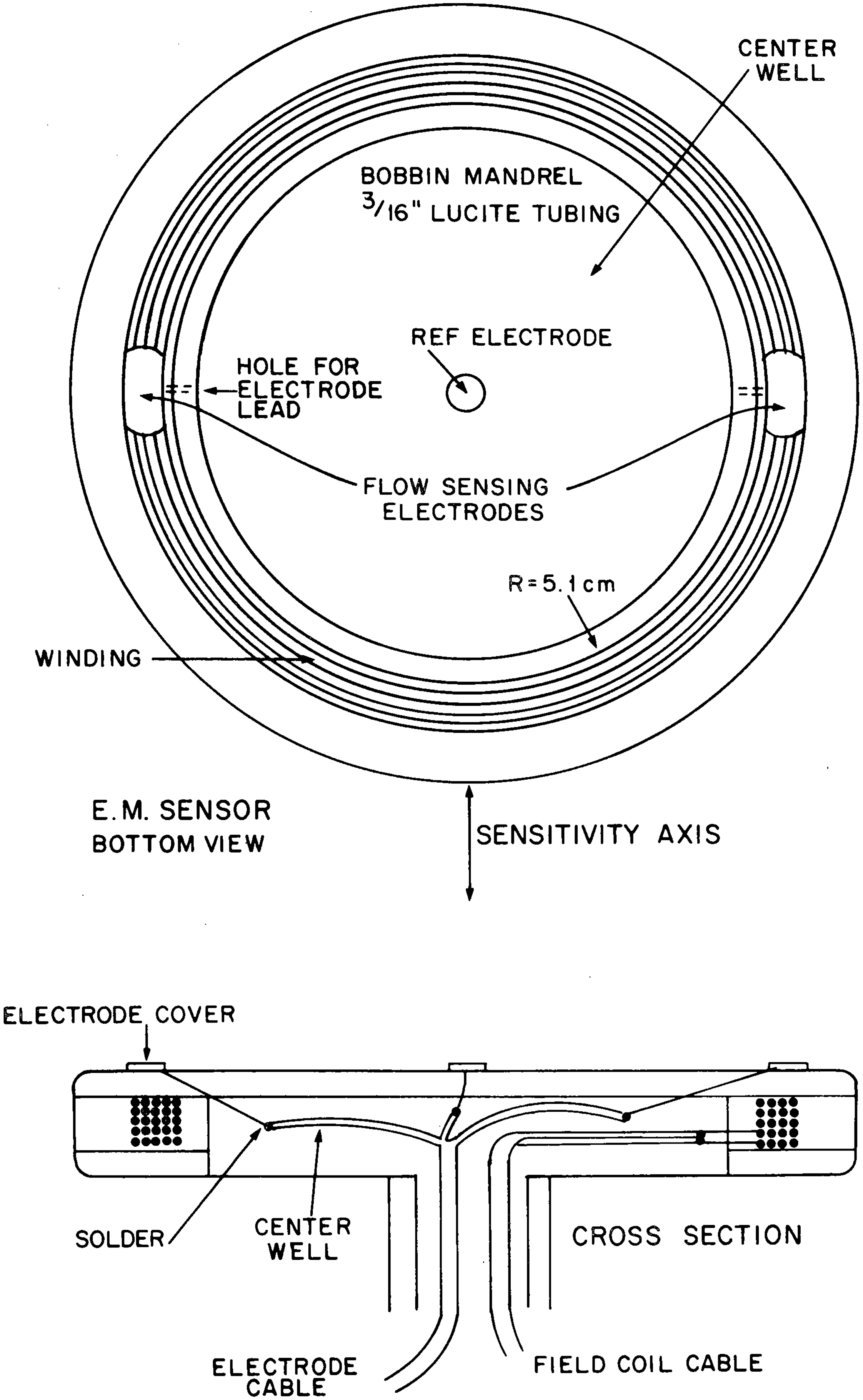


Figure 1. Flow Sensor

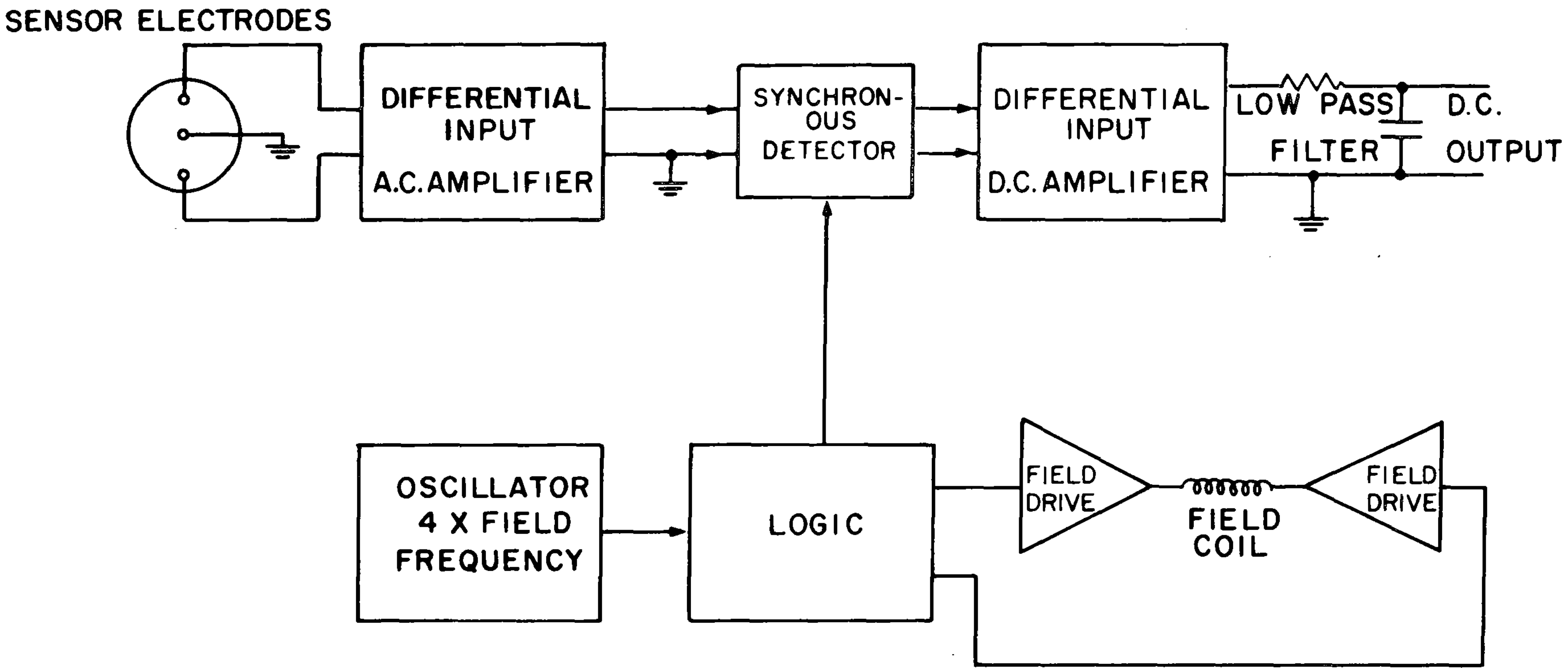


Figure 2. Block Diagram of Electronics

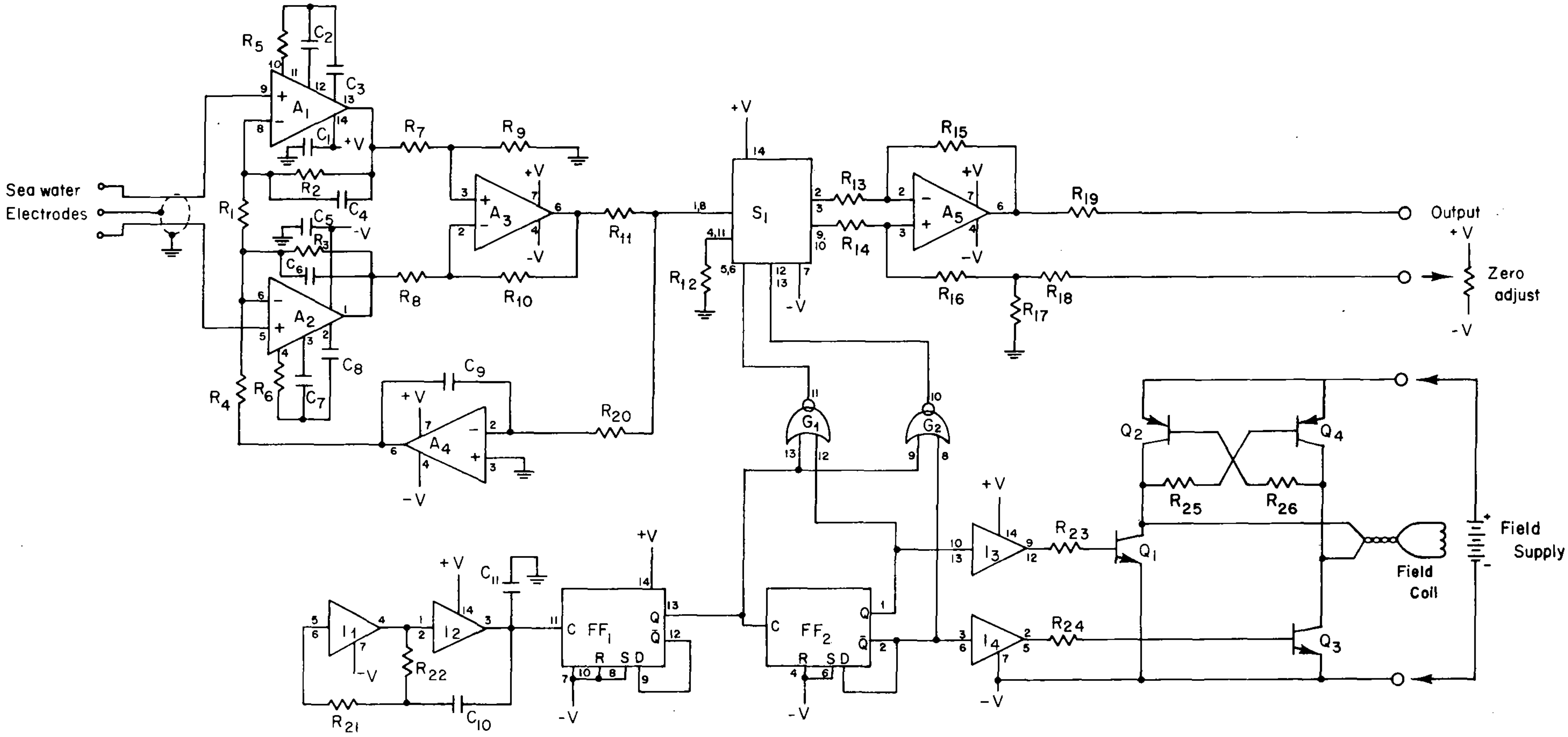


Figure 3. Schematic Diagram of Electronics

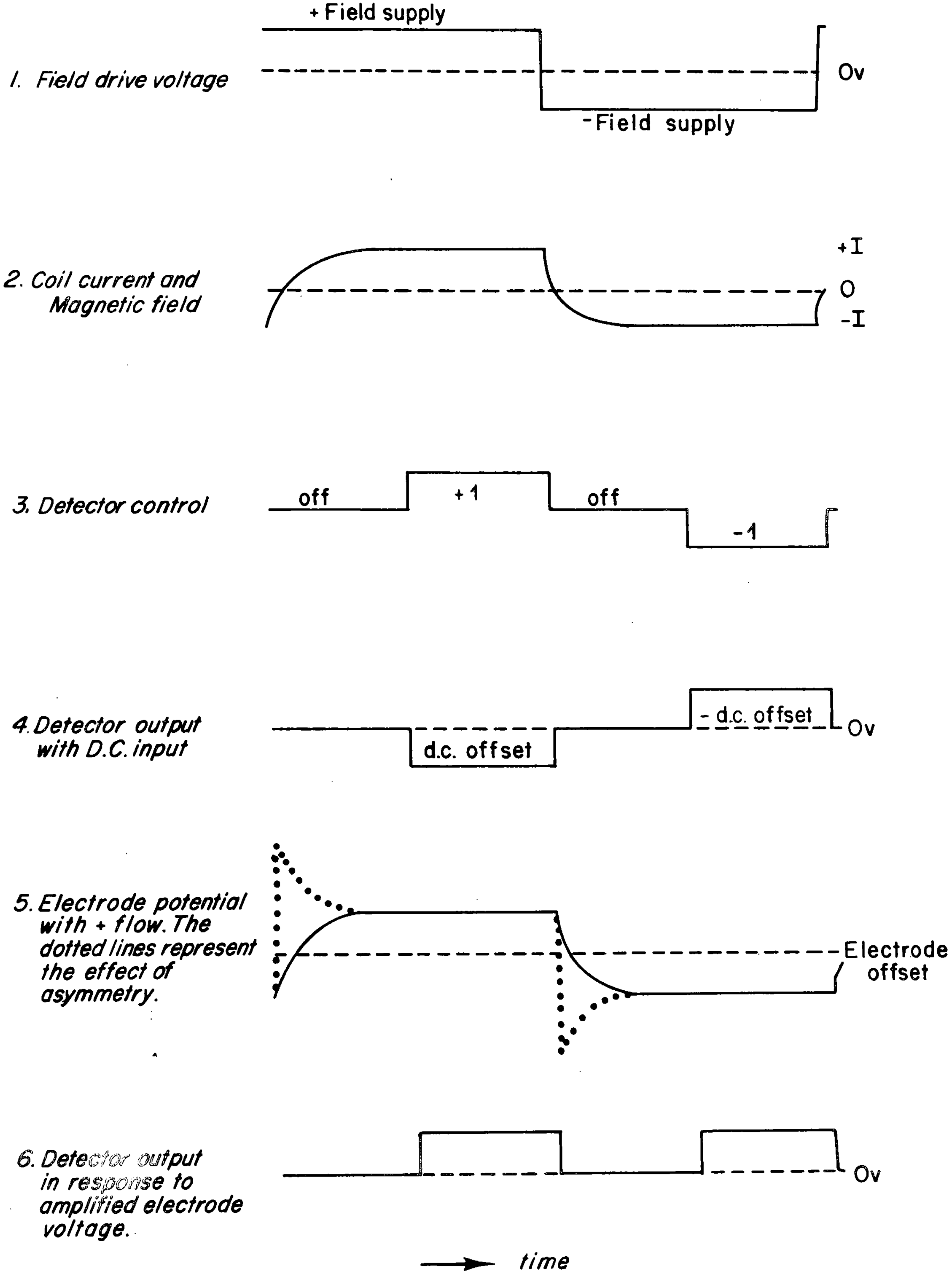


Figure 4. Waveforms

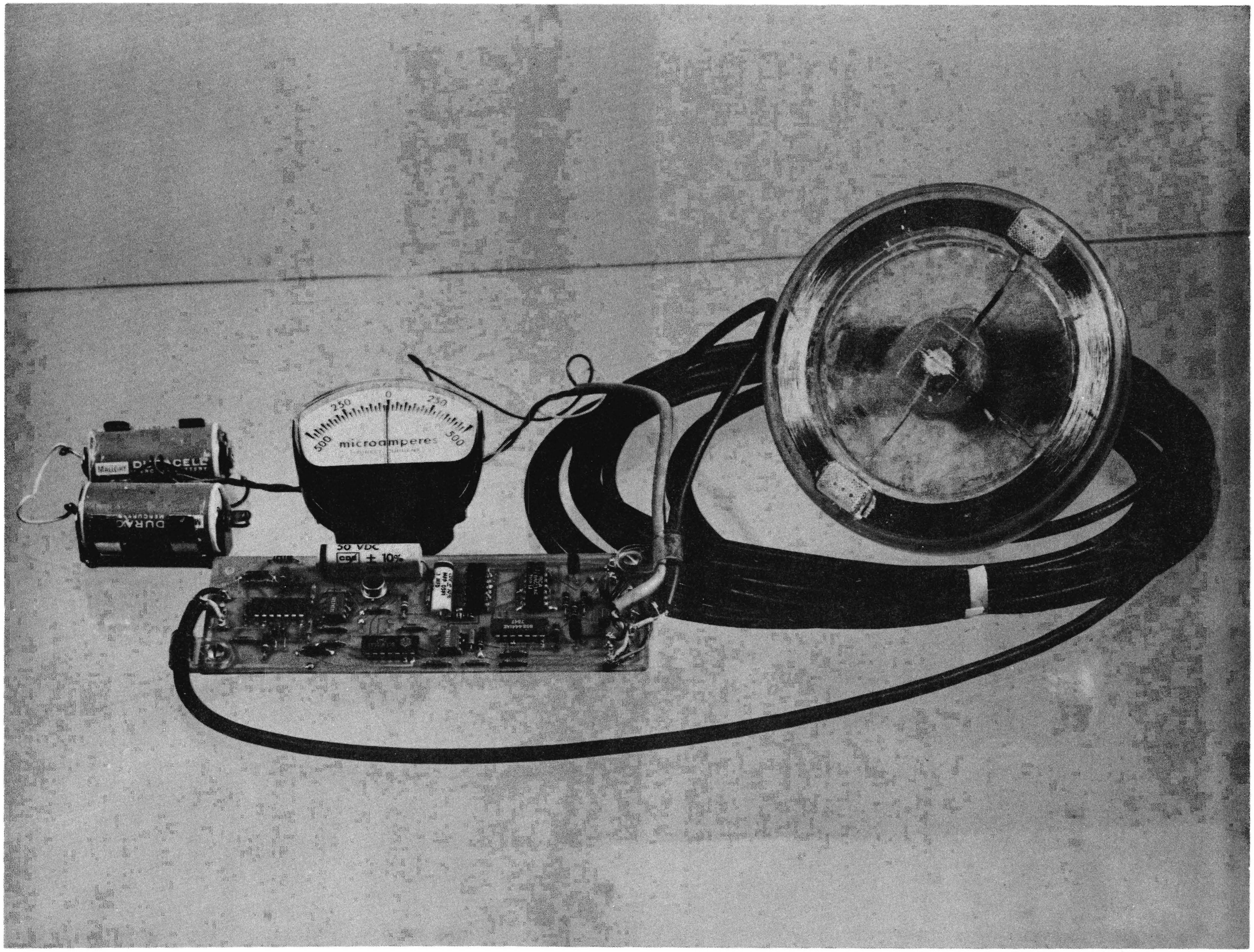


Figure 5. Electromagnetic Sensor, Electronics, Battery Power Source, and Meter Display

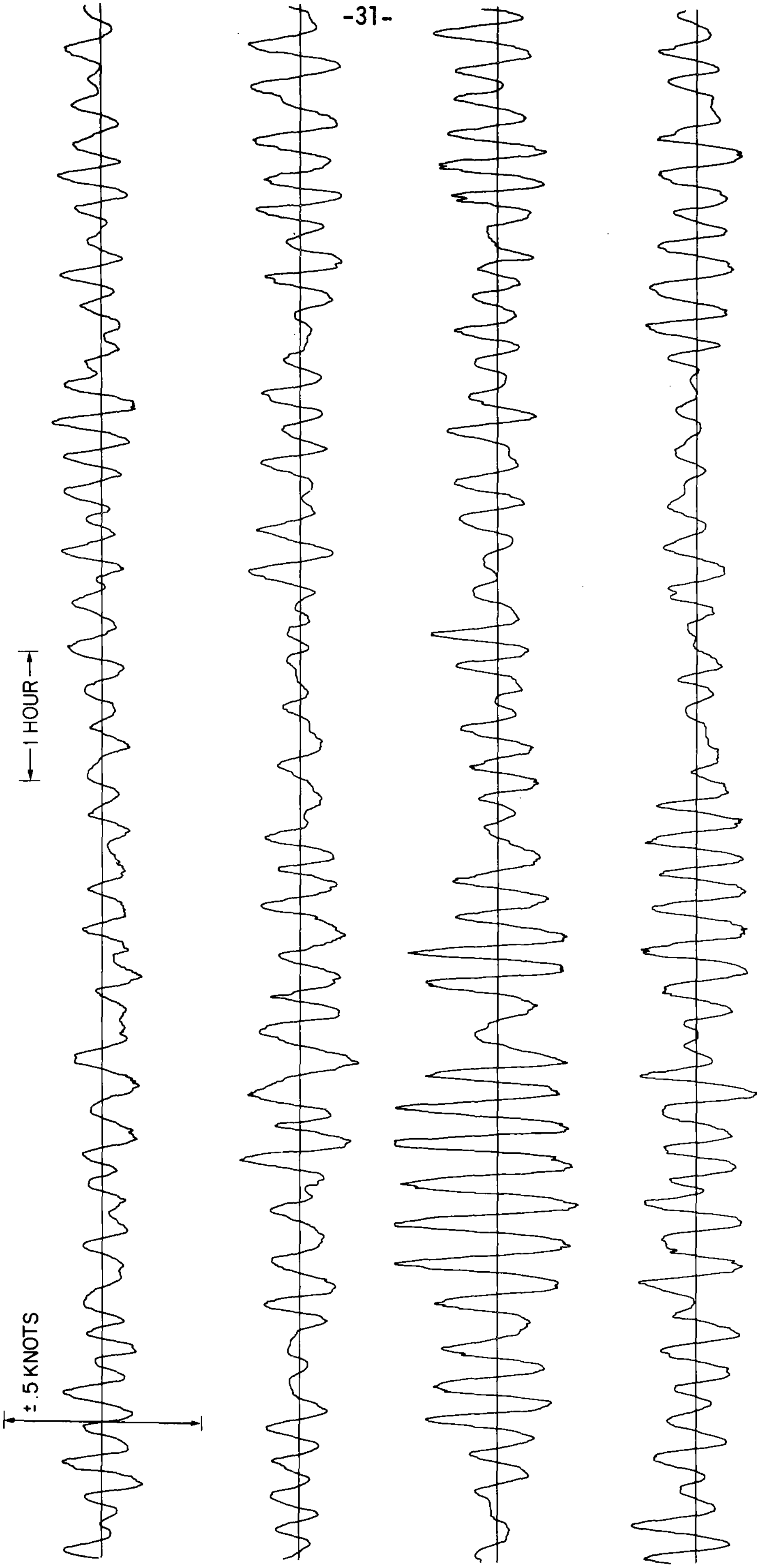
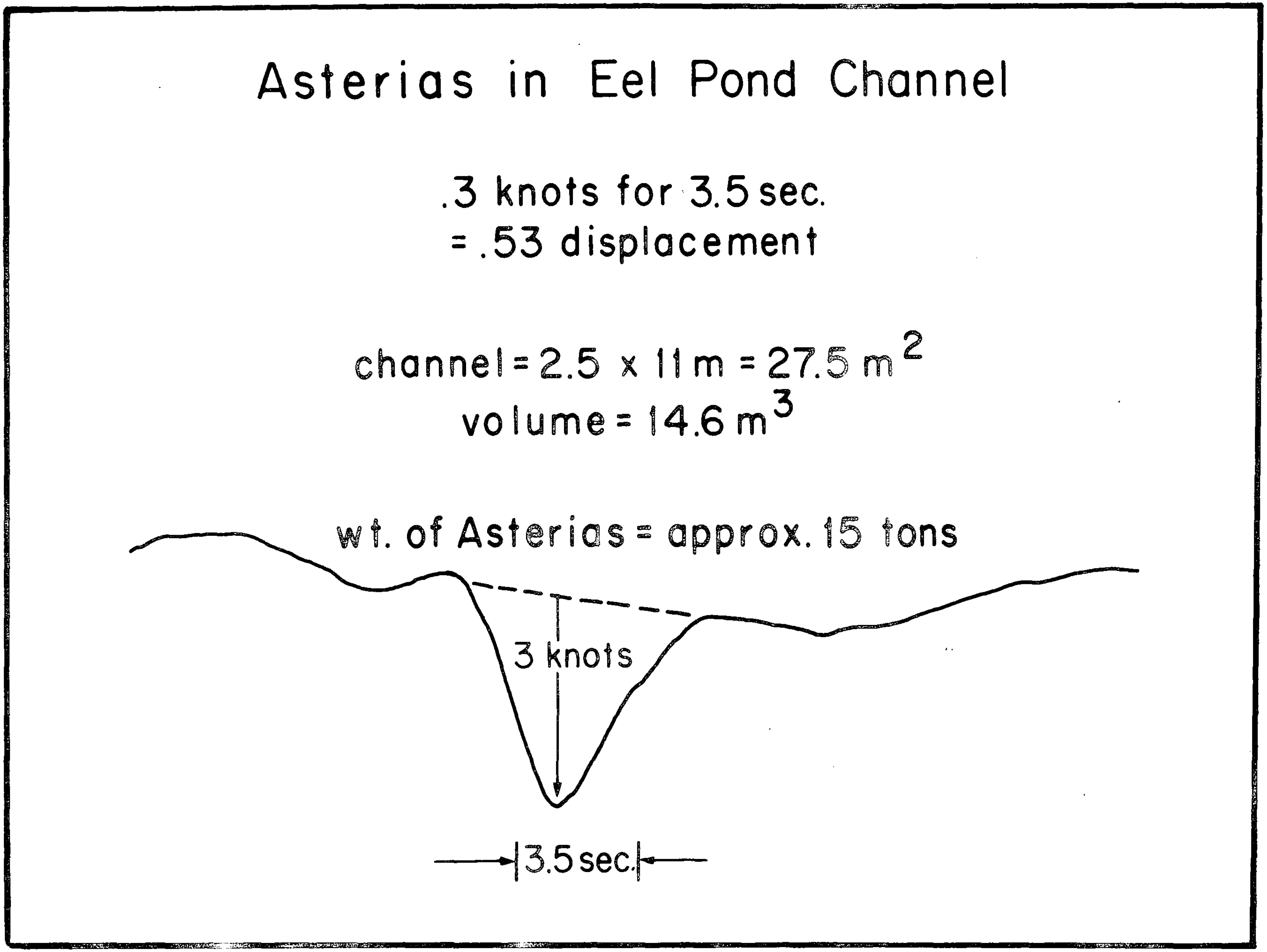


Figure 6. Water Movement in Eel Pond Channel



Asterias in Eel Pond Channel

.3 knots for 3.5 sec.
= .53 displacement

channel = 2.5 x 11 m = 27.5 m^2
volume = 14.6 m^3

wt. of Asterias = approx. 15 tons

Figure 7. Asterias in Eel Pond Channel

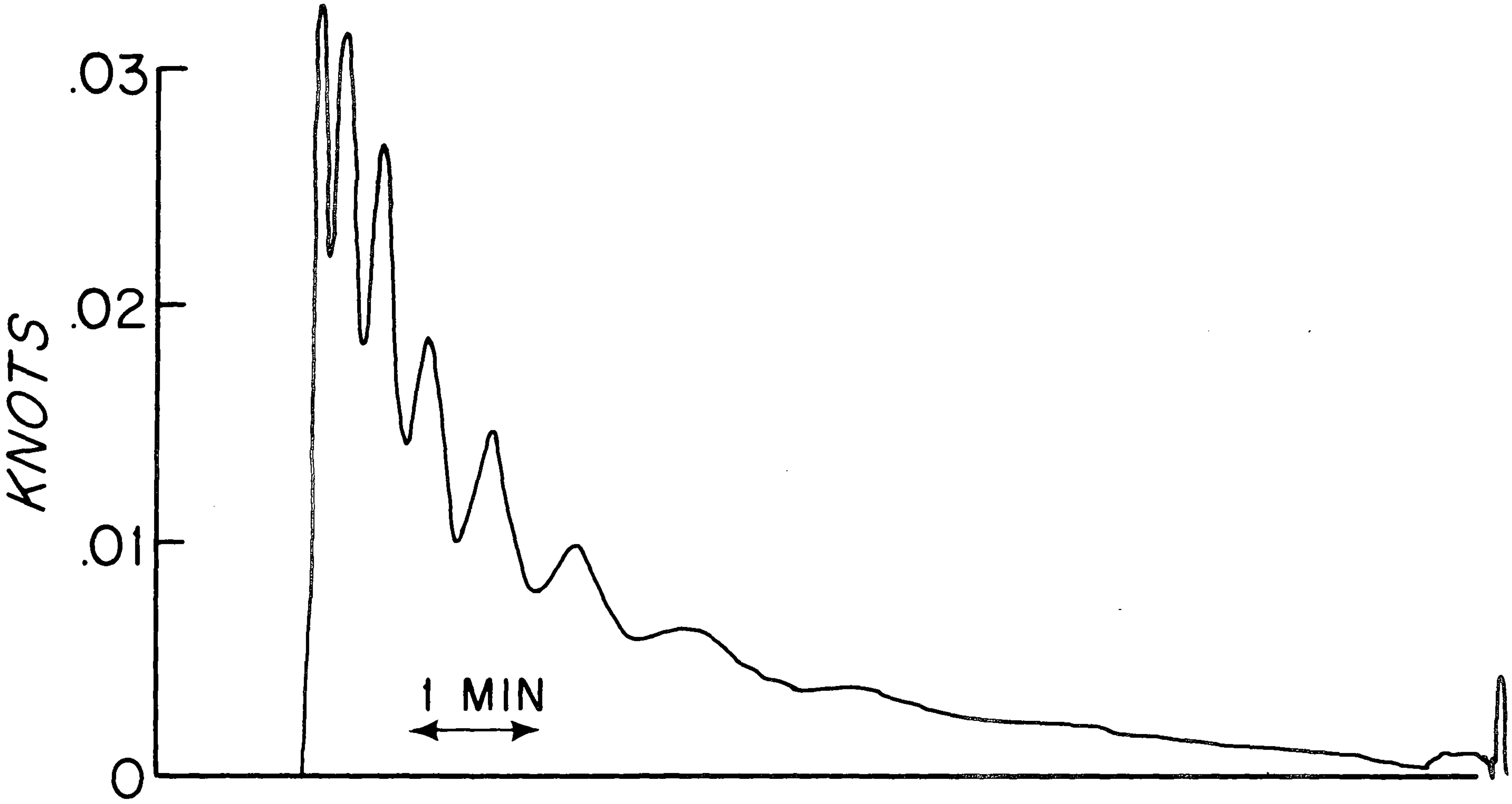


Figure 8. Decay of Circulation in a Tub

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ELECTROMAGNETIC FLOW SENSORS by Kenneth Lawson and John Kanwisher. 33 pages. March 1974. National Science Foundation Grant GA-31987.

Flow sensors based on the principle of electromagnetic induction were investigated as alternatives to commonly used mechanical devices utilizing rotors and propellers. Prototype sensors were constructed showing considerable promise. Measurement accuracy in excess of .01 knot seems feasible with devices suited to long term battery operation. The inertial effects and many of the reliability problems inherent in moving part devices would be overcome by use of an electromagnetic sensor.

1. Flow Sensing
2. Current Meters
3. Displacement Sensor

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II. Kanwisher, John
III. NSF Grant GA-31987

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16. Abstracts

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2. Current Meters
3. Displacement Sensor

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17c. COSATI Field/Group

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