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Technical Report No. 63

SACLANT ASW
RESEARCH CENTRE

A NEUTRALLY-BUOYANT, CONTINUOUSLY SELF-RECORDING, OCEAN CURRENT METER FOR USE IN COMPACT, DEEP-MOORED SYSTEMS

by

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TECHNICAL REPORT 63

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R. Frassetto

APPROVED FOR DISTRIBUTION

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[redacted]

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A NEUTRALLY-BUOYANT, CONTINUOUSLY SELF-RECORDING, OCEAN CURRENT METER FOR USE IN COMPACT, DEEP-MOORED SYSTEMS

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ABSTRACT

A continuously self-recording current meter for deep ocean measurements is described. It has near-neutral buoyancy, is of small size for use on miniaturized subsurface moored systems, and is made mostly of stock item components.

The main features are its utmost simplicity, low cost, and reliability of recording. Recording is made on a miniature chart recorder capable of running for over two months. Noise on the records, principally originated by mooring line motions, is filtered visually during the data-reduction phase. Data are digitalized by semi-automatic methods before being fed to an electronic computer for analysis.

INTRODUCTION

The basic reason for designing a new version of a rather conventional current meter was to obtain a system that combined economic and versatile sea units with a sophisticated laboratory data-processing system that represents a durable investment.

The sea-unit described in this report is a self-recording meter for the measurement of current speeds and directions, designed for use from compact subsurface moored buoys (Ref. 1). It has been assembled mostly from components available on the market.

The associated data-processing unit consists of a semi-automatic read-out system capable of digitalizing the data from the analogue trace of the instrument's chart-recorder. This is used together with a standard electronic computer for the analyses of the converted data and their display on an X-Y plotter.

1. GENERAL DESCRIPTION

The main characteristics of the sea unit are near-neutral buoyancy, small size, continuous recording ability, the ability to work at considerable depths, and the simplicity of the electronic circuits.

It is composed (Figs. 1 & 2) of two sensors — one to measure direction and the other to measure speed — electrically connected to a chart-recorder and power supply assembly. The sensors are clamped on the mooring line, and the container of the recorder is attached coaxially between two line sections of a subsurface buoy system. Several such assemblies can be attached to the same torque-free mooring line at various depths.

In selecting the sensors, a review of the most advanced systems was made. It was felt that the complex, high-precision systems using electrolytic and doppler sensors are, as yet, too impractical for adaptation to moored buoy arrays. Such sensors are also affected by variable temperatures, pressures, and salinities, and a simple method to eliminate these effects has yet to be developed. Moreover, they are expensive and hence do not meet one of the primary specifications. Thus,mechanical systems appear to be the most reliable and inexpensive at the present state of the art.

For the current velocity sensor, the most advantageous mechanical system seemed to be the Savonius rotor (Ref. 2), for it is the only sensor on the market whose performance has been thoroughly investigated, its limitations well established, and its fabrication standardized (Refs. 3, 4 & 5). The details of its adaptation to our purpose are given in Chapter 2.

For the current direction sensor it appears that a 360° potentiometer is still the simplest form of transducer. A miniature precision version was found on the Swiss market. Direction vanes of great stability were obtained by the adaptation of badminton shuttle-cocks, which eliminated vortex shedding effects. Details of the construction are given in Chapter 3.

Recording is made on an analogue, two-channel, miniature chart recorder. This is mounted, together with the power supply and any necessary auxiliary equipment, within a pressure-resistant glass sphere. Details of this part of the unit are given in Chapter 4.

The system combines a relatively high storage capacity (1 month at 1 in/h paper transport) with a high sampling rate (1 or 2 sec). This eliminates aliasing problems and gives a reliable identification of the true signal and of the noise.

The instrument has been used from buoys moored in the Strait of Gibraltar, where unusual oceanographic conditions are met. Buoys were moored at eleven different stations and a total of 1873 hours of good recordings has been obtained.

2. THE CURRENT-VELOCITY SENSOR

2.1 Construction

The Savonius rotor was selected as the velocity sensor because of its large range capabilities, its low density and its low price ($ 2.50). Furthermore its calibration is practically standard, its performance at various angles of inclination is known and reasonably repeatable, and it is a stock item. Its main disadvantage is its size, although a half-size rotor should be equally as good at speeds over 0.1 kn (Gaul, personal communication). One of the principal objects in the present current-meter design (Fig. 3a) has been to minimize its weight by using low-density plastics and by reducing the sensors' "bird-cages" to only their indispensable metal parts. The velocity sensor now weighs only 550 gm in water, the rotor itself weighing 25 gm.

The cage is made of two triangular, 1 mm thick, stainless-steel plates, embossed to give the required rigidity. The three stand-offs are of 6 mm O.D. stainless-steel tubes, with enlarged washer heads secured to the plates by socket screws.

The cage supports the rotor's bearings. Each of these is composed of a stainless-steel, mirror-finished nipple turning on a highly-polished synthetic saphire. The latter is embedded in a hole broached in a teflon or nylon head-bolt secured to the end-plate by a teflon or nylon nut. The bearings were made large enough to operate equally efficiently if the light-weight cage should be accidently deformed — as may happen during launching. Teflon or nylon was used in the bearing assembly to give a greater resistance to the vibrations communicated to the cage by the cable. It has been shown that this construction is less damaged by shocks than is the standard metal-to-metal type of bearing.

The lower plate of the rotor carries ten Hamlin permanent magnets along its peripheral edge, for the actuation of a magnetic reed switch. These magnets measure $^{1}/8$ x $^{1}/8$ x $^{3}/4$ in. each and weigh a total of 11 gm. They are embedded in an extra polyestrine plate of the rotor to eliminate vortex and drag effects.

The complete sensor is clamped tightly to the mooring cable by two specially-designed turning clamps of PVC and neoprene.

In summary, the specifications of the current-velocity sensor are:

Speed Range : 0.05 - 6.0 kn in variable ranges (0.05 - 1.0, 0.1 - 4.0, etc.)
Accuracy : ± 3%
Pulse Rate : 88 p/min/kn (nominal)
Pulses per Revolution : 10
Sensitivity : 0.02 kn
Information Pick-off : Magnetic reed switch, encapsulated
Weight in Air : 1.33 kg
Weight in Water : 0.55 kg

2.2 Operation (Fig. 3b)

The ocean current, through the Savonius rotor and its electronic circuit, is transformed into a proportional dc current, which is used to drive the galvanometer stylus of the miniature Rustrak Chart Recorder.

The intermittent switching of the reed (S) at the rate of 10 times per rotor revolution is transformed into electrical pulses by resistance R_1, which is connected to the 24 V dc power supply. The resistance R_2 and capacitor C_1 form a filter to reduce noise from reed-bouncing.

When S is closed, C_2 discharges through R_3 and diode D_1. When it is open, C_2 charges through R_1, R_3, D_2, C_3, and C_4. This produces a voltage across C_3 and C_4, and current in R_4 and at the input of the recorder.

The driving current, proportional to the switching frequency f of the reed switch, can be expressed by

$$i = E\, C_2\, f$$

where E is the reference voltage R_1 (24 V dc) and C_2 is the value of capacitor C_2, which can be selected to establish the particular measurement scale required.

The resistance R_4 is variable, to permit fine full-scale setting. The capacitors C_3 and C_4 must have a high value to permit continuous recording at very low switching rates, i.e. with low-speed currents.

With the present arrangement, the switching frequency of the rotor is integrated over a period of 3 sec, which corresponds to integrating 2.4 pulses per second at 0.1 kn.

2.3 Performance

General performance and tilt errors were checked under two conditions:

(a) At low speeds — from 0.3 kn down to stalling point — in a small tank (4.5 x 3 x 2 m). (See para 2.4).

(b) At high speeds — 1 to 6 kn — in the recirculating David Taylor Model Basin (Maryland, U.S.A.).

The low-speed calibrations were made to study the effects of different bearings before and after long-term operations, and to determine the stalling point of the rotors. The bearings described above were developed during this process, it being found that their greater shock-resistance was achieved at the expense of a slight increase in the stalling speed. This came at about 0.025 kn — a value higher than that given by the rigid-bearing and frame models used by Gaul in his study of rotor capabilities (Ref. 3, 4,& 5). However, calibrations made from this point up to 0.3 kn gave results acceptable for our requirements. The mean deviations did not differ from those of Gaul's model.

Calibrations in both tanks allowed a fixed revolution rate — or pulse frequency — per knot to be determined throughout the complete speed range. This is convenient for data processing. It was found that within the speed range from 0.5 to 3.0 kn the revolution rate increases linearly within an acceptable degree of accuracy. Below and above these speeds, calibration curves must be used for data-processing.

It was also determined that errors due to tilt vary with speed. For example, with a 15° tilt there was a -5% error at speeds of from 0.1 to 0.3 kn and a -10% error at speed of from 1 to 3 kn. Furthermore, at 0.05 kn the error was negligible with some rotors, but positive with others. This suggests that each rotor has a particular minimum speed at which the lift given by the 15° positive angle of attack of the rotor plates starts to counter-balance the rotor's weight, thereby reducing the bearing friction experienced when the rotor is vertical.

However, the tests showed that the errors due to tilting of up to about 10° to 15° can be neglected in the majority of ocean measurements because they fall within the expected accuracy of the meter. It would therefore be advantageous if the lift-to-drag ratio of the moored buoy system could be engineered to ensure that the cable catenary keeps the meter at angles of less than 15° at the speeds being measured.

2.4 Routine Calibration

As a rule it is a good policy to check and adjust the velocity probes before and after each extended operation at sea.

Because the rotors are standard and have quite a stable calibration curve, it is generally sufficient to make a single-point calibration, such as at 0.1 kn, to check whether the bird-cage assembly and the bearings are in good order. This can be done in a small tank, such as the one shown in Fig. 4, equipped on the basis of the experiences described in Refs. 3, 4, & 5.

A light carriage fitted with a rod of the same diameter as the buoy's cable supports the rotor at the proper depth and at the desired tilt angle. The carriage runs smoothly along a wire that is highly tensioned with turnbuckles. The wires that transport it are also under tension and are driven by a motor that has a large flywheel to ensure uniform travel of the carriage.

The rotor's turning speed is recorded on one channel of a two-channel brush recorder for comparison with a precise time scale (10 pps) on the other, the passage of the carriage past the beginning and end of a 2 m base line being marked by the switching of two reed switches. Although, as was seen in para 2.1, the ten magnets of the rotor normally activate only one reed switch, for accurate calibration at low speeds a second reed switch is incorporated in the rotor, thereby giving a record of 20 pulses per rotor revolution.

3. THE CURRENT-DIRECTION SENSOR

3.1 Construction

This sensor (Figs. 5a & 6) consists of an external vane coupled by a magnetic clutch to the body of a 360° potentiometer, and of a compass suspended from the same potentiometer's low-torque cursor. As with the current-velocity sensor, minimum weight was obtained by using low-density material and reducing the metal parts of the bird-cage to a minimum. Although the cage is somewhat shorter than that of the velocity sensor, the plates and clamps are standard for both. The weight of the entire unit in water is 800 gm.

A particular feature of the sensor is the vane, which is made of two plastic badminton shuttle-cocks. These are found to set into the current with great stability because they do not produce shedding vortices. They are particularly desirable when strong currents are to be measured, but with very weak currents (0.01 - 0.04 kn) the standard V-shaped vane is more sensitive. The threshold speed for the shuttle-cock vanes is about 2 cm/s (0.04 kn).

The potentiometer-compass assembly below the vane is contained within a plexiglass upper body and a lower neoprene 'booth', the former being attached to the lower plate of the cage and sealed by an O-ring. The whole is fitted with oil and the assembly operates exposed to external pressure.

The magnetic-clutch coupling the vane with the body of the potentiometer, which is inside the oil-filled housing, is made of four cylindrical

5 x 6 mm magnets forming a closed flux of magnetic lines. The two external magnets are glued inside a polypropylene flat cylinder, and the two internal magnets are glued to a 5 mm thick iron cylinder coaxial with the brush assembly and the body of the potentiometer. The iron plate acts as a magnetic screen for the compass.

The potentiometer is also a special feature, because, being of a sturdy microtorque construction and having a 2 mm OD spindle, it permits rough handling of the unit. This is of particular importance when being launched as part of a moored-buoy system. The potentiometer is an OHMAG (Neuchatel, Switzerland) Model G — non-magnetic type, originally designed for oil-well research. The friction between cursor and coil normally permits a direction sensitivity of ± 3°. However, in oil-well research it was found that this could be increased to ± 1° by connecting it with a 1 Hz vibrator. In our application such vibrations are frequently supplied by the tensioned mooring cable (see Ref. 1) and no additional vibrator has been found necessary. The specifications of the potentiometer are:

Dimensions	30 x 40 mm
Weight	16 gm (0.56 oz) in air
Torque	0.5 gm/cm
Electrical Rotation	356 ± 1° continuous
Linearity	0.5%
Resistance Range	2000
Resistance Tolerance	± 3%
Number of Spires	466

The potentiometer turns freely on 'New Hampshire' miniature ball-bearings, and continuous electrical contact is maintained by a gold-plated slip-ring and brush assembly mounted coaxially on its upper part.

As a reference basis for the measurements, the potentiometer cursor is always oriented to the magnetic north by being attached to a 70 mm long, 10 mm diameter, permanent magnet. This magnet is embedded in a polipropilene plate suspended from the potentiometer's spindle by miniature aluminium gimbals that allow it to operate at up to 42° of tilt. The torque of the cursor in dry air is 0.5 gm/cm and is even less in oil. This is amply provided for by the magnet described. The weight of the complete compass assembly in the oil bath is 26.5 gm.

In summary, the specifications of the current-direction sensor are:

Direction Range : 0° to 360°, referenced to magnetic north
Accuracy : ± 3°
Maximum Tilt : 42°
Readout : Linear, potentiometric
Compass : Magnet bar - Viscous damped
Weight in Air : 2.3 kg
Weight in Water : 0.8 kg

3.2 Operation (Fig. 5b)

The current direction is transformed into a proportional current (0-100 A) that drives the stylus of the second channel of the chart recorder.

The potentiometer's coil — to which the vane is coupled — is supplied with 0.6 V at the output of diode OA 200, which is in series with the recorder motor. The cursor — to which the compass is coupled — is connected to the galvanometer of the recorder stylus through a variable resistance that provides zero scale setting.

3.3 Performance

The sensitivity of the unit is found to reach 1° when it is vertical and subject to cable vibrations. Without the cable vibrations — which help to decrease cursor friction — the sensitivity of a quiet assembly is of the order of 3°.

4. RECORDER AND CONTAINER

A miniature Rustrak automatic chart recorder is used to record direction and velocity on two separate channels. The instrument measures about 13 x 8 x 9 cm and weighs about 1.4 kg. The recording paper moves at speeds that depend on the selection of a variety of motor-reduction-gear assemblies. The signals are recorded by the styluses of galvonometer needles pressed on the waxed paper at rates variable from one to a few seconds. By using the striking rate of 1 second, one obtains a neat trace of successive dots representing the signal and sparse dots representing the noise.

Eighteen mercury batteries (Mallory 2550 R) provide a 24 V dc power supply for 60 days of continuous operation at a cost of about $1 per day.

The recorder and power supply are contained within a pressure-resistant container and can therefore work in a dry ambient at normal atmospheric pressures; they weigh 3 kg.

The container (Fig. 2) is a 10 in.OD sphere made of two hemispheres of 0.360 in. (± 0.020 in.) Corning glass clamped together. Its net buoyancy is about 4.75 kg and it will withstand pressure of up to 10 000 $\mathrm{lb/in}^2$ (7 500 m depth). An electrical feed-through for ten conductors has been made near the pole of the upper hemisphere by boring a 0.135 in. (± 0.005 in.) hole. The hole is slightly bevelled at both the inside and outside edges, and its surface has been fine-ground to improve the bond with the Araldite glue used to hold the ten deep-sea (Mecca) connectors.

The buoyancy of the container (4.75 kg) compensates for the instrument payload (3 kg) and the weight of the two probes in water, thereby bringing the entire unit to neutral buoyancy.

5. AUXILIARY EQUIPMENT

A timer, with its necessary power supply, is useful for making an hourly mark on the recording paper. On some occasions a time-delay for triggering a mechanical anchor-release has been incorporated. The system can also incorporate probes that measure the tilt and depth of the instrument and the ambient temperature; a clock-driven switch mechanism can make these recordings intermittently and in an appropriate sequence.

Space for all of these items is available in the glass sphere by careful use of the space and by selecting miniaturized components.

6. RESULTS

6.1 Display of Records and Reliable Signal

The instrument was used from buoys moored in the Strait of Gibraltar, where unusual oceanographic conditions are met. A total of 1873 hours of good recordings have been collected from eleven stations.

Measurements were made generally with units at both ends of the mooring line: near the lifting buoy (200 - 300 m deep) and near the bottom (800 - 900 m deep).

Figure 7 shows recording samples of two such units recording simultaneously. Record C6A is from the shallow meter and C6B from the one near the bottom. On each record, the trace on the upper channel indicates the direction (D) towards which the current flows and the trace on the lower channel indicates the velocity (V) of the current in knots. Different velocity scales were chosen to suit the different conditions expected (0-4 kn and 0-1 kn).

The paper transport speeds were selected as 1 in/h. for the upper unit and 2 in/h. for the lower one, in order to give different resolution.

These records were selected because they illustrate the good performance of the meter. In both records, the velocity decreases from left to right, reaches a minimum value at the time of low water (L.W) in Gibraltar, and then increases again while the direction changes from eastward (90°) to westward (260°). At the time of current reversal, interesting wave-like oscillations, having periods of 16 to 20 min, were recorded. Orbital motion of water particles, which characterizes internal waves, is most probably the cause of these periodic wave-like deflections ranging from 20° to 140° for D and from 0.1 to 0.4 kn for V.

6.2 Noise

Random or periodic oscillations of both speed and direction having periods shorter than five minutes are more likely to be originated by self-noise of the system than by turbulence of the sea.

In most records, such as C6B in Fig. 7, the velocity fluctuations attributable to noise appear to have periods of from 1 to 3 min and an average amplitude of 0.05 kn, which is a value equivalent to the lowest reliable current velocity that one can measure with this instrument.

The direction trace, on the other hand, shows interesting, random, periodic vane deflections. It appears that the vane deflects from a fixed direction only in one sense, (counter-clockwise in the records of Fig. 7). The vane in fact does not over-shoot the fixed direction represented by the clearly defined dark line composed of overlapping dots. This effect is attributable to mooring line motions.

In normal cases, when data are digitalized by means of a pencil-follower system or by reading average values over established intervals, the operation of filtering the noise is made visually. This is probably the most valuable feature of the instrument. Aliasing is avoided with a very simple and reliable method that is possible only with an intermittent high sampling rate, which produces 3 600 dots in one inch per hour, as in our system.

Noise appears with greater amplitude, and often with values comparable to the signal, in extreme or accidental cases. Records obtained in some of these cases are shown in Fig. 8.

Record 1 was made by a current meter placed near the bottom and being disturbed probably by periodic vertical motions of the mooring line induced by strong and turbulent currents at the level of the lifting buoy. The velocity amplitude of these oscillations, having periods averaging 3 min, was of 0.05 to 0.1 kn. Variations of 10 to 15 min with ΔV of 0.05 to 0.2 kn were interpreted as signal. Even in this case, however, the visual method of averaging is rather simple and can be made with reasonable reliability. In this case the vane exhibited little deflection from the true direction of the current.

Record 2 in Fig. 8 shows the effects of an accidental condition. A vertical array of instruments, 200 m long, which had been placed between two buoys at 50 m and 250 m depths, had broken loose from the upper buoy and remained pendant from the lower one, which was supporting a current meter near the bottom. In certain phases of the tidal current the pendant must have been fluttering violently, causing motions on the deep buoy that were transmitted all the way down the mooring line to the bottom current meter.

This accidental motion was recorded as noise having a quite different character from the one recorded in the normal cases shown in Fig. 7. The current velocity oscillations reach amplitudes of 0.32 kn, with periods averaging 2.2 min; the current direction oscillations are pendular and random at the most critical times (between 01.00 and 03.00), and then become more normal.

Another proof that the curious one-way deflection of the vane is due to a particular set-up and movement of the mooring line in our system is shown by record 3 in Fig. 8. As long as the system was moored (before 12.45) the vane effect previously described was clearly recorded, leaving a dark line representing the true direction of the current and a cloud of random dots on one side of this line representing the noise. At 12.45 the moored system was released automatically from its anchor and, rising to the surface, started to drift with the surface currents. As a consequence, from 13.20 to 14.50, the current meter, then at the trailing end of a 500 m wire, started oscillating in a pendular motion. This is shown on the D trace as a large uniform band of dots with a darker centre band, and on the V trace as a thickening of the line (representing high-frequency variations in speed). The record after 14.50 was made while the buoy was being recovered by the ship.

6.3 Comparison with recordings made by a Richardson Meter

Measurements made with a Richardson current meter in the same area of the Strait of Gibraltar by other institutes are shown for comparison in Fig. 11. They were also made near the bottom, and the meters were also supported by a subsurface buoy system. Although details of the particular instruments, such as the time constant of the sensors, are not known, the data display is typical of this instrument. (The visual display in Fig. 9 was obtained by the data-processing of the original film record.)

The Richardson system differed from our system in that:

a. The buoy and mooring lines were larger.

b. The cages around the sensors (both of velocity and direction) were bulkier.

c. The sampling period was 10 min, compared with our 1 sec.

d. The number of counts per rotor revolution was only one, compared with ten in our system.

The records in Fig. 9 show oscillations in the traces that can be interpreted as system noise. Their apparent periods and maximum amplitudes are as follows:

Inclinometer: Period about 10 min. Amplitude about 1°, which is negligible.

Velocity in the 0-4 kn scale	Period about 10 min. ΔV about 0.1-0.2 kn.
Velocity in the 0-0.4 kn scale	Period is random. ΔV about 0.01-0.05 kn. (The difference in ΔV between the two scales must be an electronic effect that is not explained in the instrument's literature)
Direction:	Period about 2 min. ΔD is pendular, with a maximum of 90°, and with high-frequency oscillations despite the 10 min sampling rate. (The "one sense" vane deflection recorded in our system is not indicated on these records. This may be due to the different design of the mooring line or to an averaging method of recording.)

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3. R.D. Gaul, "The Savonius Rotor Current Meter," The A & M College of Texas, Project 268(D), 1 February 1962.

4. R.D. Gaul, "Influence of Vertical Motion on the Savonius Rotor Current Meter," The A & M College of Texas, Project 329, 1 February 1963.

5. R.D. Gaul, "Evaluation of the Hytech Corporation Current Meter Calibration System," Bissett-Berman Corp., Technical Report (Unpublished Report).

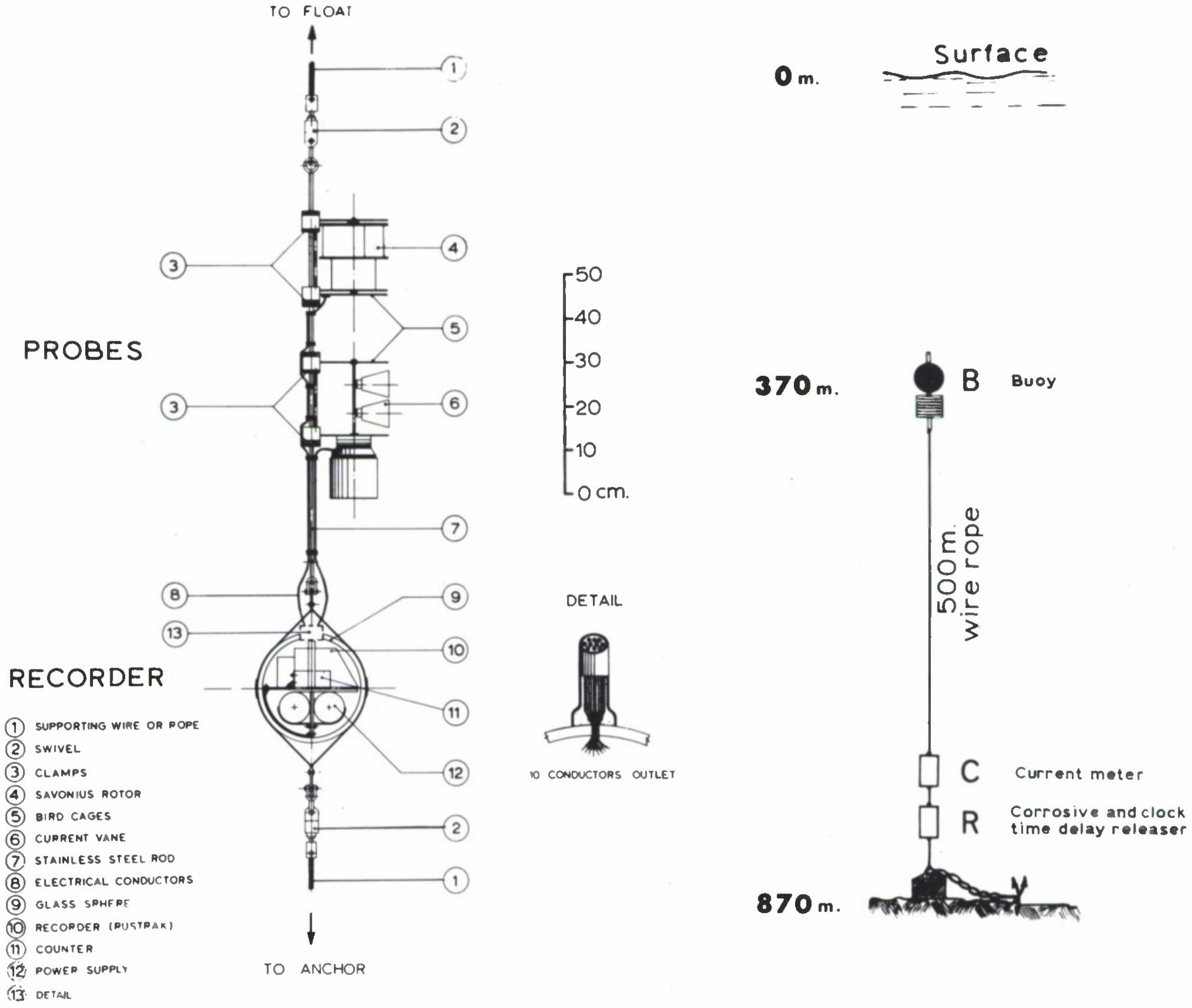


FIG. 1 GENERAL CONFIGURATION OF THE CURRENT METER
THE PROBES ARE MADE SO THAT THEY CAN ALSO BE USED IN OTHER ARRAY SYSTEMS. THE DETAIL SHOWS A 10-CONDUCTOR OUTLET THROUGH A 0.1 in HOLE IN THE GLASS SPHERE TO PERMIT CONNECTION WITH THE CURRENT-MEASURING AND OTHER SENSORS (temperature, pressure, etc.) OR WITH TIME-DELAY ANCHOR RELEASERS. THE MOORING ARRANGEMENT SHOWN ON THE RIGHT IS TYPICAL OF THOSE USED IN THE STRAIT OF GIBRALTAR.

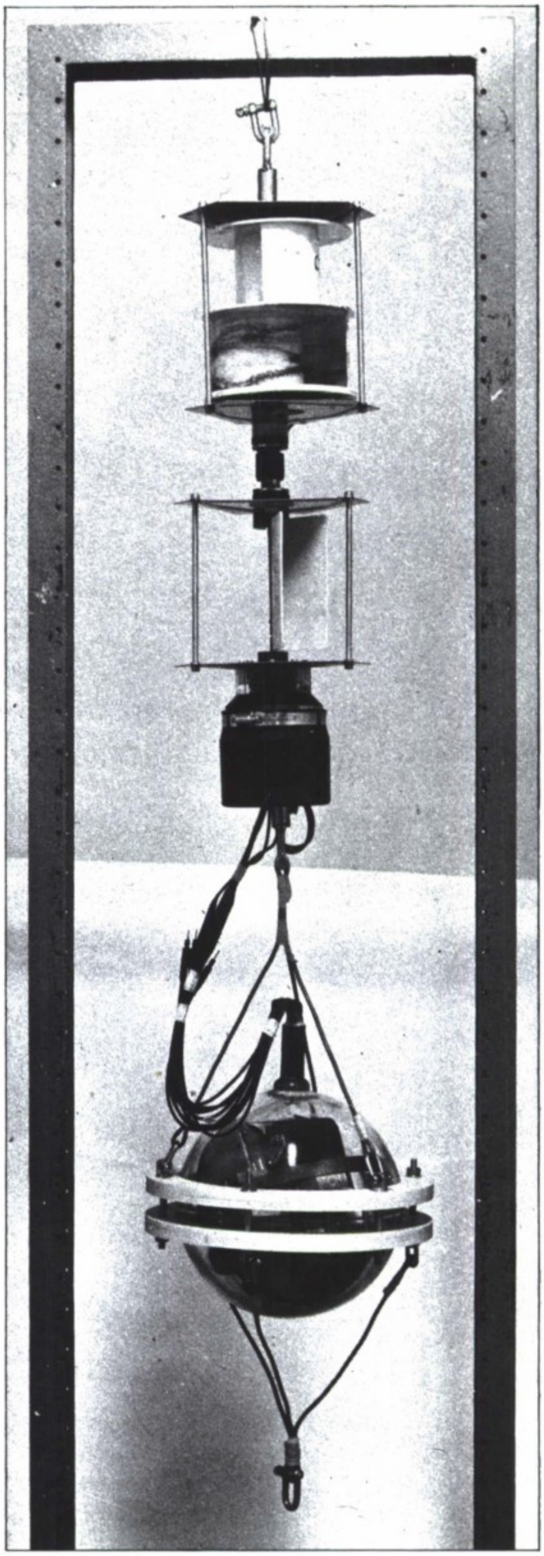


FIG. 2 PHOTOGRAPH OF THE CURRENT METER.
FROM TOP TO BOTTOM ARE THE SAVONIUS ROTOR VELOCITY PROBE (0.55 kg.), THE DIRECTION PROBE AND ITS MAGNETIC-COMPASS/POTENTIOMETER ASSEMBLY (0.8 kg.), AND THE GLASS SPHERE CONTAINING THE POWER SUPPLY AND RECORDER UNIT (the whole being neutrally buoyant).

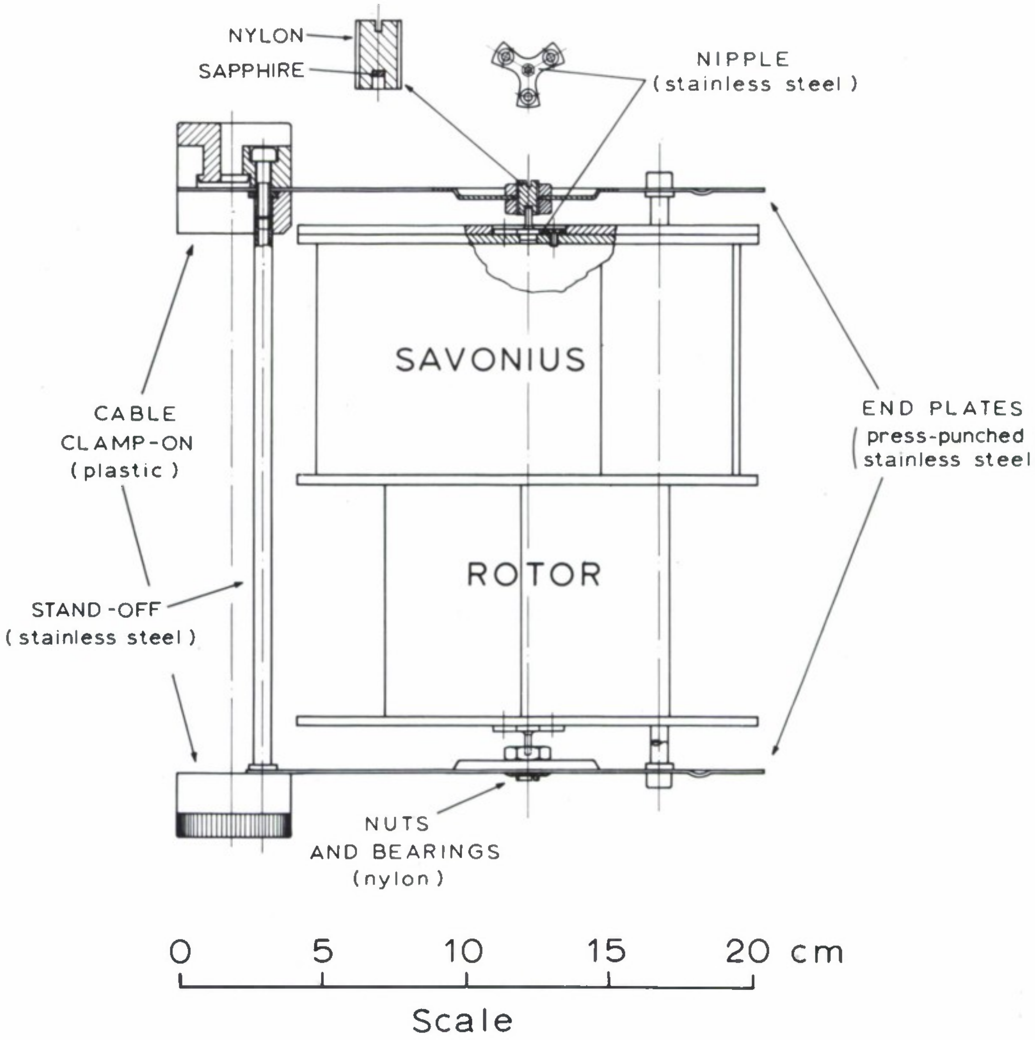


FIG. 3a

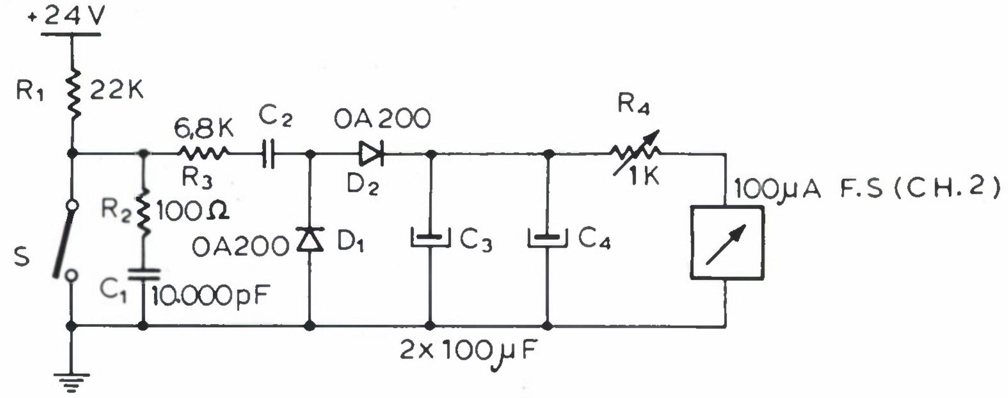


FIG. 3b

FIG. 3 THE CURRENT VELOCITY SENSOR.

THE BEARING ASSEMBLY SHOWN IN DETAIL AT THE TOP OF FIG. 3a HAS BEEN DESIGNED FOR MINIMUM WEIGHT, SHOCK RESISTANCE, AND FREEDOM OF OPERATION. A REED SWITCH (not shown on fig. 3a, but as S on fig. 3b) OPERATED BY TEN SMALL MAGNETS (not shown) ON THE LOWER FACE OF THE ROTOR IS CONNECTED TO THE ELECTRONIC CIRCUIT (fig. 3b) IN THE GLASS SPHERE SHOWN ON THE PREVIOUS FIGURE.

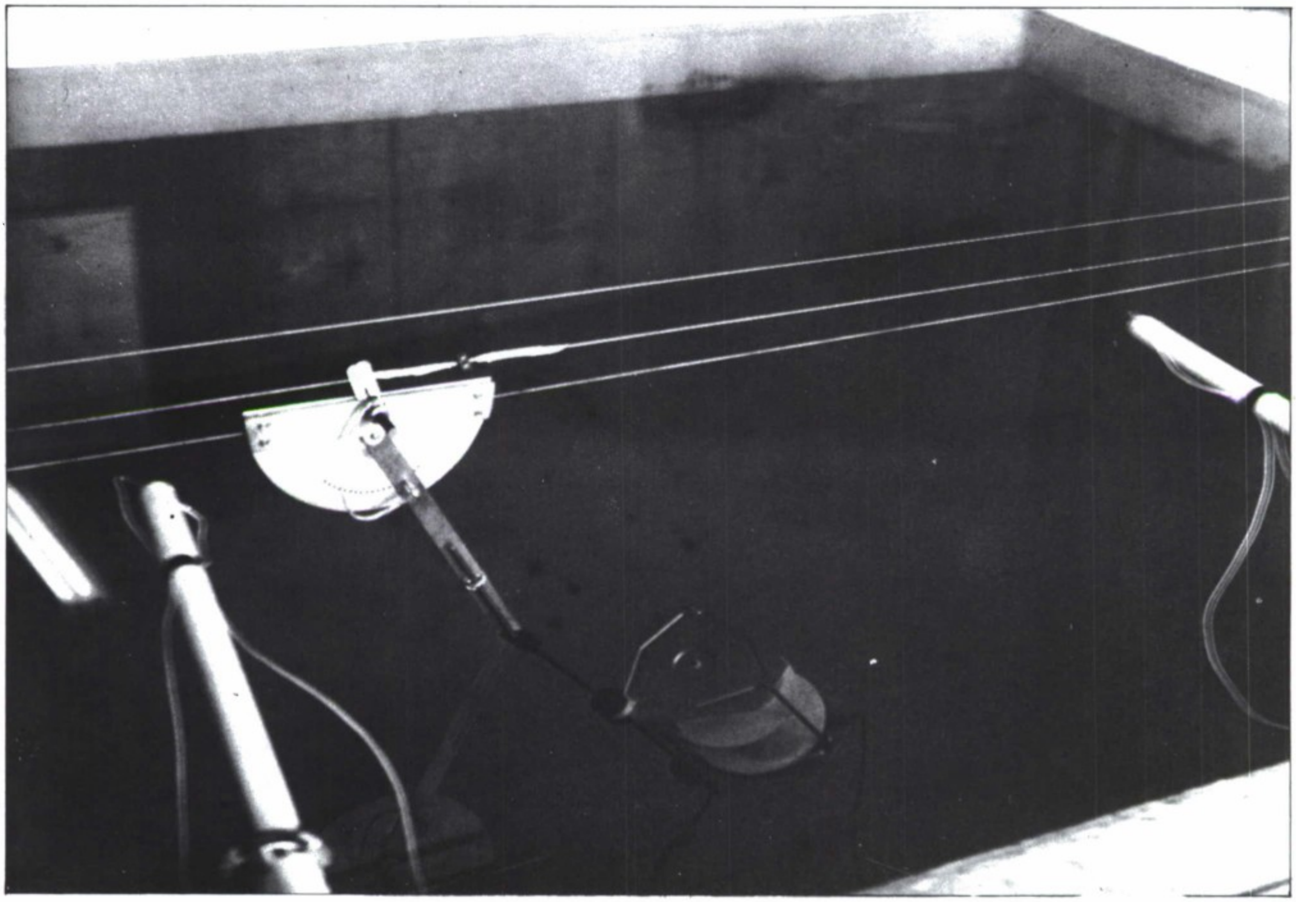


FIG. 4 CALIBRATION OF CURRENT VELOCITY SENSORS.
THE WATER IN THE SMALL TANK (4 5 x 3 x 2 m) IS KEPT PERFECTLY STILL THE ROTOR IS TRANSPORTED AT VARIOUS TILT ANGLES AND ITS REVOLUTION RATE IS RECORDED ON A TIMED RECORDER TRACE

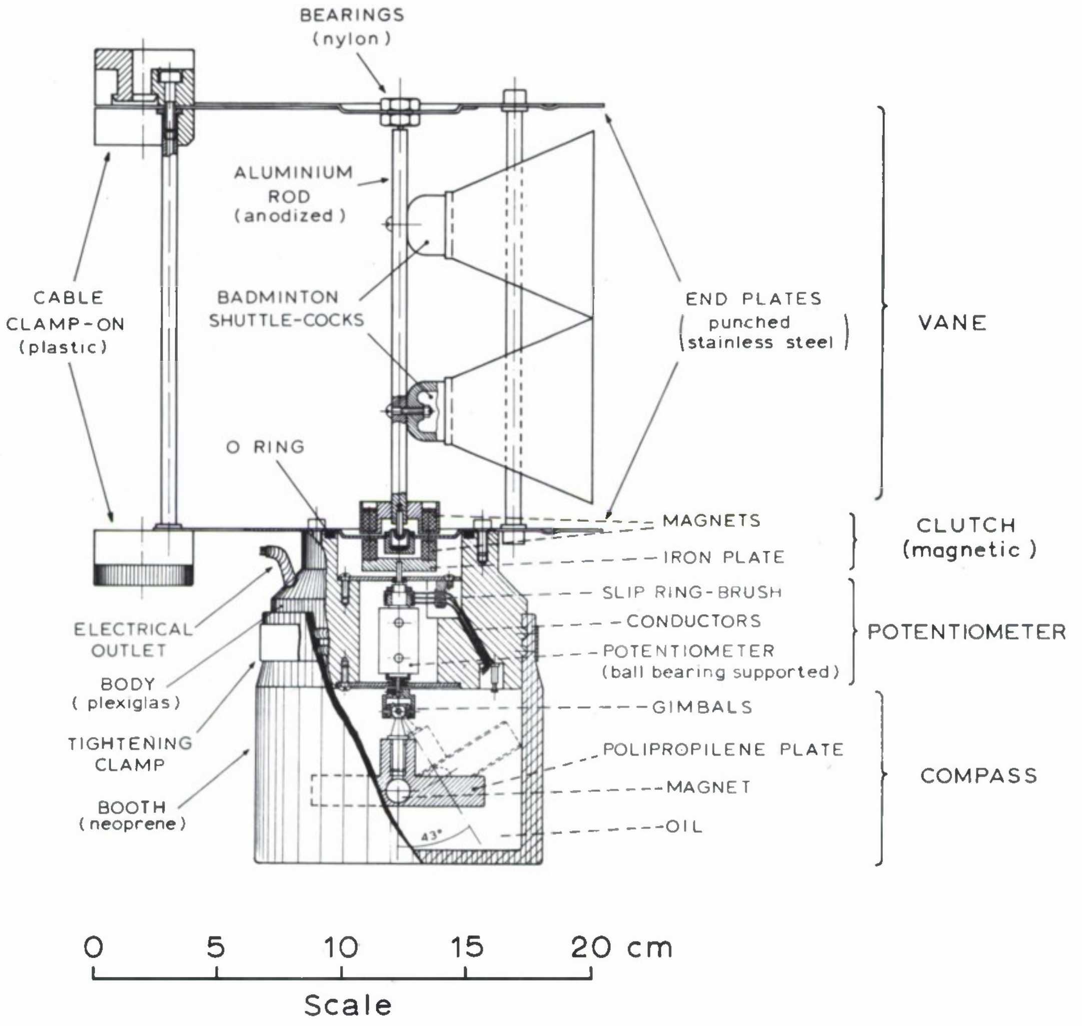


FIG. 5a

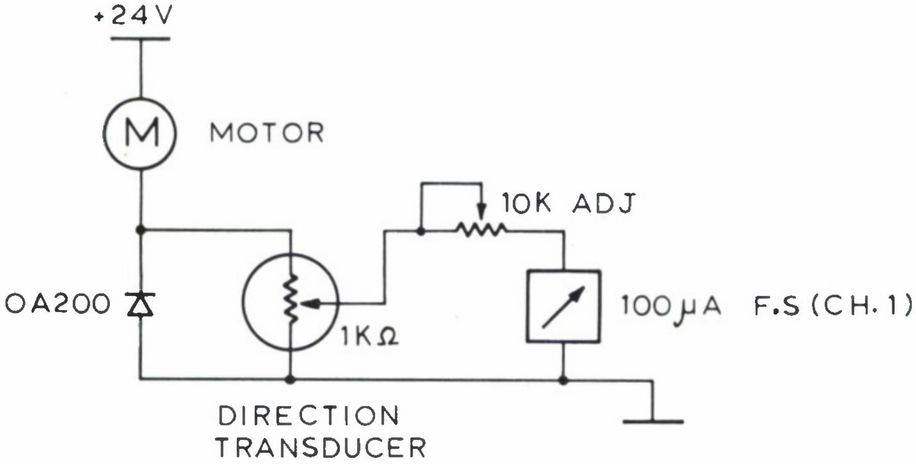


FIG. 5b

FIG. 5 THE CURRENT DIRECTION SENSOR.
THE TWO SHUTTLECOCKS FORMING THE VANE GIVE STABILITY IN STRONG CURRENTS. THEY TURN A POTENTIOMETER/COMPASS ASSEMBLY THROUGH A CLOSED-LOOP MAGNETIC CLUTCH THE CIRCUIT IS SHOWN IN Fig. 5b.

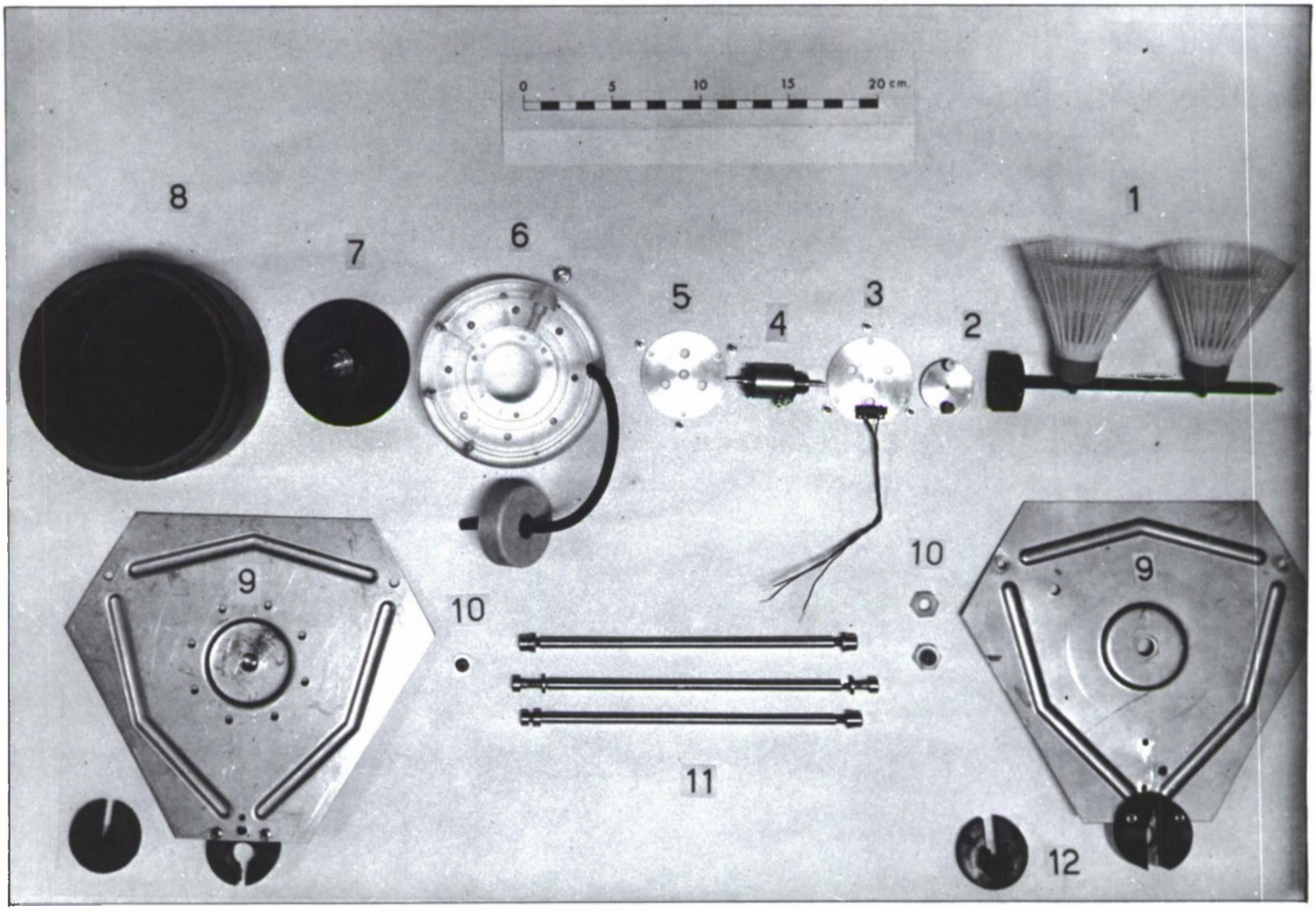


FIG. 6 COMPONENTS OF THE CURRENT DIRECTION SENSOR.
THE WEIGHT OF ALL PARTS HAS BEEN REDUCED TO A MINIMUN CONSISTENT WITH RIGIDITY

1. *PLASTIC BADMINTON SHUTTLE-COCKS FOR VANE*
2. *MAGNETIC CLUTCH*
3. *BEARING AND BRUSH SUPPORT PLATE FOR POTENTIOMETER*
4. *POTENTIOMETER OHMAG – 360°, 2000*
5. *LOWER BEARING END-PLATE*
6. *PLEXIGLASS HOUSING WITH ELECTRICAL OUTLET CABLE*
7. *COMPASS ASSEMBLY WITH GIMBALS*
8. *NEOPRENE BOOTH*
9. *STAINLESS-STEEL PRESS-PUNCHED PLATES*
10. *BROACHED NYLON SCREW FOR BEARINGS*
11. *STAINLESS-STEEL TUBE STAND-OFFS 6 mm OD*
12. *CABLE-CLAMP COMPONENTS*

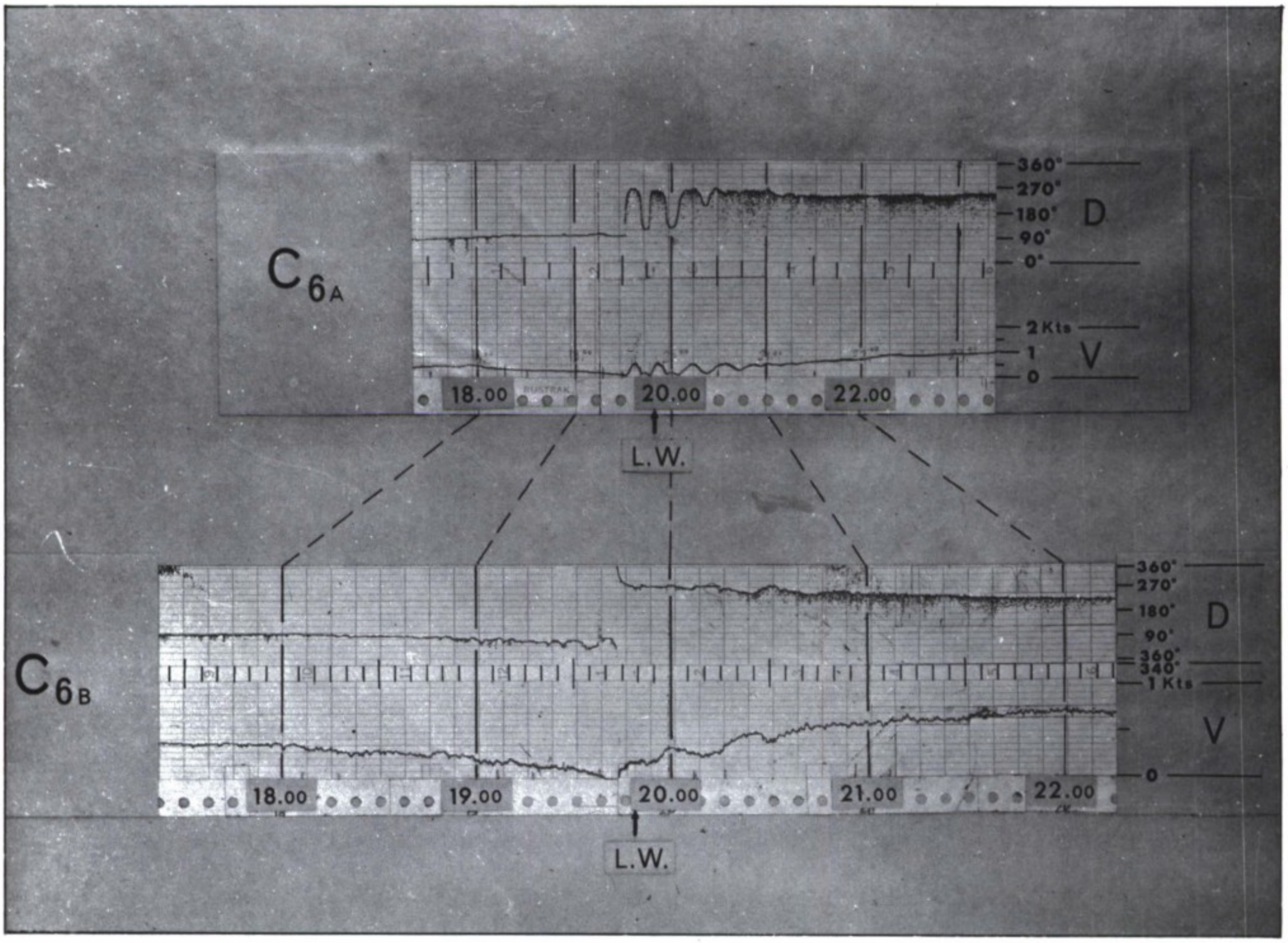
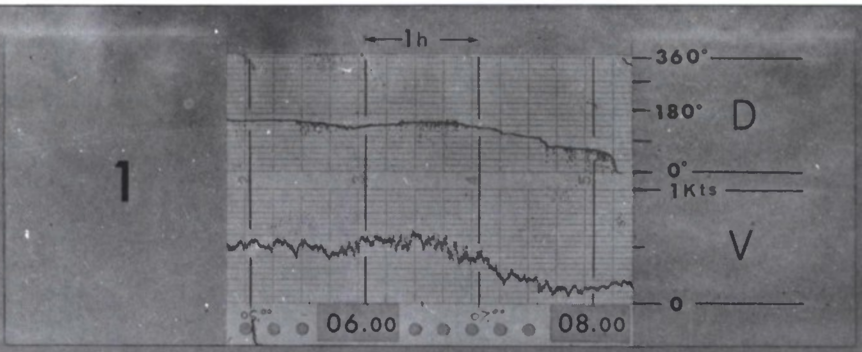
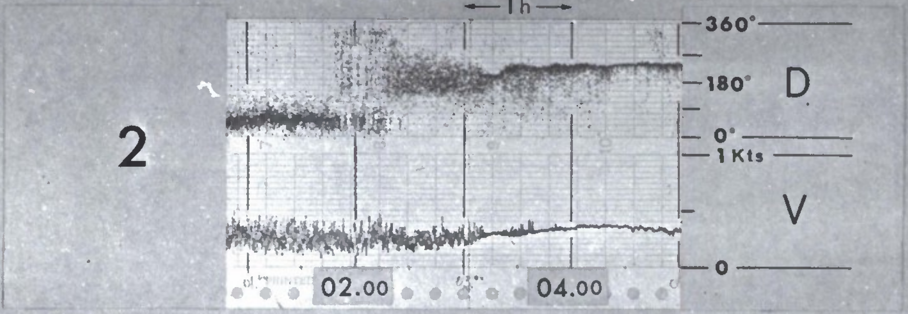


FIG. 7 EXAMPLES OF RELIABLE RECORDS.
THE RECORDS SHOWN ARE FROM TWO CURRENT METERS MEASURING AT THE SAME TIME BUT AT DIFFERENT DEPTHS (C6A at 300 m and C6B at 870 m) AND WITH DIFFERENT TRANSPORT SPEEDS (C6A at 1 in/h and C6B at 2 in/h). INTERNAL WAVES ARE SEEN IN C6A AT THE TIME OF THE CURRENT REVERSAL (from about 90° to 250°). THE SIGNAL IS REPRESENTED AS A DARK LINE ABOVE A CLOUD OF DOTS REPRESENTING NOISE ORIGINATING FROM MOORING MOTION.



Noise: period ~3 min. – Δv max. 0.1 Kt.

Signal: period ~ 10-15 min. – Δv max. 0.2 Kt.



Noise: period ~2.2 min. – Δv max. 0.32 Kt.

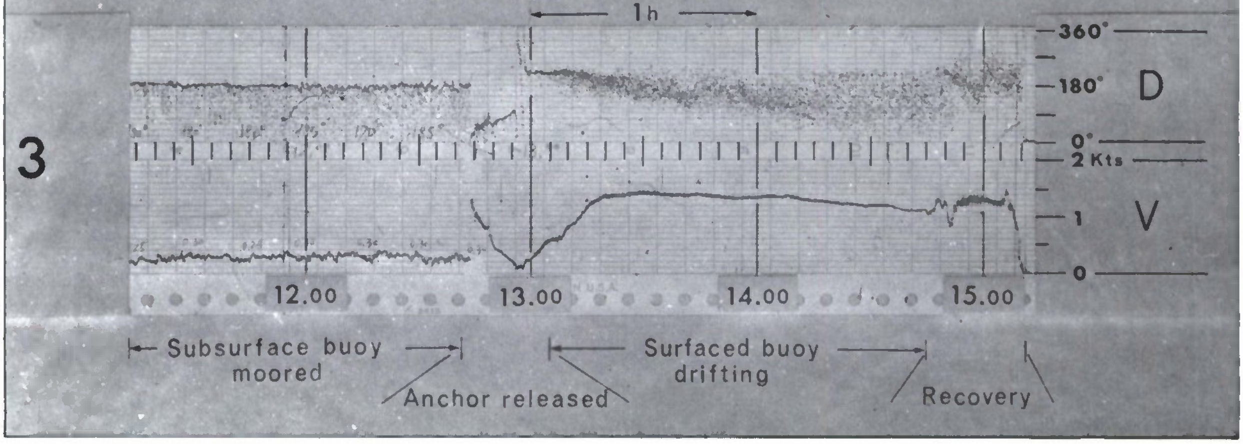


FIG. 8 EXAMPLES OF RECORDS ILLUSTRATING CERTAIN FEATURES

THESE ARE DISCUSSED IN PARA 6.2.

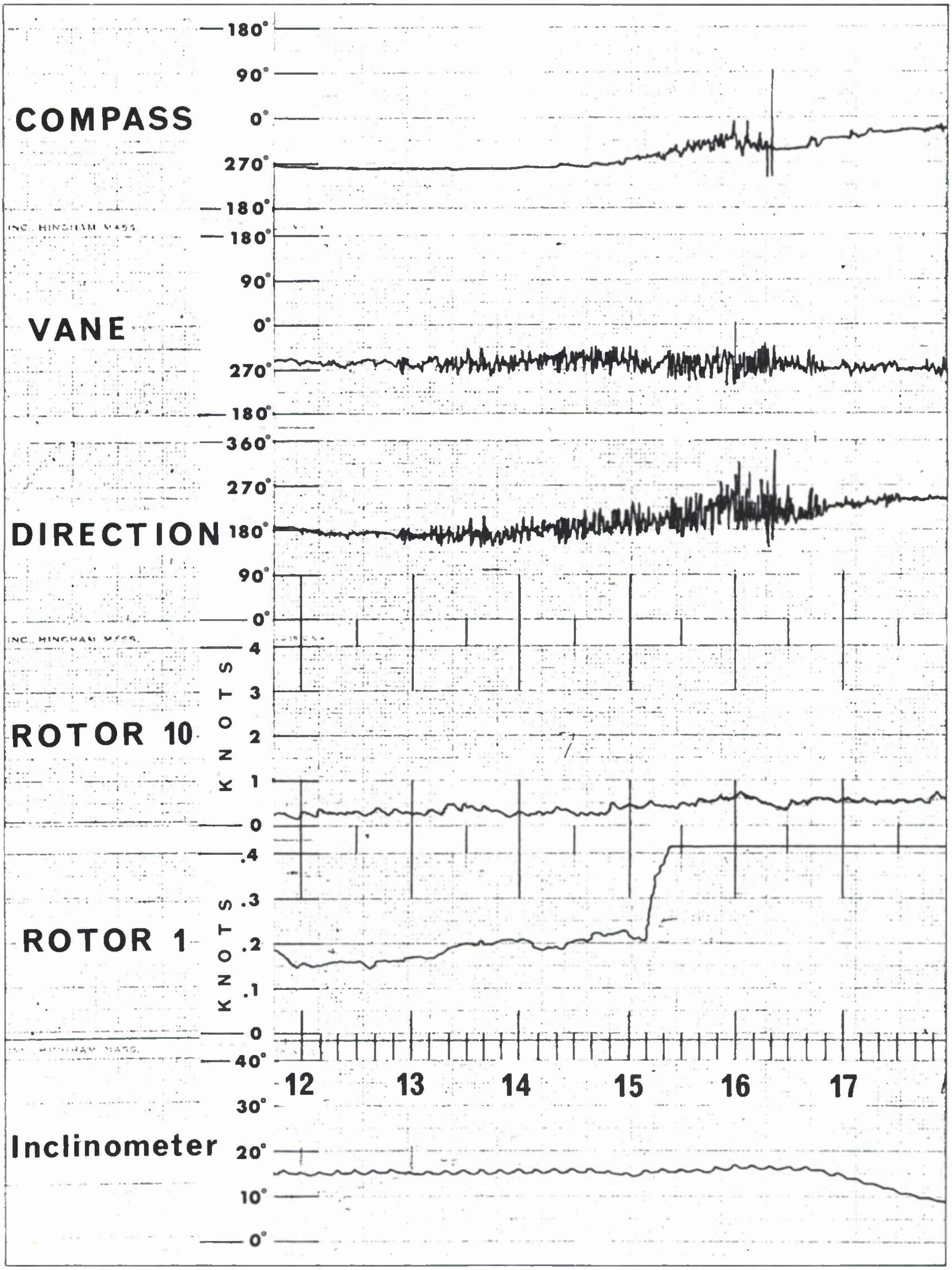


FIG. 9 EXAMPLE OF RICHARDSON CURRENT METER MEASUREMENTS.

MADE BY THE DATA-PROCESSING OF THE ORIGINAL FILM RECORD THE MEASUREMENTS WERE MADE IN THE SAME AREA OF THE STRAIT OF GIBRALTAR BY OTHER INSTITUTES. THEY ARE DISCUSSED IN PARA 6.3.

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