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A Technique for Measuring Deep Ocean Currents Close to the Bottom with an Unattached Current Meter, and Some Preliminary Results[1]

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ABSTRACT

A new system for measuring deep ocean currents close to the bottom is described. The device is moored in suspension with a float. Four sets of measurements, totaling 75.8 hours, were made at depths down to 5337 m. For one 16-hour period, a steady current of 17 cm/sec was recorded 3.5 m from the bottom at 5192 m. One measurement at 3584 m, 60 miles northeast of Cape Hatteras, indicates that the Gulf Stream extended to the bottom in this region.

Introduction. Attempts to measure currents near the bottom in the open ocean have employed variations of three basic techniques: (i) a current meter has been lowered to the bottom with wire from a ship (Pratt 1963); (ii) a current meter has been suspended from an anchored buoy (Richardson et al. 1963); and (iii) a current meter has been attached to a submersible ship such as the TRIESTE (LaFond 1962). Currents have also been inferred from bottom photographs of ripple marks on the bottom (Hurley and Fink 1963). Various free-falling instrument packages have been developed. The device described here is derived from the work of Isaacs and Schick (1960). The instrument, when launched, sinks to the bottom, remains there for a predetermined length of time, and then surfaces.

The Instrument. The instrument system, illustrated in Fig. 1, consists of five components: the current meter, the release mechanism, the weights, the flotation device, and the transmitter. In air, the system weighs approximately 217 kg. Except for the transmitter case and the aluminium brackets for holding the glass balls, which were manufactured in our shop, the system is standard

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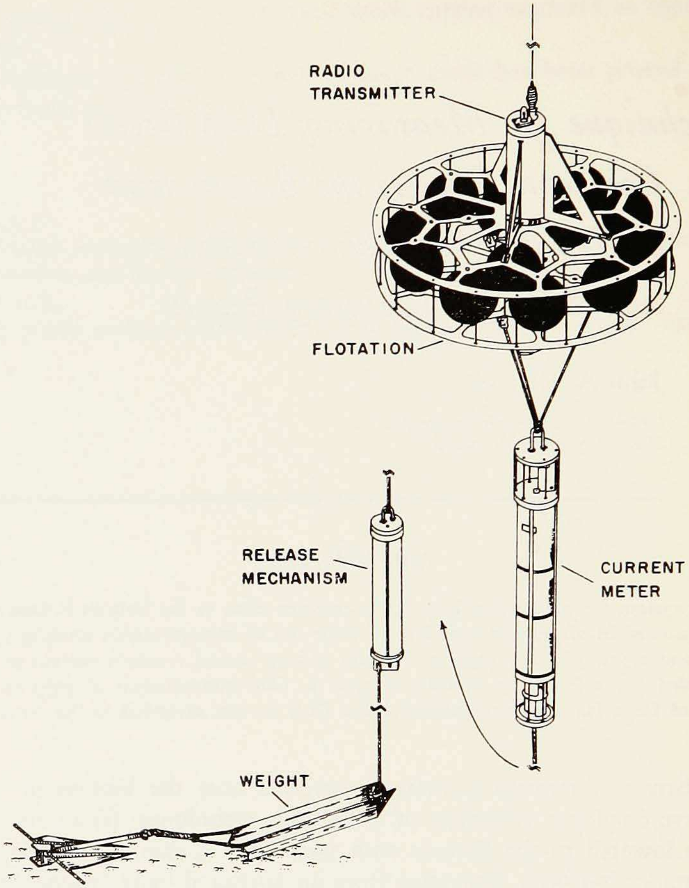

Figure 1. The current-meter system.

equipment. The total cost of the instrument package is approximately $4900. Complete details of the instrument are available on request.

The current meter, a self-recording instrument, has been described by Richardson et al. (1963). Data are recorded on photographic film: the speed of the current, as measured by a Savonius rotor, in analogue form; the direction, as measured by a vane, digitally; the instrument tilt from the vertical in five-degree increments, in analogue form. The sampling frequency is adjustable. After the film is developed, the data are "read" by an automatic scanning device and stored on magnetic tape.

The release mechanism can be set to go off in any 20-minute interval up to 140 days. At a predetermined time, an explosive device releases the line attached to the anchor and the gear floats to the surface. Both the current meter (model A-100) and the release mechanism (model A-393 with 9000-psi pressure case and heavy-duty lifting pad) are manufactured by the Geodyne Corporation, Waltham, Massachusetts.

The 30-cm (10-inch) glass spheres, which provide flotation, have been designed to withstand pressure at 6700 m (10,000 psi) and are manufactured by the Corning Glass Company. These balls are slightly below the critical Archimedean number of one.[2]

The radio-transmitter case contains a hydrostatic switch that is activated automatically within 10 m of the surface; this turns on the radio beacon and xenon light. The radio beacon (type TR-4), manufactured by Concord Control, Inc., Boston, Massachusetts, has a power output of 2.5 watts in the 3000-kc frequency band and broadcasts for five out of every 15 minutes. The xenon light (model 219), manufactured by Edgerton, Germeshausen, and Grier, Inc., Boston, Massachusetts, has a flash rate of 2.5 seconds and energy input of 0.25 watt-sec. Both the light and transmitter, in experiments, had sufficient battery power for four days of operation. The radio-detection finding equipment (model DFR-12) aboard R. V. TRIDENT was manufactured by Apelco Electronics, San Francisco, California. Most of the difficulties experienced in this first set of experiments were related to the problems of calibration of the RDF. Approximately one meter of torque-balanced nylon line connects each of the components. (However, calculations indicate that the amount of "overshoot" of any component as the system reaches its destination would not exceed 10 cm.)

Operation. Prior to launching, the amount of anchor weight and the number of glass balls are adjusted so that the equipment is approximately 20 kg heavy and 20 kg light on descent and ascent, respectively; the rate of fall and ascent of the package is about 0.5 m/sec. Also, the time for release of the current meter by the release mechanism is set before launching. At the set time, the squib fires, shearing a pin and releasing the line attached to the weights; the meter and transmitter are floated to the surface by the flotation component. The radio signal from the transmitter is detectable at 20 miles with the detection equipment aboard R. V. TRIDENT. On a moonless night and a calm sea the flashes of the xenon light were visible at 4.5 miles.

The response of the Savonius rotor in the meter may be nonlinear below 3 cm/sec, and it has been difficult to achieve reproducible calibration curves in this range. Threshold values range from less than 0.5 cm/sec to 3 cm/sec, depending on the mounting of the rotor and the method of calibration (Gaul 1962, Sexton 1964). The threshold of the vane is less than that of the rotor. At speeds between 1 and 3 cm/sec, it is thus possible to infer the direction of

2. The Archimedean number is a nondimensional number that determines the relative cost of flotation equipment for deep submergence. It is the cost of the flotation gear in pounds Sterling divided by pounds buoyancy. The glass balls cost $ 30 a piece and give 11.5 pounds buoyancy per ball. Their Archimedean number is 0.9.

TABLE I. Hourly Averages and Ranges of Current Speed and Direction Close to the Bottom at Four Deep Atlantic Stations.

Drop No. 1

Position, 32°11′N, 68°13′W
Depth, 5192 m
Start (Z), 1824, 22 June
End (Z), 1001, 23 June
Mean velocity (cm/sec), 16.8

Direction, 130.1°
No. of observations, 22,510
Range of values:
Speed (95°/₀), 14–21 cm/sec
Direction (95°/₀), 119–139°

Time (Z)	Velocity (cm/sec)	Direct. (°T)	Time (Z)	Velocity (cm/sec)	Direct. (°T)
19	17	133	03	16	126
20	17	132	04	17	124
21	17	134	05	17	124
22	16	137	06	17	124
23	16	135	07	18	128
24	17	131	08	17	131
01	16	130	09	17	134
02	16	128	10	18	134

Drop No. 2

Position, 32°05′N, 68°12′W
Depth, 5182
Start (Z), 0240, 26 June
End (Z), 1002, 26 June
Mean velocity (cm/sec), 11.8

Direction, 124.7°
No. of observations, 10,610
Range of values:
Speed (95°/₀), 10–15 cm/sec
Direction (95°/₀), 114–133°

Time (Z)	Velocity (cm/sec)	Direct. (°T)	Time (Z)	Velocity (cm/sec)	Direct. (°T)
03	13	129	07	12	118
04	12	130	08	12	122
05	11	127	09	11	124
06	11	121	10	12	129

the current, even if the estimate of the speed is in doubt. Since the system rotates during its descent and ascent with a period of approximately one minute, the record of the rotations indicates when the instrument reached its destination and when it began its ascent.

Following initial experiments in Narragansett Bay, the equipment was tested in deep water from 12 June to 3 July 1964. As is usual with newly developed equipment, a number of unforeseen difficulties arose. However, all problems were of a minor nature, and it is thought that, with certain comparatively simple modifications, this system can be used routinely to measure currents close to the bottom at depths up to 6000 m. Although preliminary measurements were made at 3.5 m above the bottom, there is no reason why the current meter could not be lowered to only 1 m from the bottom; conversely, there is no reason why the current meter or a series of meters could not be suspended at greater distances from the bottom.

TABLE I. (Cont'd)

DROP NO. 3

Position, 34°24′N, 69°47′W
Depth, 5337
Start (Z), 2240, 27 June
End (Z), 1030, 29 June
Mean velocity (cm/sec), 0.6

Direction, 028.8°
No. of observations, 51,600
Range of values:
Speed (95 %), 0–2 cm/sec
Direction (66 %), 19–72°

Time (Z)	Velocity (cm/sec)	Direct. (°T)	Time (Z)	Velocity (cm/sec)	Direct. (°T)
23	1.2	356	17	1.4	007
24	1.1	355	18	1.5	027
01	1.5	358	19	2.3	038
02	1.7	012	20	1.8	040
03	1.6	023	21	1.4	037
04	1.6	029	22	1.7	031
05	1.4	038	23	1.6	035
06	1.1	054	24	0.6	037
07	1.2	058	01	0.0	–
08	1.4	067	02	0.0	–
09	1.1	067	03	0.0	–
10	0.6	063	04	0.0	–
11	0.0	–	05	0.0	–
12	0.0	–	06	0.0	–
13	0.0	–	07	0.0	–
14	0.0	–	08	0.0	–
15	0.7	345	09	0.0	–
16	1.4	358	10	0.0	–

DROP NO. 4

Position, 36°04′N, 73°13′W
Depth, 3584 m
Start (Z), 1858, 30 June
End (Z), 1157, 1 July
Mean velocity (cm/sec), 9.7

Direction, 032.8°
No. of observations, 24,460
Range of values:
Speed (95 %), 7.5–14 cm/sec
Direction (95 %), 27–40°

Time (Z)	Velocity (cm/sec)	Direct. (°T)	Time (Z)	Velocity (cm/sec)	Direct. (°T)
20	10	039	05	9	035
21	10	031	06	10	032
22	10	028	07	11	031
23	9	035	08	12	032
24	9	033	09	10	033
01	9	034	10	10	030
02	8	036	11	11	033
03	9	034	12	10	031
04	9	033			

Preliminary Results. In four launchings and recoveries in deep Atlantic water (Table I), the current meter operated successfully. The meter was adjusted so that the direction was read every 2.5 seconds; the speed was determined over a single rotor revolution, and the meter tilt was recorded once a minute.

The data were averaged over five-minute increments (120 observations). There was very little change in either the speed or the direction from one five-minute period to the next or even from one hour to the next. A mean current velocity for each hour for each of the four lowerings is given in Table 1. On each of the four drops, 95% of the five-minute averaged values were within 2 cm/sec of the mean speed. The meter tilt was less than 5° at all times on all four lowerings.

There was apparently little energy in fluctuations at higher frequencies. Histograms of the speed and direction data taken at 2.5-second intervals were plotted. They showed essentially the same distribution of values as the five-minute averages. The range of values in which 95% of the observations fell is given in Table I.

Central Atlantic Observations. The first two observations were made about 200 miles west of Bermuda on the western slope of the Bermuda Rise. The gradient is 1:700 and the bottom slopes down toward the Hatteras Abyssal Plain to the west. The area is characterized by gently rolling hills 200–1000 km wide, 40–100 m high (Heezen, personal communication).

The first drop showed a steady current of about 17 cm/sec flowing toward 130° over the 15.6-hour recording period. The second drop showed a 12 cm/sec current flowing toward 125° over the 7.7-hour recording period. The two drops were 6.1 miles apart. There was a 64-hour time interval between the end of the recording for Drop No. 1 and the start of recording for Drop No. 2. It seems possible that during this 4-day period there was a steady current close to the bottom, moving between 10 and 20 cm/sec toward 125°–130°.

The third observation, the longest of the four (35.8 hours), was made about 150 miles northeast of the first two observations on the northern edge of the Hatteras Abyssal Plain. The abyssal plain deepens to the south with an approximate gradient of 1:4300 (Heezen, personal communication). The results indicate that the current velocity was low and that there were no oscillations of periods of less than 24 hours having speeds equal to, or greater than, the mean speed. Tidal currents or inertial oscillations, if present, must be less than 2 cm/sec. Any further interpretation of the results should be done with caution for reasons noted under *Operation.* However, since the threshold of the vane is less than that of the rotor, we can speculate about the current velocity during the periods when the speed is less than that of the threshold of the rotor. The direction record indicates that, during the first period of "zero speed," the vane rotated clockwise from 070° to 335° at a rather constant rate over the 4-hour period; during the second period of "zero speed," the vane indicated a current direction between 030° and 075° for nearly ten

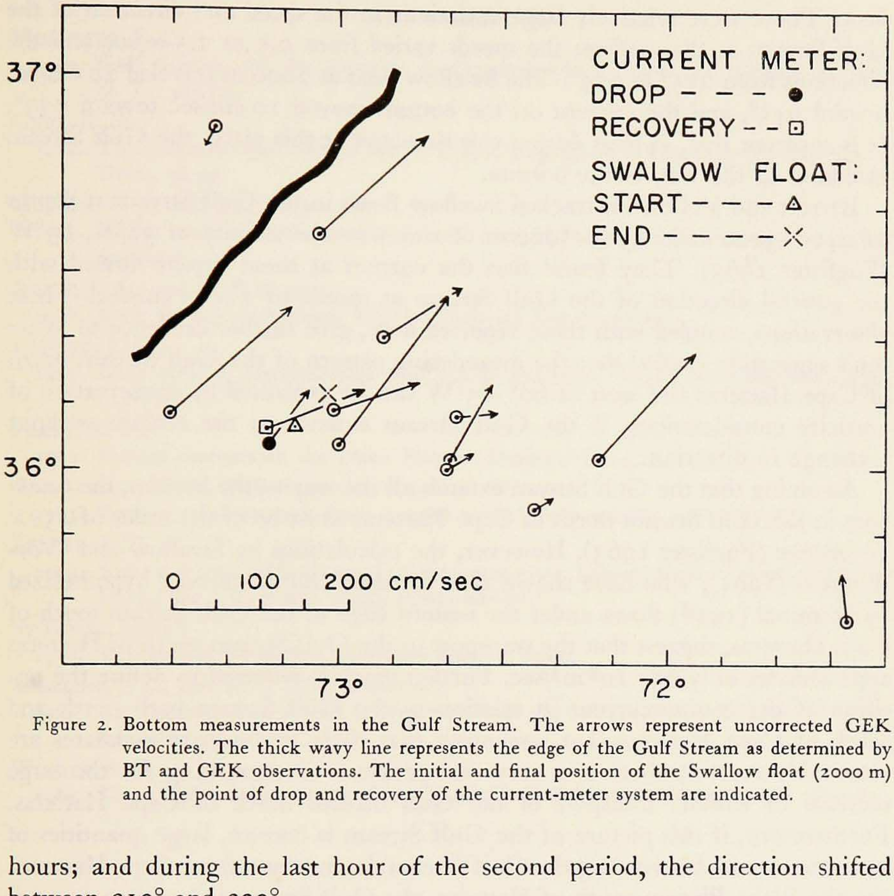

Figure 2. Bottom measurements in the Gulf Stream. The arrows represent uncorrected GEK velocities. The thick wavy line represents the edge of the Gulf Stream as determined by BT and GEK observations. The initial and final position of the Swallow float (2000 m) and the point of drop and recovery of the current-meter system are indicated.

hours; and during the last hour of the second period, the direction shifted between 310° and 320°.

Gulf Stream Observations. The fourth observation, of 17 hours duration, was made in the Gulf Stream, about 60 miles downstream from Cape Hatteras. Prior to the drop, the position of the Gulf Stream was determined by measuring the surface velocity with a Geomagnetic Electrokinetograph (GEK) and the slope of the isotherms with a bathythermograph (BT). While the current meter was on the bottom, a Swallow float at 2000 m was tracked for approximately 24 hours. After the current meter was retrieved, another GEK and BT run was made across the Gulf Stream to determine whether its position had changed; it had not. From the GEK and BT observations, it was determined that the current meter on the bottom and the Swallow float at 2000 m were from 50 to 60 km southeast of the northwestern edge of the Gulf Stream.

Fig. 2 shows the uncorrected GEK velocities and the approximate edge of the Gulf Stream as well as the position of the current meter and the Swallow float. There were relatively large variations in the speed and direction of the Gulf Stream at the surface; the speeds varied from 0.5 to 2.5 m/sec and the directions from 035° to 075°. The Swallow float at 2000 m traveled 20 cm/sec toward 045°, and the current on the bottom moved 10 cm/sec toward 033°. It is apparent that, at least during this time and at this place, the Gulf Stream extended all the way to the bottom.

Barrett and Volkmann tracked Swallow floats in the Gulf Stream at depths of 2400–3000 m in 4500–5000 m of water in the vicinity of 38°N, 65°W (Fuglister 1963). They found that the current at these depths flowed with the general direction of the Gulf Stream at speeds of 11–17 cm/sec. These observations, coupled with those reported here, give further credence to Warren's suggestion (1963) that the meandering pattern of the Gulf Stream north of Cape Hatteras and west of 60°–65°W can be explained by conservation of vorticity considerations, if the Gulf Stream extends to the bottom without a change in direction.

Assuming that the Gulf Stream extends all the way to the bottom, the transport in the Gulf Stream north of Cape Hatteras must be of the order of 150×10^6 m^3/sec (Fuglister 1963). However, the calculations by Swallow and Worthington (1961), who have shown that the deep countercurrent hypothesized by Stommel (1958) flows under the eastern edge of the Gulf Stream south of Cape Hatteras, suggest that the transport in the Gulf Stream south of Hatteras approximates only 65×10^6 m^3/sec. Further work is required to define the position of the countercurrent in relation to the Gulf Stream both north and south of Cape Hatteras, but, assuming that these preliminary estimates are reasonably correct, there is a very real problem in accounting for the large increase in volume transport of the Gulf Stream north of Cape Hatteras. Furthermore, if this picture of the Gulf Stream is correct, large quantities of new water must be entering the Gulf Stream downstream from Cape Hatteras. On the Blake Plateau south of Hatteras, the Gulf Stream is less than 1000 m deep and the heaviest water has a potential density of about $\sigma_\theta = 27.5$; at a depth of 3600 m northeast of Hatteras, where the current meter was recording 10 cm/sec, $\sigma_\theta = 27.9$.

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