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Woods Hole Oceanographic Institution

Woods Hole, Massachusetts

SECOND REPORT ON THE GEOMAGNETIC ELECTROKINETOGRAPH

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THE GENERAL THEORY OF THE ELECTRIC POTENTIAL FIELD INDUCED IN DEEP OCEAN CURRENTS

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I Summary Introduction

Since the appearance of the first report on the Geomagnetic Electrokinetograph (von Arx 1947)* research has been directed toward an evaluation of the capacities and limitations of the instrument. Effort has been spent in both the field and laboratory toward improvement of its operation and on direct measurement of the effects of the physical environment on its behavior. All of this work was furthered by help from the Naval Ordnance Laboratory. Drs. Rumbaugh, Maxwell, and Green and Messrs Bleil, Dobrin, Haddad, and others of NOL were most cooperative in providing technical information of both verbal and written kinds. Through them and the Hydrographic Office (Oceanographic Division) temporary loan of two reports on collateral researches (McKelvey 1944) and (Report 85 M.S.BuShips) was secured. During the summer the help of Messrs Osborn and Duys was also secured at W.H.O.I. for field and laboratory work. Mr. Osborn reviewed the existing literature on the Faradic Effect, and also made progress toward a mathematical statement of the effect as it applies to the Electrokinetograph (Osborn 1947). Mr. Duys was primarily concerned with the installation of gear, repairs and maintenance, and stood relief watch on most of the cruises at sea. Mr. Dobrin of NOL joined the observing staff on Cruise B-16 of the Balanus and made independent measurements of propeller noise and other effects with NOL equipment (Dobrin 1947).

Following this cruise materials became available for the manufacture of NOL-type Silver-Silver Chloride electrodes. These electrodes are in many ways superior to the W.H.O.I. type but they ~~also~~ have an unstable zero-point in changing environments of temperature and salinity which complicates field procedures and hinders direct application of the Electrokinetograph principle to navigational aids. Of the experiments conducted to measure the forward speed of the ship, and its set in a current, neither were wholly successful because of zero-point drift. Studies of zero-point drift and its dependence on the temperature and salinity of the environment have been made in the laboratory. Future work in this direction faces the Law of Diminishing Returns and so it has been decided to abandon further experiments with electrode materials and phenomena until it can be arranged for a competent theoretical electrochemist to study the problem.

Approximately six weeks were spent at sea with the Electrokinetograph (Balanus Cruises 6,9,14,16 & 17 and Atlantis Cruise 149; see figure 0) to gather data on the validity of the instrument as a current measuring device. Half of this sea time was spent in water shoaler than 150 fathoms to determine the effects of depth and bottom resistivity on the value of k the correction coefficient in the fundamental relationship

$$\text{Emf} = (\underline{E})\, 10^{-8} = (\underline{V} \times \underline{H}_z)\, 10^{-8} = k(\underline{ir}) \qquad (1)$$

(*) Reprinted and bound between these covers following the index. This report is essentially an announcement of early results and contains a few representative voltage traces together with Faraday's original statement of the physical effects which he expected would produce them.

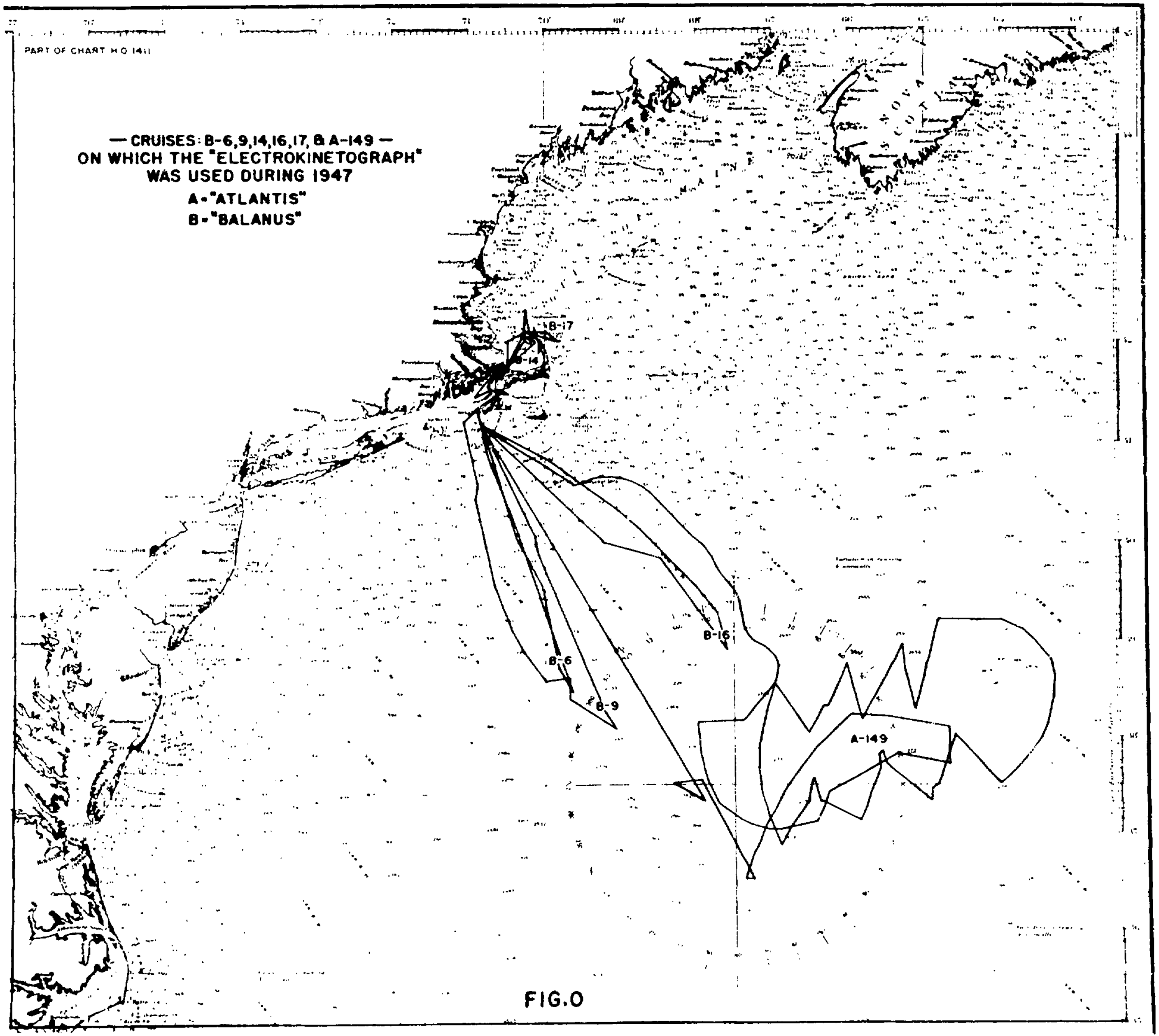
PART OF CHART H.O. 1411
— CRUISES: B-6,9,14,16,17, & A-149 —
ON WHICH THE "ELECTROKINETOGRAPH"
WAS USED DURING 1947
A - "ATLANTIS"
B - "BALANUS"
B-17
B-14
B-16
B-6
B-9
A-149

FIG. O

The value of k was found to be unity everywhere outside the 50 fathom contour regardless of bottom character, but to vary over wide ranges within that depth for a number of reasons.

These cruises also provided acquaintance with the "normal" voltage trace. Hours on watch spent in following the trace as it was written on the strip chart made it possible to discern characteristic voltage signatures for various maneuvers of the ship and various kinds of water motions. Sufficient data were collected for a few tentative ideas to have been developed concerning the water motions themselves. Several experimental sailing plans were devised on these cruises designed to reveal further details of the oceanographic features through which the ship made her way and to gather these data with the greatest economy of time and effort. Of the voltage signatures recorded a large number were ascribable to sources other than water motions. These are called artifacts and have been satisfactorily explained and distinguished from the water motion signals. While earth-current signals are discussed under this heading they are of natural origin and have received separate study along with the control observations of earth-currents for the purpose of extracting these background signals from the Electrokinetograph records. An arbitrary scale of earth-current intensities has been developed and standardized in absolute units and the changes of the absolute magnitude of these intensities between the land and the sea have been measured a number of times.

Instrumentation of the Electrokinetograph has been improved considerably as has its general convenience. Auxiliary circuits have been devised which will control the amplitude of the wave signal and thus reveal the amplitudes and characters of less obvious water motion signals, renew and adjust the electrode surfaces for proper operation without having to haul the electrodes aboard, and also measure the electrode resistance without disturbing their zero-point. A Magnesyn compass has been installed on the instrument panel so that the course of the ship can be studied both as a check on the helmsman during the execution of the "sailings" and as a guide to the accuracy of current direction measurements. The power supply section is now divorced from the ship by a high grade isolation transformer and the input voltage and frequency are presented on the panel by appropriate meters. These indicators and controls increase the stability of performance and time registration of the strip-chart recorder. The speed of response of the recorder has been increased from 12 seconds full scale sweep to 1.7 seconds. This enables most wave signals to be recorded without appreciable mechanical amplitude suppression as was formerly the case.

The theory of the instrument has undergone further clarification from the standpoints of both practical observation and mathematical analysis. Certain questions are too cumbersome or obscure for effective mathematical treatment but most of these can be answered by means of experiments in the field. While this approach lacks academic elegance and to some extent clouds the issues with uncertainty, it has been used in addition to the mathematical treatment whenever possible. Some of the present knowledge of the effects and capacities of the instrument is wholly of experimental origin and some is desk work. The zone of overlap between the two is widening as time goes on, and as theory and practice are reconciled.

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II Directional Errors, Magnitude Errors

The determination of current direction by means of the Electrokinetograph is theoretically as exact as the precision of voltage measurements and theory of errors will allow. But practically, there are other errors to be accounted for as follows: The directions along which voltage measurements are made are measured by the ship's compass which is subject to small systematic and accidental errors. This compass also acts as a guide to the helmsman who does his best to curb its wanderings. In correcting the course of the ship to make the compass read the requested heading his course yaws more or less from side to side of the heading depending on the wind and sea state. Ordinarily the yaw is of the order of 2 or 3 degrees, but in bad weather it may reach 15 or even 20 degrees in small ships. The interelectrode portion of the cable is about 2.5 times the ship's length away and consequently yaws somewhat less than the ship does. But it must yaw. For this reason a course must be held for a sufficient length of time for the yawing process to pass through several cycles so that the voltage changes from the turn signals generated can be averaged out. The turn signals are negligible but the sinusoidal path of the ship may be terminated at any point in which case the average direction of the ship's course from the initial point to the end point may be different from the requested heading. The amount of this difference has been studied during observations of currents at sea.

For this study a remote indicating Magnesyn compass was installed separately from the ship's compass and the indicator placed on the panel of the Electrokinetograph. In this way the voltage signals and the behavior of the ship's head could be followed together. It was found that the turn signals were inconsequential but that the yawing ranged between the values given above. In general the helmsman "worked the wheel" about twice each minute so that the period of the sinusoidal track in time is fairly uniformly of the order of 1 minute. In one minute the ship travels 600 feet at 6 knots and if the half-angle of yaw is 2.5 degrees the maximum distance off the intended track is roughly 13 feet. Taken over a period of 4 minutes on a jog this amounts to an uncertainty of only 17 minutes of arc on either side of the heading, closer than the accuracy of the compass. But for yaws having a half angle of 7.5 degrees the greatest departure is about 40 feet on either side of the course, which again over a 4 minute course amounts to an uncertainty of about 1 degree on either side of the steered heading. Thus the probable error of heading for both courses is less than ± 2 degrees under the most adverse conditions. On longer legs or in better weather or in bigger ships the probable error of heading becomes negligible, provided the ship's compass is in good adjustment.

Accompanying the directional error there is an error in magnitude of the resultant voltage and the current calculated from each pair of component measurements. If the components are at right angles, as is standard practice, the greatest magnitude error occurs when the resultant bisects this angle and when the angular errors are in opposite directions from the resultant. To calculate the magnitude error, it is the angular difference between the lines connecting the true initial point with the true end point and the intended end point of a component course that must be considered. In good

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weather, as explained above, this angle totals 34 minutes and rises to 2 degrees in bad weather. If the bad weather error is made in opposite directions on two component courses at 90° to each other and the resultant bisects this angle the greatest magnitude error is under 5%. A number of experiments in deep water in both good and bad weather with control measurements of current speed show that magnitude errors seldom exceed 5%.

The forward motion of the observing ship has no effect upon the reception of signals from the water, neither does it produce an error in the direction between the compass heading of the ship and that of the interelectrode line. The basis of this assertion is simply that the ship and the electrode line in a current are acted upon by the same forces and relative to the current there is no motion except the forward motion of the ship and the towed electrodes. Taking the bottom and the magnetic field of the earth as the inertial system, however, there is more to consider. In this case the progress of the ship and electrodes lies along the resultant composed of the ship's forward motion vector and the current vector. This still does not alter the alignment of the ship's keel and the electrode line, but does produce a lateral component of motion which is greatest when the ship is sailing at right angles to the current. In this case the cable connecting the electrodes sweeps out an area per unit time which has the shape of a square if the ship is hove-to across the current and the shape of a parallelogram if the ship is underway. The area of the square (ab) is exactly the same as that of the parallelogram (ab) no matter how fast the ship may go since the lateral set of the ship (a) is not altered and neither is the interelectrode distance (b). The product of these two quantities define the area swept by the interelectrode line per unit time.

If the ship is not sailing at right angles to the current but at some arbitrary angle θ the area of sweep is determined by the product of the set of the current per unit time and the interelectrode distance corrected for the cosine of θ. Again the forward speed of the ship does not enter and is of no consequence to the measurements.

This reasoning has omitted the effects of wind on the ship for the good reason that wind causes trouble. Wind from any direction except dead ahead and dead astern sets the ship without setting the electrodes. This produces an error in alignment between the heading of the ship and the azimuth of the interelectrode line. The magnitude of this angular error depends upon the set the wind gives the ship rather than on the strength of the wind itself. It can be defined easily as the ratio

$$\frac{\text{Ship's leeway} \quad \text{(knots)}}{\text{Ship's speed forward} \quad \text{(knots)}} = \tan \alpha \qquad (2)$$

where α is the alignment error between the ship's keel and the electrode cable. In the numerator it is the sideways motion (leeway) of the ship that is important and not the total windage for the reason that the component of windage parallel to the keel merely alters the ship's forward speed. Forward speed is measurable by the log even though it is not entirely imparted by the engines or sails. The greater the ship's speed through the water the smaller both $\tan \alpha$ and α itself become. This error is quite large during rough weather in small ships like the Balanus which makes leeway in beam winds and waves of force 4 as rapidly as 1 knot. Her forward speed under such conditions must be reduced to 5 knots which brings the value of α to a little more than 11 degrees. Much rougher weather was experienced on the Atlantis, a bigger ship, deeper and heavier in all respects yet even her leeway was between half and three-quarters of a knot. Her forward speed however, could be held at 7 knots without discomfort. In this instance the value of α was 5 degrees; still not inconsiderable. Fortunately this error is systematic, and if the ship's windage can be measured by chip or current meter its components can be allowed for on all headings and the current measurements corrected accordingly.

A similar alignment error will arise when the Electrokinetograph is used for the measurement of deep currents. The observing ship floating in the surface current will be set by that current while the electrodes in a deeper current or another portion of the surface current will experience a different set. Thus the azimuth of the keel of the ship will not coincide with that of the interelectrode line because that will be aligned with a resultant which is the "effective current" produced by the ship's geographic motion and the deep current. This resultant is calculable only when both vectors are known, consequently it will be necessary to observe the resultant directly by incorporating a direction indicator on the interelectrode portion of the electrode cable. This expedient would also cure the difficulty of windage errors in the measurement of surface currents and make the observation procedure wholly independent of winds, currents, leeway and ship's speed. Such an installation (Magnesyn remote indicating compass system is contemplated) is relatively simple and can be accomplished at any time. It has been delayed because it more than doubles the number of conductors required in the outboard cable and increases the stiffness and cost of the cable many fold. It would also increase the bulk and drag of the outboard gear to a point beyond the ability of one man to handle it without mechanical aid. This complication has to be met, however, if the greatest precision and usefulness is to be gained from the instrument as a whole.

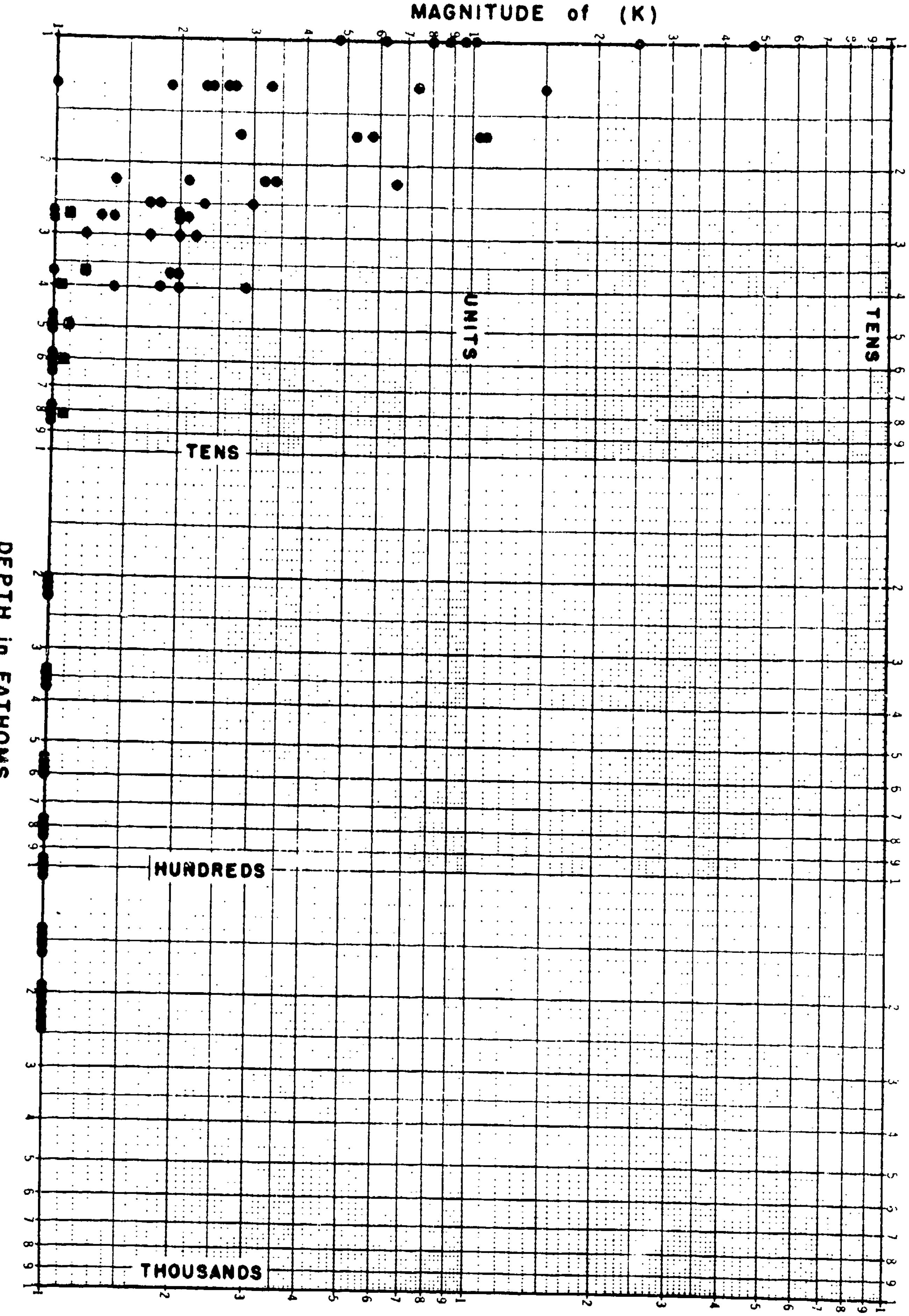
MAGNITUDE of (K)
DEPTH in FATHOMS
UNITS
TENS
TENS
HUNDREDS
THOUSANDS

FIG. I

 [redacted]

III Validity Studies

The validity of current measurements made with the Electrokinetograph has been under scrutiny from the very beginning. Four methods have been employed thus far:

a) Comparison of measured currents with predicted currents near lightships listed in the Current Tables, Atlantic Coast, 1947.

b) Comparison of measured currents with other measurements made from an anchored ship with "von Arx Meter" Model 2.

c) Comparison of measured currents with current determined from repeated Loran fixes on a drifting ship whose drift is corrected for windage.

d) Comparison of measured currents with currents determined from current poles released near a temporary buoy and fixed on by angles to shore points or measured by sailing at constant speed from the end of the pole field to its origin.

Concerning (a) remarkable coincidence of direction has been obtained by this method in rotary currents on the continental shelf. The magnitude of the current is usually in error by a constant amount due to the effects of the k factor. These comparisons were made in excellent weather during the summer when wind drift errors were small. The absence of wind drift effects is attested to by the fact that the ratio (k) of the observed and predicted currents remained nearly constant for a large variety of current directions.

Concerning (b), this method was largely inconclusive for the reason that no experienced observers were available to man the propeller type current meter suspended from the anchored ship. It is very difficult for an inexperienced observer to detect and exclude the signals generated by the yawing and riding of a ship on her anchor from those of the true current. The Model 2 meter provides the deck observer with continuous indications of the relative current composed of the motions of the ship on her anchor and the true current. By studying the rhythm of the ship's motions an observer can extract the true current with reasonable certainty, but due to the effects of rather large waves on the small boat and on the digestive tracts of the observers not much was accomplished in this way.

Concerning (c) a number of prolonged (3 to 5 hours) drift stations were occupied both inshore and at sea during which the Loran was used at 20 minute intervals. In addition the ship's windage was measured repeatedly by means of the Model 2 meter overboard and the average of that motion subtracted vectorially from the geographic drift. The result gave the current component which showed excellent agreement with the currents indicated by the Electrokinetograph. Currents as swift as 5.5 knots were verified by this method in the Gulf Stream.

Concerning (d), which is self explanatory, disappointing results were secured until a sufficient number of observations were made in different

[redacted]

depths of water to indicate the existance of the k factor. The data concerning the k factor, to be discussed later, were accumulated by this method only at first and later by methods (a) and (c).

The problem of measuring currents is inherently so difficult that one is put to it to devise satisfactory methods for checking an instrument that probably measures currents more certainly than any of its checks. To date no comparison has been made between currents measured with the Electrokinetograph and those deduced from Dynamic Computations. This is an extremely interesting experiment from many points of view and may be executed very soon.

All reliable measurements made with the methods just outlined have been compared with current measurements made at the same times and stations with the Electrokinetograph. As it is difficult to say "which is correct" the directional differences between the two measurements are tabulated as follows:

Table 1

Method	(a)	(b)	(c)	(d)	
Total tests	45	28	37	21	(131)
No. Agreements within ± 2°	18(40%)	0(0%)	10(27%)	4(19%)	
No. Agreements within ± 5°	27(60%)	3(11%)	26(70%)	9(43%)	
Average angular disparity	4°	35°	5°	12°	

The poor results from method (b) are almost certainly due to improper interpretation of the indications from the propeller type meter. It is interesting to note that the average angular disparity for method (d) lies within the values for the angular divergence of a field of poles, which at Bikini was found to vary from 8° to 14° and at Woods Hole to range between 11° and 15°. Dye trails show a similar angular divergence and when run with current poles there is a strict correlation of the boundaries of the dye trail and the greatest width of a field of current poles released from the same point at the same time. It is reasonable to expect that the angular resolving power of the Electrokinetograph is low in terms of small angular variations in the direction of water motion which can be encompassed between the electrodes and that it is sensitive to something approaching the mean motion between these limits. Therefore, if the Electrokinetograph measures the average direction of water motion between the electrodes and the signal is read as the average over several minutes run, it is reasonable to conclude that the angular disparity of each pair of comparative measurements results from the difference between the average direction of water motion and the detailed motion of any small parcel shown by the current pole. The improved correlations existing between the

Electrokinetograph measurements and those by methods (a) and (c) bear out this argument since both of these latter methods involve the average direction of water motion accumulated from a large number of observations in the case of (a), and a relatively long time span in the case of (c).

<u>k factor</u>

The correlation of current magnitude as shown by the Electrokinetograph measurements with measurements made by other methods (a), (b), (c) and (d) reveals a systematic difference which apparently depends upon the total depth of water. More than half of the comparative tests were made in water shoaler than 150 fathoms. In figure 1 the results of these observations are plotted against station depth. The coordinates are logarithmic in both directions so that the details are less crowded near the origin.

The factor $\underline{k}$ was originally defined

$$k = \frac{E}{e} \quad \frac{\text{the "expected voltage"}}{\text{the observed voltage}} \qquad (3)$$

This choice of possible definitions is admittedly a poor one but it serves to reveal the relationship between the voltage expected from Faraday's Equation for a given magneto-mechanical situation and the voltages actually observed. As $\underline{e}$ is commonly less than or equal to $\underline{E}$ the value of $\underline{k}$ is correspondingly equal to or greater than unity. Of the 98 values of $\underline{k}$ plotted in figure 1 all but 6 are equal to or greater than unity. The 6 less than unity are plotted as their reciprocals and denoted by small squares so as to compress the ordinates within the compass of two logarithmic cycles.

It appears from the points on this graph that beyond 50 fathoms the assurance of unit $\underline{k}$ is extremely high; but why 50 fathoms? The whole matter will be explained in Chapter VII on Theory but let it be hinted here that the total depth is far less important than the ratio of the depth of the surface current to the total depth. Within the 50 fathom curve rotary tides dominate the current systems. These tides cause water motions which extend almost to the surface of the continental shelf. For this reason the "surface" current thickness and the total depth of water are very nearly the same and as a result the value of $\underline{k}$ rises abruptly. At the edge of the shelf the tidal motions are less significant and the surface water motions are underlain by relatively thick layers of water which do not necessarily participate in the surface motion. These layers produce the natural short circuit required to lower the value of $\underline{k}$ to something approaching unity.

Superficial features in the water such as turbulence structures, waves and thin layers of water driven by the wind are probably recorded at very nearly unit $\underline{k}$ values even though the thicker current in which they occur may have a high $\underline{k}$ value.

Measurements of sea bottom resistivity (McKelvey 1944) show that the electrical depth is very little greater than the physical depth. That is the total conductivity of the sea bottom when converted to a prism of sea water

 [redacted]

of equal conductivity, adds little to the effective conducting prism offered by the sea water alone. Work on this problem conducted along the Eastern and Gulf seaboards of the United States shows that a prism of sea water ranging from 0 to 15 or 25 feet thick need be added to the local depth to give the same total conductivity as the combined conductivity of the sea water and water saturated bottom material. Thus the k factor rises in shoal water when the current extends to the bottom even though there is a stationary conducting path in the sedimentary floor. If the sea floor were composed of a thick carpet of copper, k would not rise in the zone of rotary tidal currents.

E-C Background

All measurements of potential in the sea made with the Electrokinetograph have a certain background or "noise level" derived from the ambient potentials and currents in the lithosphere and hydrosphere. It is not fully known to what sources these currents owe their origin but they are associated in their times of occurrence and magnitude, with fluctuations in the magnetic envelope of the earth, the occurrence of solar flares, and perhaps the interaction of streams of charged particles from these flares with the magnetic field of the earth. The arrival of such streams may be the cause of aurorae which are also associated in time and magnitude with earth currents. Whatever their origin, earth-currents are recorded by the Electrokinetograph at sea. The intensity of the earth current background varies from day to day and reaches "storm" intensity on the average of from about 3 to 6 days per month. During "storm" conditions the earth-current signal is larger than the signal received even from very swift water motions, consequently such periods are unsuitable for current measurements. At other times during each month there are "disturbed" days when the earth-current background has roughly 3 to 5 times its "quiet" amplitude. This rise in the background noise level raises the threshold velocity sensitivity of the Electrokinetograph from 1 cm/sec to about 5 cm/sec but does not influence its directional sensitivity appreciably. Oceanographic measurements to the nearest 5 cm/sec is sufficient accuracy for many purposes, consequently only 10 to 20 per cent of each month is completely lost through background interference. These estimates are based on present conditions and those of the past year, a year of exceptional solar activity. For this reason they may be somewhat pessimistic compared with estimates for quiet solar years. Nevertheless, even the present estimate of time lost through geophysical interference is not discouraging and if the threshold values of sensitivity of the instrument are recognized as being variable, reliable work should be capable of accomplishment on more days per month than are usually available when only meteorological interference is considered. The occurrence of meteorological and geophysical disturbances are completely unrelated at any given point so that it is entirely possible for a day of excellent weather to be lost through excessive background. On the other hand very bad weather meteorologically may be ideal geophysically in which case observations of water motions during heavy storms can be made with perfect confidence. Such observations are of great value to oceanography.

As yet it is impossible to determine from the Electrokinetograph record itself just how much of the signal is due to water motion and how much comes from the earth-current background. For this reason it is necessary to maintain a control which records earth-currents alone and to operate this control station throughout every cruise. The present technique employs the well established fact that earth-currents are of a world-wide nature (Rooney 1947; Fleming 1941) and that observations made at one station may be assumed to indicate the conditions at a distant station quite well. This assumption is thought to be especially valid in the sea because of the electrical homogeneity of the medium in which the earth-currents flow. Stations on the lithosphere are subject to local interference from the channeling of earth-currents in portions of the crust which have lower resistivity than the surrounding region (Rooney 1947). This changes the absolute magnitude of the earth-current potentials and may also alter the character of their fluctuations somewhat by changing the direction of flow. The sea is close to having perfectly isotropic resistivity and consequently the direction and magnitude of earth currents in deep water are very nearly the same over areas tens of degrees square. Near shore some influence of the increasing proportion of bottom resistivity is probably to be felt but the superficial layer of electrolyte undoubtedly has the effect of smoothing out variations of the bottom resistivity when the entire prism of sediment and electrolyte is taken into account. There is a further effect at the shore line pointed out by Barber (A.R.L.) that arms of the sea tend to collect earth-currents as they offer a path of lower resistance than is found in the land. This effect would tend to exaggerate the magnitude of earth-currents measured in embayments of all kinds, and diminish them around promontories. There is no apparent reason to expect either effect to alter the relative amplitude changes and general character of recorded earth-current fluctuations except to change their direction in some degree.

The present method of extraction of background from the Electrokinetograph records is quite crude. Observations at sea and at the shore station are made simultaneously. At the end of the cruise the shore station record is studied and the periods of "storm", "disturbed" and "quiet" are determined on the basis of 3-hour indices beginning at 0000 GMT. The trace amplitudes are measured against an arbitrary scale from 0 to 9 and the average character of each 3-hour period given an index number. In this way each day's earth-current activity is reduced to an eight digit number which can be tabulated and read with considerable efficiency. The scale corresponds to potentials in millivolts per kilometer as follows:

Table 2

0	1	2	3	4	5	6	7	8	9
1.0	2.0	3.5	6.0	11.5	18.0	26.5	35.0	38.5	40.0 mv/km and over
("quiet")		("disturbed")		("storm")					

The ranges of indices corresponding to "storm", "disturbed" and "quiet" classifications are different for each of the periods which have been discriminated thus far as shown in table 3. But taken as a whole the trace can be classified as shown above. Portions of the voltage trace from the Electrokinetograph having a background index of 0 or 1 are considered to have an accuracy of magnitude of 1 cm/sec, for indices 2, 3, and 4 an accuracy of 5 cm/sec is assumed, and for 5 or more the records are rejected as unreliable. These limits are derived from the background voltage picked up at sea along an interelectrode distance of 38 meters, which in local magnetic latitudes gives a sensitivity of 1 mv/knot on the Electrokinetograph tape. This tape is graduated to 0.1 mv divisions which can be read to the width of the ink line 0.01 mv which is also the value of the minimum discriminable signal. This corresponds to a water motion of 0.5 cm/sec. It has been found that records of the same background disturbance at sea and ashore differ in itensity by a factor of from 4 to 10, the records taken at sea being the smaller. This is understandable because of the lower resistivity of the sea.* Allowing a factor of 5 between the records ashore and at sea a shore-recorded background of 2.6 mv/km can be tolerated without invalidating an assumed accuracy of 1 cm/sec. An accuracy of 5 cm/sec corresponds to a background voltage disturbance within the compass of 0.1 mv on the Electrokinetograph and a maximum tolerable earth-current variation of 13.0 mv/km as measured by the shore based recorder. Backgrounds larger than this are so irregular and contain large amplitude variations in the 1 to 60 minute range which badly confuse the records of current boundaries, eddies and currents themselves.

It has been necessary to make a careful study of the characteristic traces of earth-current records in order to distinguish them from the signals originating in the sea. In character both kinds of signals are periodic or semi-periodic but those generated by water motions are smoother and more nearly sinusoidal than the spiked and sharply variable short period signals from earth-currents. This subjective difference is confused by a zone of uncertainty which is particularly broad for the long period variations. Signals having periods under 20 seconds are easily verified as they are principally caused by waves.

The earth-current variations which have been discerned in the Woods Hole records are the dirunal variations, variations of the order of an hour's duration possibly related to the "range effect" of Guelcke and Schoute-Vanneck (1947) and still other very short period variations requiring the order of 10 minutes, 1 minute and fractions of a second to execute a cycle. The amplitudes of these variations change with the total signal amplitude in the manner shown in table 3.

(*) It has been found that the amplitudes of earth-current signals of "storm" intensity measured at sea are less than those measured during the same storm at Woods Hole. Simultaneous measurements in the same azimuth yielded voltages which 200 miles at sea were on the average only 1/5 as large as the corresponding signals picked up across Woods Hole. This may be the result of intensification of earth-currents in embayments suggested by Barber in his recent paper to the Royal Astronomical Society (Geophys. Sect'n) or may result from the change in total resistivity resulting from the replacement of water for earth in a prism of given depth as the currents make their way seaward.

[redacted]

Table 3

Values in millivolts per kilometer of the several kinds of periodic earth-current disturbances recognized in W.H.O.I. data.

	Storm	Disturbed (max.)	Quiet	Minimum
Diurnal	Greater than 26.5 >6	3.5 - 11.5 (2) - (4)	3.0 - 4.0 (2)	3.0 - 4.0 (2)
Range Effect (30-60 min.)	11.5 - 26.5 (4) - (6)	11.5 - 26.5 (4) - (6)	1.0 - 3.5 (0) - (2)	less than 1.0 (0)
10-30 minute	11.5 - 40.0 (4) - (9)	3.5 - 18.0 (2) - (5)	1.0 - 3.5 (0) - (2)	less than 1.0 (0)
1-10 minute	11.5 - 18.0 (4) - (5)	2.0 - 11.5 (1) - (4)	1.0 - 3.5 (0) - (2)	less than 1.0 (0)
less than 1 min.	3.5 - 6.0 (2) - (3)	1.0 - 2.0 (0) - (1)	less than 1.0 (0)	less than 1.0 (0)
less than 1 sec.	2.0 - 6.0 (1) - (3)	1.0 - 2.0 (0) - (1)	less than 1.0 (0)	less than 1.0 (0)

N.B. Disturbances having periods between 1 and 6 hours have also been infrequently observed.

The values given above in millivolts per kilometer result from expression of the index scale in absolute units and should not be interpreted as more than a guide to the order of magnitude of the potentials. The values are also distorted by the non-linearity of amplitude response of the galvanometer to frequencies higher than 3 cycles per minute.

Some effort has been made to discover a means for detecting the state of the earth-current background at sea while observations are in progress. A number of possibilities suggest themselves and some have been studied by others (summary Chapman and Bartels, 1940 and Fleming, 1941); the state of the ionosphere as reported at frequent intervals by WWV, the degree of fading noted by the ship's radio operator, observation of the general spottedness of the sun with particular attention to spots transiting near the center of the sun's disc, observation of the polar aurorae and also of the general illumination of the night sky compared with a "radiolite" standard kept in darkness, subjective estimates of background from the Electrokinetograph trace itself, but so far no single phenomenon gives sufficiently close correlation to the record of the shore-based earth-current recorder to be used as an independent guide at sea. A final attempt is being made to correlate the intensity of the OI line (5577 Å) in the spectrum of the night sky with earth-current traces. This line is thought to result directly from the arrival of charged particles from the sun thought by some to be fundamentally responsible for the bulk of earth-current disturbances as well as the electrodeless discharges in the upper atmosphere. Results of this experiment are still too meagre to permit discussion of its probable outcome.

The best single estimate of background that can be made at sea is the subjective study of the "sense" in the signal record. Ordinarily the observer can anticipate the character of trace to be written during the execution of maneuvers by the helmsman. For example in running squares for calibration and fixing instrumental zero the observer anticipates that the signal on the east and west courses will lie symmetrically on either side of the zero established by running the north-south courses. In times of earth-current disturbance this does not often happen. Other clues to background disturbance arise when the trace shifts from side to side giving "turn signals" when the ship is not turning, or when erratic drift of zero is complicated by kinks and cusps in the voltage trace recorded on a straight run. The periodic earth-current disturbances have nearly the same period and amplitude as turbulence signals from strong currents like the Gulf Stream, but possess a much more irregular character than the smooth undulations of voltage generated by the moving water. Earth-current disturbances of "storm" intensity frequently begin instantaneously, the background index rising from 1 to 8 or 9 in less than a minute, followed by slow subsidence of signal amplitude during the ensuing 12 to 36 hours. The onset of such storms can be discerned if the voltage record is compared with that of the shore-based recorder, and if it is a severe storm the onset can be detected at sea. During such storms nothing makes sense. Ship's maneuvers produce meaningless changes of voltage when they are superimposed on a rapidly fluctuating background. When puzzling effects are encountered the background usually has increased to an index of 5 or more.

IV Characteristic Voltage Signatures Recorded by the Electrokinetograph

A variety of signals are now recognized as being characteristic of a number of phenomena observable with the Electrokinetograph. These fall naturally into two categories, ARTIFACTS and SEA WATER MOTIONS:

Artifacts	Sea Water Motions
Turn Signal	Wave Signal
S-T Signal	Turbulence Signal
Temperature effect	Eddy Signal
Salinity effect	Current Signal
Zero drift	Current boundaries
E-C Background Signals	
Thunderstorm Signals	

ARTIFACTS

The TURN SIGNAL is the potential signature between the steady potential registered on one course and the steady potential measured on another course immediately following. The connecting trace begins to become a turn signal from 10 to 30 seconds after the ship has started turning, depending on the speed of the ship and the length of cable out, and lasts as long as the ship's turning time. It varies in complexity from a simple shift from the old potential to the new one, to an exaggerated sine wave. The phase of the wave is opposite for right and left hand turns. The signal is caused by the drogue which produces side-slip of the interelectrode portion of the cable cutting the corner of the turn just made by the ship. If the sea is flat and the ship has turned in such a way that the side slip produces a voltage in the same direction but smaller magnitude than the change of course produces, a simple line results; if opposite, the turn voltage will register and then be gradually overpowered by the steady voltage on the new course. In smooth and rough weather helmsmen often overshoot their turns and have to come back to the new heading. This produces a double curve in the cable and consequently a right and left hand signal successively. When the ship has been running with the wind and turns to take it on her beam the signal usually is simple. When she has been running against the wind and turns to take it on her beam a double curve results in the cable as her leeway picks up and a sinusoidal signal is generated. This effect is often augmented by overshooting the turn.

The S-T SIGNAL is a sudden change in the trend of the average potential picked up on a straight course which correlates with a coincidental shift of salinity and temperature in the STD* trace. These signals are encountered along the northwest margin of the Gulf Stream and along the margins of Gulf Stream eddies.

(*) "STD" refers to the Salinity-Temperature-Depth Recorder developed at W.H.O.I. (under Contr. NObs-2083) for obtaining continuous vertical sections of salinity and temperature against depth at a given station, or, when the detecting element is secured to the ship's side, a trace of the horizontal distribution of temperature and salinity at constant depth recorded with the ship under way.

They are listed among the artifacts because they have a compound origin; (a) a natural origin in the change of water velocity and (b) an artificial origin in the change of interelectrode potential resulting from the change of chemical environment around the electrodes. The artificial effects have been studied in the laboratory in an attempt to disentangle the two and discover how much of the total signal is due to water motion by evaluating and subtracting the chemical and thermal effects.

These studies have shown that the effect of changing environment is very large if the changes are not encountered simultaneously at both electrodes, but quite small if the changes are precisely simultaneous. The magnitude and sign of the effects also varies with different electrode pairs. The temperature effects are smaller than the salinity effects.

THE TEMPERATURE EFFECTS. When a change of temperature occurs at both electrodes simultaneously or very nearly simultaneously a voltage signal is produced which depends on the rate of temperature change

$$\frac{d\Theta}{dt} = -a\left(\frac{dV}{dt}\right) - b \qquad (4)$$

where a and b are constants peculiar to the selected electrode pair which have values near 0.060 and 0.130 respectively. The effect is of the order of 10 microvolts/min. for a temperature change of 0.5°C/min., the order of rate of change of surface temperature found in crossing the edge of the Gulf Stream at 6 knots.

The signal resulting from the difference in instantaneous temperature of the two electrodes is much larger. This effect has the form

$$V = c(T_2 - T_1) + d \qquad (5)$$

where T_1 and T_2 are the respective instantaneous electrode temperatures and c and d are constants peculiar to the pair. The value of d is zero if the origin is chosen properly and the value of c is near 0.5 if V is expressed in millivolts and $(T_2 - T_1)$ is Centigrade degrees. The horizontal surface temperature gradient at the edge of the Gulf Stream is shown by the STD to be near 0.3°C/100 meters. For a ship sailing parallel to this gradient with an interelectrode spacing of roughly 40 meters the instantaneous temperature difference between the electrodes is approximately 0.1°C yielding a voltage of the order of 50 microvolts.

Thus the total artificial signal from the two effects discussed so far is 60 microvolts (0.060 millivolts) which correspond to an error in deduced current of 6% or about 0.06 knot.

THE SALINITY EFFECT has been similarly treated in the laboratory. For a simultaneous change of salinity at both electrodes the ultimate voltage change follows the linear relationship

$$V = e\,(S_2 - S_1) + f \qquad (6)$$

[redacted]

where e and f are constants peculiar to the electrode pair. The constant f represents the voltage of the initial "zero point" and e has a value near 0.010 when S is expressed in parts per thousand and V is expressed in millivolts. The shape of the time vs. voltage trace is that of an overdamped oscillation. The time required to complete a shift of zero point due to simultaneous change of salinity at both electrodes depends upon the electrode pair to a large degree, as well as the magnitude of the salinity change. For an instantaneous change of salinity of 2 ‰ the new equilibrium voltage is reached in 5 minutes. Such a change will shift the equilibrium or zero point voltage 1.00 mv. which leads to an error of 1 knot in the current readings if the shift is not apprehended. In practice the salinity gradients in the sea do not change more rapidly than 1 ‰ per 6 or 7 miles which from a ship moving parallel to the gradient at 6 or 7 knots means a change of salinity of 1 ‰ per hour. A pair of electrodes about 40 meters apart moving down this gradient experience a small difference of salinity in their respective environments amounting to about 0.003 ‰. The effect of this is to produce a slow but determined shift of zero point the rate of which depends as much on the matching of the electrodes as anything else. Even for an unmatched pair the rate is slow enough for equilibrium to be maintained and the shift is quantitatively logged by the routine hourly or half-hourly zero point check. If equilibrium is only imperfectly maintained there is some tendency for voltage hysteresis on the "jogs" hence it is important to have electrodes matched to give zero potential in a static salinity and temperature environment and in a changing one as well. This selection can be made by appropriate tests in the labcartory.

The problem of salinity and temperature sensitivity of Silver-Silver Chloride electrodes is a difficult one to solve. It is so difficult indeed that there is little hope at present of solving it at all. No known electrode is completely inert and free of contact potential or susceptability to polarization. Until such time as theoretical electrochemistry brightens the outlook in this direction the problem of existing electrode surface behavior must be studied.

Laboratory studies of salinity effects show that for the case in which the salinity at one electrode remains the same while the other changes, enormous signals are generated. If one electrode is in a bath at constant temperature which has a salinity of 32 ‰ and the other is suddenly transferred to a bath at the same temperature having zero salinity the voltage shift is greater than 500 millivolts. Recovery from this disturbance takes 2 or 3 days, but the electrodes will adjust to these new conditions. At the equilibrium point the Chlorinity of the original salt solution and the fresh water become more nearly the same. Evidently the products of the concentration cell thus produced are

$$\underline{AgCl} + \underline{Ag}, (Cl^-)_1 \rightleftharpoons (Cl^-)_2, \underline{AgCl} + \underline{Ag} \qquad (7)$$

(Disturbed electrode) (Undisturbed electrode)

in which the disturbed electrode produced Cl^- ion to replenish the concentration about it by the reaction

$$\underline{AgCl} + e \longrightarrow \underline{Ag} + Cl^- \qquad (8)$$

and the undisturbed electrode provides the necessary electron as

$$Cl^- + \underline{Ag} \longrightarrow \underline{AgCl} + e. \tag{9}$$

In so doing the contact potentials of the two electrodes are changed so that through the combination of electrode surface potential (Polarization) and the reactions given above, electrical equilibrium is reached before $(Cl^-)_1 = (Cl^-)_2$. The curve of voltage against time for this reaction has the form of an overdamped oscillation for which the ultimate rest point lies on the opposite side of the time axis from the initial deflection. This curve is a member of a family of the mathematical form

$$V_t = e^{(-i/2n)t}(A + Bt) - (V_o + at) \tag{10}$$

where $\underline{i}$ is the coefficient of ionic diffusion, $\underline{n}$ the quantity in mols of Cl^- ion transferred in the equilibrium shift, $\underline{A}$ and $\underline{B}$ are constants depending upon the change of concentration of Cl^- ion at the disturbed electrode and the magnitude of the concentration at the undisturbed electrode, and $\underline{a}$ is the coefficient governing the rate of change of polarization of the electrodes. The constants of this equation have not been evaluated.

The more practical case of the parallel lag of salinity change at each of two electrodes has been studied. It amounts to a continuous solution of the above equation in terms of V_o and V_t as $\underline{t}$ approaches infinity. This value is called V_a, the voltage to which V_t is asymptotic with time. It has been found experimentally that the initial deflection of zero point decreases in magnitude as the rate of salinity change is decreased. For slow changes of the order of 1 $^o/_{oo}$ per minute the initial deflection practically vanishes and the instantaneous equilibrium voltage moves directly toward V_a. This effect should be completely evaluated for ordinary oceanographic conditions since it is responsible for voltage hysteresis during sudden changes in the rate of change of the salinity gradient which occur during the execution of calibration squares and jogged courses. It may also contribute to the shape of TURN SIGNALS discussed in the previous section.

It may be concluded about S-T SIGNALS that they are of small magnitude (perhaps 3 to at most 5 cm/sec) for the cases discussed but may on occasion become very significant wherever abrupt irregularities of salinity and temperature exist. To evaluate the records of the Electrokinetograph one must take into account the STD trace and, for the present, disregard violent fluctuations of indicated current whenever there are rapid changes in salinity and temperature. Mean values through such water can almost certainly be relied upon however as they have checked out very well against currents computed from loran and windage measurements.

ZERO DRIFT is a slow but determined trend of the zero point voltage toward one side of the scale. It is caused by unequal electrode reaction to persistent unidirectional gradients of salinity and temperature for the most part, but may also occur when one electrode is flushed more vigorously than the other. It can be cured by packing both electrodes very tightly in glass wool and selecting electrodes to be used as a pair for their identity of response to changes of salinity and temperature. Out of a dozen new electrodes perhaps two or three pairs will be found which have suitable gradient response. The remaining electrodes can be saved for possible pairing with members of a new lot of electrodes.

BACKGROUND SIGNAL is a periodic or semi-periodic oscillation of voltage arising from the geophysical background against which water motion signals are measured. The nature and magnitude of the background due to earth-currents has been discussed in detail. There is thus far no technical means of eliminating these signals; instead, they must be allowed for by comparison of control observations made ashore with the traces recorded at sea. Other sources of background are presumably to be found in submarine ore-bodies, UEP signals, propeller "noise" from the observing ship, and variations of H_z during magnetic storms. Thus far none of these have been found to be troublesome. The electrodes are towed 2 to 3 ship-lengths astern so that the UEP and magnetic effects of the ship are of negligible magnitude.

THUNDERSTORM SIGNALS occur only when there are cloud to earth discharges. They produce very brief pulses of potential in the sea which vary in intensity inversely as some function of the distance of the flash and seem to change sign as the discharge point moves from one side to the other of the perpendicular bisector of the interelectrode line. No serious interference has occurred furing any of a number of thunderstorms experienced at sea. Observations made throughout thunderstorms show no evidence of unreliability.

Signals from SEA WATER MOTIONS

The total signal from the sea is composed of three major components each present in varying degrees. These are the WAVE SIGNAL, the TURBULENCE SIGNAL, and the CURRENT SIGNAL respectively.

The WAVE SIGNAL is an oscillatory voltage fluctuation having a complex period which is the harmonic sum of all the wave periods present, and a complex amplitude which is the algebraic sum of all the horizontal wave particle velocities normal to the interelectrode line. The principal period is that of the wave having the greatest amplitude and the principal amplitude is that of the wave group having the highest particle velocity. The same wave group is usually responsible for the principal period and amplitude unless two or more wave groups interact to produce interference effects in which case the voltage signal is most simply described in terms of the "beats" they produce.

The wave signal is highly directional. When running in the troughs the maximum signal is received since the motional electromotive force is at right angles to the direction of particle motion. When bucking or running with the sea much smaller signals are received, but they are not zero. The signal amplitude also decreases as the electrodes are made to run deeper in the sea, and there is also a reduction in the complexity of the trace as the shorter period waves exert less and less influence on the particle motions. Quantitative studies of these effects are being planned.

During current studies it is convenient to suppress the wave signal by means of large capacitors shunted across the input terminals to the voltage recorder. This technique is capable of removing the wave signal entirely but restricts measurements of periodic motions in the sea to periods of greater length than the longest wave period. It is also possible to damp out chop and reveal the ground swell by this method, but since pure capacitance does not possess low pass filter characteristics with sharp cut-off, the amplitudes of longer period wave signals are diminished somewhat. The design of variable low pass filters with sharp cut off frequencies for wave studies is under consideration.

The TURBULENCE SIGNAL is a slow oscillation of voltage resulting from coarse turbulence in the sea composed of eddy-type motions each cell of which to be measured, must be of the order of or larger than the interelectrode distance. This kind of signal is non-directional in the sense that it appears much the same regardless of the course of the ship or course changes. It is not derived from background because earth-current background has directional characteristics which are rather marked when the intensity is this high. Turbulence signals of the kind described have been found to occur along the northwest margin of the Gulf Stream and to a lesser extent in the slope water adjacent to it. They have also been recorded in channels such as Vineyard Sound, Nantucket Sound (Western end), off Race Point and in the Cape Cod Canal. In these shoal water areas the k factor is rather large for currents but since no independent measurements have been made of turbulent structures their k factor is unknown. If the structures are small it is possible that k is also small since there is a relatively large volume of water surrounding each turbulent mass with the independent motions which when integrated over the width and depth of the channel has little characteristic motion other than the tidal transport. Such a mass is capable of providing the low resistance return circuit needed to keep k at a low value. Even though the velocity structure of turbulent masses is uncertain in shoal water for want of a k factor, the horizontal dimensions can be measured and have been found to vary from about 100 to 500 meters in the waters around Woods Hole and from 300 to 1500 meters and more across in the deep waters in and near the Gulf Stream.

These figures are subject to criticism since the sections taken through these presumably circular structures are not necessarily central. By selecting for measurement the signals which show the greatest amplitude for a given period it is thought that diametrical sections are more probably represented. It is also possible that the signatures which have the longest period for a given amplitude may represent diametrical sections, but this too is uncertain for the lack of information concerning the size distribution of the turbulent structures. While the data accumulated are uncertain for the above reasons at least, it appears that the turbulent structures have a different maximum tangential velocity/radius ratio as the radius increases. The maximum tangential velocity rises as the radius increases in all cases, but the peripheral velocity may be asymptotically limited at some value of the order of 300 or 400 cm/sec. It is also recognized that the turbulence structures do not possess the rotational character of solid bodies or centrally energized vortices. The tangential

 [redacted]

velocity at any point on a given radius increases as the radius to a point something like 0.707 times the greatest length of that radius and then decreases again to zero. The value 0.707 R_{max} is considered to be the effective radius of such features since it describes the circle of greatest angular momentum. The volumes inside this circle and between this circle and the outermost circle may contain nearly equal quantities of angular momentum.

EDDY SIGNALS are sinusoidal or longitudinal mirror image fluctuations of voltage on a given course on which turbulence signals may be superimposed. Eddy signals are "directional" in character because the radius of motion is large enough to permit considerable maneuvering of the ship within the area of the feature. The turbulence signal accompanying eddy motion is increased near the boundaries of the eddy. S-T signals may also occur at the edges of an eddy. Data on these features have been accumulated more or less accidentally to date. It is hard to recognize an eddy until it has been crossed and even then its definition is not clear until the STD trace has been examined as well. Cruise 149 of the <u>Atlantis</u> was largely devoted to the survey of a very large sausage-shaped eddy on the southeast side (?) of the Gulf Stream. While this structure essentially satisfies the definition of an eddy it was apparently composed of a race of current moving around a core which had no marked current structure. The current in the race reached 6.0 knots at one point and ranged between 1.0 and 3.0 knots along a large part of its length. It would be hard to specify the "radius" of any part of this structure or the location 0.707 R_{max} because there is no center common to all parts of its boundary. Thus it is clear that as the dimensions of eddies increase so does the complexity of definition and as greater understanding of their properties is achieved further subdivision will be possible and indeed necessary.

The CURRENT SIGNAL is a steady deflection of recorded voltage from the zero point on which are superimposed all the foregoing kinds of signal. The current signal is highly directional and quite constant over spaces of an hour's run except at the boundaries of the principal currents of the ocean where sharp discontinuities appear. Tidal currents on the continental shelf are particularly steady and their rotary behavior can be followed as was shown in the first Electrokinetograph report (von Arx, 1946). Near the Gulf Stream there is an entrainment current which increases in strength as the ship approaches the Stream and suddenly changes its velocity (in the space of a mile) to the full strength of the Gulf Stream current. The turbulence signal increases in amplitude in the same way but the size of the turbulent cells also increases so that the period of the turbulence signal is lengthened. The turbulence signal can become so large that in a jogged sailing plan it is necessary to run much more than the customary 4 minutes on the jog to obtain a reliable average signal for the steady motion of the current. This can be predicted in advance from the period of the turbulence signal recorded on course. If the period is of the order of 6 minutes as it often is in the Gulf Stream it is necessary to jog for 12 or 15 minutes to be certain of the position of the mean voltage through the better part of at least two turbulence cells. The on course signal is taken as the average voltage through perhaps 4 or 5 cells. The extraction of a current signal in turbulent water from the maze of superimposed motional voltages requires some practice and care. In quiet water the process is greatly simplified.

The CURRENT BOUNDARY signal is a sudden change in the trend of the average voltage on a given course. On approaching the edge of the Gulf Stream the turbulence signal increases and the signal from the entrainment current increases to the point where the actual edge (seen in the water) is reached. At this point the voltage trace bends so sharply (see first Electrokinetograph Report (von Arx 1947)) that a pencil point can be placed on the spot, and a new regime of current and turbulence signals begins. It was once a matter of concern to estimate how much of this Current Boundary signal was caused by the S-T signal and how much was a real current change. The steepest temperature and salinity gradients recorded by the STD at the Gulf Stream boundary were reproduced in the laboratory and it was found that the S-T signal could produce no more than 0.1 knot error in the total Current Boundary signal. Thus it is concluded that the very marked changes of from 1.0 to as much as 3.5 knots change in current speed are real at the northwestern edge of the Gulf Stream. The entrainment current may reach a speed of from 1.2 to 3.0 knots before it gives way to the higher speeds in the Stream itself. The edge of the stream is defined as that point at which this marked velocity discontinuity occurs together with an equally marked change in temperature and salinity. Other smaller velocity discontinuities are found in "bubbles" and detached eddies near the edges of the Gulf Stream. The criteria of this definition must be applied with caution as the "edge of the Stream" is an elusive boundary having a rather complicated shape familiarly baffling to those who have worked in and around it (Fuglister 1947).

An additional signal of despicable origin is the BT signal. This signal is generated when the bathythermograph fouls the electrodes and hauls them in. A loop of wire, usually caught up somewhere between the electrodes, is towed in at the speed of the ship plus the rate of the winch. The voltage signal goes off scale almost immediately as the rate of flux cutting is very great. The signal can be restored to normal by notifying the BT observer who will stop his winch and cooperate in your efforts with a boat hook. The problem can be avoided entirely by streaming the electrodes from the end of a long boom on the opposite side of the ship. To avoid fouling an electrode line 350 feet long, a distance of 40 or 50 feet should be maintained between the outboard end of the BT boom and the outboard end of the electrode boom.

V Theory and Practice of the Sailings

The sailings employed in oceanographic reconnaissance with the Electrokinetograph are governed by two principal considerations. The courses must run in such a way that useful information is derived from them, and the electrodes must be made to double back on themselves every so often so that accurate knowledge of the zero point of the electrodes is had at all times. It is also necessary to keep the ship under way to hold the electrodes in a horizontal line.

The Electrokinetograph in its present form is capable of measuring water motions in the horizontal plane which are at right angles to the line connecting the two electrodes. Thus it is necessary to alter the azimuth of the interelectrode line by an appreciable angle to secure the data necessary for a current fix which is derived from the composition of the vectors representing the thwartships currents on each of two courses. Since the magnitudes of these vectors are measured from an origin on the potentiometer scale which does not necessarily coincide with the mechanical zero of the instrument, it is necessary to reverse the electrodes in the sea and determine the value of the line on either side of which the direct and reflected signals from the same current are equally and oppositely recorded. This line is the locus of the zero-point on the strip chart as time progresses. The reversal can be accomplished slowly, by turning the ship 180°, or quickly, by reversing the order of the electrodes in their distance astern of the ship. To accomplish the latter a line is run from the deck to the stern of the more distant electrode. On hauling in this line a length equal to or slightly greater than the interelectrode distance the reversal is accomplished. Unfortunately this simple solution leads to difficulties in fouling the line around the electrode cable and it also presents a larger target for the BT. If arrangements can be made to stream the electrode cable well outboard and to secure the reversing line inboard or even on the opposite side of the ship, if a BT is not being lowered, less trouble should arise. It is also recommended that braided white line be used, as a manilla line unlays when wet and under tension and is more likely to foul by twisting around the electrode cable. The difficulties mentioned have been so serious that for most work the slower and more cumbersome method of reversing the ship has been used almost exclusively. It poses no burdens on the helmsmen other than the unpopular but necessary jogs and squares, and reduces the labor of the Electrokinetograph observer very greatly. It has been found that with due allowance of time for averaging the signals in turbulent water the zero points indicated by the two methods are identical.

CIRCLES are theoretically the best sailing plan for direct observation of the direction of the electromagnetic vector in the sea. A ship in a 360° turn steadily changes the azimuth of the electrodes towed astern but the instantaneous azimuth is uncertain because the electrodes tend to cut inside the turning circle of the ship due to their greater drag than the connecting cable. This produces a turn signal which varies with the turning rate of inconstant value due to windage, waves and steering irregularities. All this produces an irregular background signal of artificial origin which is further complicated by the unknown angle between the interelectrode line and the keel of the ship. Values derived from this technique of measurement are therefore unreliable.

SQUARES avoid these difficulties by allowing the electrodes to come to mechanical equilibrium with the conditions affecting the course of the ship. Except for the effects of windage on the ship the electrodes trail dead astern and the azimuth of the interelectrode line is the same as that of the keel. In a square the interelectrode line is presented to the motional electromotive force in the sea in a successively direct and a reserve sense along each of two perpendicular lines. Thus it is possible to get two measurements of the zero point and five measurements of the local current from each square. The two measurements of zero point are derived from the direct and reverse presentation of the electrodes to the prevailing motional EMF on the two pairs of opposite sides in the square. The five current fixer are derived from the component voltages recorded at each corner of the square and from the averages of voltages on opposite sides (signs taken into account) providing an average current over the whole area of the square and over the time required to execute it.

For convenience the sailings on a square are directed toward the cardinal points, either on true or magnetic bearings depending on the kind of compass aboard ship, and are executed clockwise (N-E-S-W) or counter-clockwise (N-W-S-E). Such squares are called RIGHT CARDINAL SQUARE and LEFT CARDINAL SQUARE respectively. An order to the helmsman is thus quickly and clearly understood. The remaining directive is the length of the legs of the square. This is determined from the ship's turning time and the character of the turbulence signal. In general the average period of the turbulence signal times the factor 2.5 is used as the sailing time for each leg. These times range from 4 to 15 minutes and the order is given "5 MINUTE RIGHT CARDINAL SQUARE" for a turbulence signal period of 2 minutes on course. This may be further qualified as "5 MINUTE RIGHT CARDINAL SQUARE BEGINNING 2000" if the maneuver is to be executed later on. No change of speed is required. As the maneuver is executed the observer should record the average of the voltages on each leg excluding the turn signals and within 10 minutes after completion of the square he can also have computed the two zero points and the five possible current fixes with the aid of an Aircraft Navigational Plotting Board BuAir Mk 3A. These data are kept in a running log in which the times and changes of course and speed, as well as data on wind force and direction, wave force and direction, STD changes and technical behavior of the Elevtrokinetograph are noted in order of time. Such log keeping is essential if the greatest possible amount of information is to be realized from the voltage traces. It is also necessary to log the times and course changes on the Electrokinetograph strip chart for purposes of exact cross-reference between the log, navigating chart, the strip chart, and the STD tape. All of these notes will eventually be referred to the shore based earth-current background recorder tape for evaluation. Time is the only common denominator among all these elements free of the influence of other factors and must be kept very strictly. But to resume the discussion of sailings, squares are used at intervals of a watch for accurate calibration of zero point. Although squares yield a large amount of information they cost a good deal of time. Instead of squares at each current fix there are a number of alternative sailing plans which yield running fixes that delay the ship much less.

JOG and SQUARE-JOG or ZIG-ZAG courses are used in smooth and turbulent water respectively. A jogged course consists of a few minute's run every half hour at right angles to the principal course of the ship. The jogs are made alternately to the right and to the left of the principal course so that for each hour's running a pair of jogs will yield a reversal of the electrodes from which a zero point check can be made. Each jog also yields two current fixes, one between the earlier on-course signal and the jog signal and the other between the later on-course signal and the jog signal. In steady water the jog may be 4 minutes running time long which means that 26 minutes running are made good on the course to the destination. This amounts to 13% loss of efficiency in progress toward the destination not counting the loss at each square. In turbulent water it is necessary to increase the time on each jog to from 12 to 15 minutes to obtain an average signal for a current fix. This produces a SQUARE-JOG, for the ship is on a jog nearly as long as it is on course. At this rate the efficiency drops to 60% and 50% respectively, again not counting square losses.

In turbulent water therefore it is seemingly more efficient to sail a ZIG-ZAG course alternately 45° to the right and left of the course to be made good. The efficiency of such a course plan is 71% and right angle course changes are maintained. But ZIG-ZAG sailing does not produce reversal of electrodes for zero point checks hence squares must be sailed rather frequently. This reduces the efficiency of ZIG-ZAG sailing very severely. If a square is sailed every two hours in "15 minute water" not only is there a great loss of zero point information but the ship is delayed 95 minutes in each 3 hours run yielding an efficiency of only 53%, very little better than 15 minute jog sailing.

There is a psychological difference shown by helmsmen toward sailing jogs or square jogs and zig-zags. The latter is much preferred probably due to the feeling that each zig and each zag brings the ship nearer her destination, while each jog is an outright delay. Squares are similarly detested but because of their infrequency they are tolerated more amiably than jogs. A further difference noted in sailing zig-zags is that men with war-time naval experience are thoroughly familiar with them, while jogs are unfamiliar and for some reason difficult to grasp at first. This probably comes from from the imperfect realization that two close parallel lines lead to substantially the same destination, for the instinctive tendency seems to be for the helmsman to want to shuttle back to his first course line at the end of the first jog and to the second course line at the end of the second, and so on. Jogged sailings, aside from their low efficiency, have their benefits in that a prolonged and virtually single section can be made through a current system which shows the true current and thwartships component of that current in the light of well established zero points. Such is not the case with zig-zags.

Both zig-zags and jogged sailings yield true-current sections along any course with current fixes at roughly quarter and half hour intervals respectively. The useful maximum efficiency of jogged sailing is 87% while that of zig-zag is 71% excluding squares. Squares are needed more often on zig-zag courses than jogged courses and as these sailings are very costly in time the jogged sailing plan is customarily employed.

Correction sheet

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Please substitute the following for paragraph ii
Two component arrays on page 27.

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P 3

Two component arrays of electrodes seem to offer a logical means for determining continuously the direction and magnitude of water currents without course changes while under way. The success of the technique depends upon two practical problems: zero point control and electrode support; for which there is no immediate solution.

The signal received from a longitudinal pair of electrodes is fully discussed in section VIII. The signal from a transverse pair is composed of the signal from the ship's forward motion minus the residual electric potential vector from the component of water motion parallel to the keel, or at right angles to the transverse interelectrode line should the electrodes have non-rigid mounting. If the ship moves through still water no external electric potential difference exists between the electrodes and the potentiometer is called upon to supply the full amount of bucking potential required to balance out the motional Emf of the ship's way. Thus the ship's speed signal is directly proportional to the ship's speed. The signal from a following water current is subtracted from the bucking potential required of the potentiometer but this subtracted quantity is less than 5% of the motional Emf induced in the electrode leads by the added speed the ship has in the following current. In this way a signal is obtained which is very nearly proportional to the ship's forward speed over the bottom.

The longitudinal pair of electrodes, if non-rigidly mounted, respond to wind induced leeway by altering their alignment with the keel. The results of this misalignment have been discussed. Should the longitudinal electrodes be rigidly attached to the ship to prevent misalignment they will receive two signals from the two kinds of leeway they experience: leeway due to beam components of wind, and leeway due to beam components of water current. The windage drives the ship through the water and over the bottom, but the beam components of water motion produce motion only with respect to the bottom. The windage drives the ship and produces no external potential difference between the electrodes. This signal is fully recorded at the potentiometer. The residual electric potential in the water due to beam components of water current is subtracted from the signal due to windage in the same direction but is again under 5% of the addative signal generated in the interelectrode length by the motion of the ship in response to the water current. Thus the 'thwartships' signal is very nearly proportional to the total crab motion of the ship over the bottom. Composition of the forward and lee motions of the ship yields her actual rate and direction of progress over the bottom, or a value very close to it.

To measure the motional electric potential vector continuously so that the responsible sea water motions may be measured continuously, the ship's speed signal must be canceled out. Two means are available: Stop the ship, or measure the longitudinal and transverse motions of the ship through the water and produce proportional electrical signals to be supplied inversely to the recorders with respect to the signals from the two interelectrode lines. A ship under no power is rarely at rest in the water so that the first alternative is not very advantageous. It is both possible and more efficient to produce electrical signals accurately proportional to the ship's speed and leeway. Dr. R. W. Guelke and Mr. C. A. Schoute-Vanneck have produced an electromagnetic flow meter employing an artificial magnetic field (J.I.E.E. 94 II 37 Feb 1947 pp 71-74). The theory of this instrument has been investigated by Longuet-Higgins and Barber and reported in ARL/R.1/102.22/W from the Admiralty Research Laboratory. This small discus-shaped instrument attached to the keel of the observing ship with its two pairs of electrodes aligned fore-and-aft and 'thwartships' could be made to produce a signal proportional to the motion of the ship's hull through the water for subtraction from the total motion signal given by the Electrokinetograph. The accuracy of this instrument when properly mounted is of the same order as the Electrokinetograph. It employs an alternating artificial magnetic field and therefore produces an alternating motional Emf which avoids zero point difficulties entirely. This signal rectified and filtered is suitable for inverse feedback to the Electrokinetograph and can be adjusted to have 1 mv/knot sensitivity and trimmed to match the local isodynamic correction applied to the Electrokinetograph signal.

This scheme seems entirely feasible. A ship so equipped could know her geographic motion over the bottom, her forward speed over the ground, her forward speed through the water, her leeway over the ground, her leeway through the water, and the true water current at all times. The difficulty as mentioned in the beginning is the instability of electrode zero in the Electrokinetograph and the problem of rigid mounting of the electrodes. Means must be provided to reverse the Electrokinetograph electrodes at regular intervals so that each pair is presented to the forces producing the motional signal in a direct and reverse sense to locate the zero points. Then too, rigid mounting presently involves very large structures to support existing interelectrode distances. These distances can be reduced as much as 80% through use of recently developed high sensitivity recording potentiometers but the finite noise level of the electrodes and cables must be allowed for and kept below 1 or 2 per cent. Because of the magnetic and galvanic effects of a ship's metal parts it seems undesirable to bring the electrodes close to the hull or to attach them to it. Further, as a ship makes her way through the magnetic field of the earth the lines of force are drawn together as the bow approaches and are relaxed again after the stern passes by reason of the relatively high magnetic permeability of her ferromagnetic parts. A pair of electrodes near the hull would be in an environment of increased magnetic flux density and, while the signal intensity would be increased, the enhanced field intensity would be only local and would be responsible for a closed circulation of electric currents through the hull and in the water near the hull of variable magnitude depending on the ship's speed, heading and overall magnetic permeability. All this added to the galvanic potentials and permanent magnetism of the hull would produce large disturbing effects and observational errors conceivably as great as several hundred per cent. These external influences would not affect the electromagnetic flow meter of Guelke and Schoute-Vanneck because of its rather high (15 Gauss) intensity artificial magnetic field, but would be troublesome to the Electrokinetograph which utilizes the geomagnetic field.

There are a multitude of alternative sailings involving current-fix corners of both less than and greater than 90°. These will not be discussed because each sailing plan will be adopted for a specific reason the details of which would run into needless volumes. The remaining sailing procedure is the straight course.

The STRAIGHT COURSE is ideally useful as an index of the set of the ship throughout its progress from one geographical point to another. Were it possible to rely on the zero point of the electrodes in all water conditions such a record would be exceedingly valuable and simple to make. Unfortunately the present development of electrodes has not yielded pairs with sufficiently similar responses to salinity and temperature changes to produce a reliable zero point signal at all times. For this reason straight courses must be broken up and reversed occasionally for the purpose of checking the zero point position if for no other.

TWO COMPONENT ARRAYS of electrodes have been considered from the first as the obvious solution to the problem of sailings. With three electrodes making lines which intersect at right angles to each other it should be possible to measure the true current continuously from a ship underway. There are a number of difficulties in the way of practical relization of this ideal. First is the electrode arrangement itself. If two electrodes are towed astern in tandem and the third towed on a paravane so as to make a right angle with the first electrode of the tandem line the immediate problem is their spacing. Paravanes are clumsy devices and behave in uncertain ways such that the transverse interelectrode line would be constantly changing its length. As the electrode zero-drift may be larger than 1.0 mv. it is impractical to reduce the interelectrode distance and signal strength and correspondingly expand the recorder scale so as to be able to hold the electrodes with some stiff member because it would be so difficult to keep the recorder pen on scale. The present interelectrode distances are too large to allow stiffeners to be used. If a stiff member could be used the paravane would be unnecessary as the electrode array could be mounted on a right triangular frame and towed astern as a whole.

Should more stable electrodes be available someday and allow closer spacing, the problem of suitable recorders becomes immanent. The industrial strip chart recorders in present use are tough reliable instruments which survive shipboard use quite well. These are available with a maximum of 1 millivolt full scale span which would decrease the present scale span by a factor of 10. This would allow reduction of the interelectrode by the same factor, but the least discriminable signal would remain at its present value of 10 microvolts or 10% of the full scale rather than 0.1% as it is now. To reach the order of magnitude of single microvolts or tenths of microvolts only unseaworthy instrumentation is available. Yet, this problem is less perplexing than the electrode problem. Should that be solved at any time the development of recording microvoltmeters and two-component computers is highly exacting but relatively straight forward engineering. A good deal more could be written about the difficulties and possibilities of two-component electrode arrays but the heart of the problem lies in the electrode problem which must be solved first.

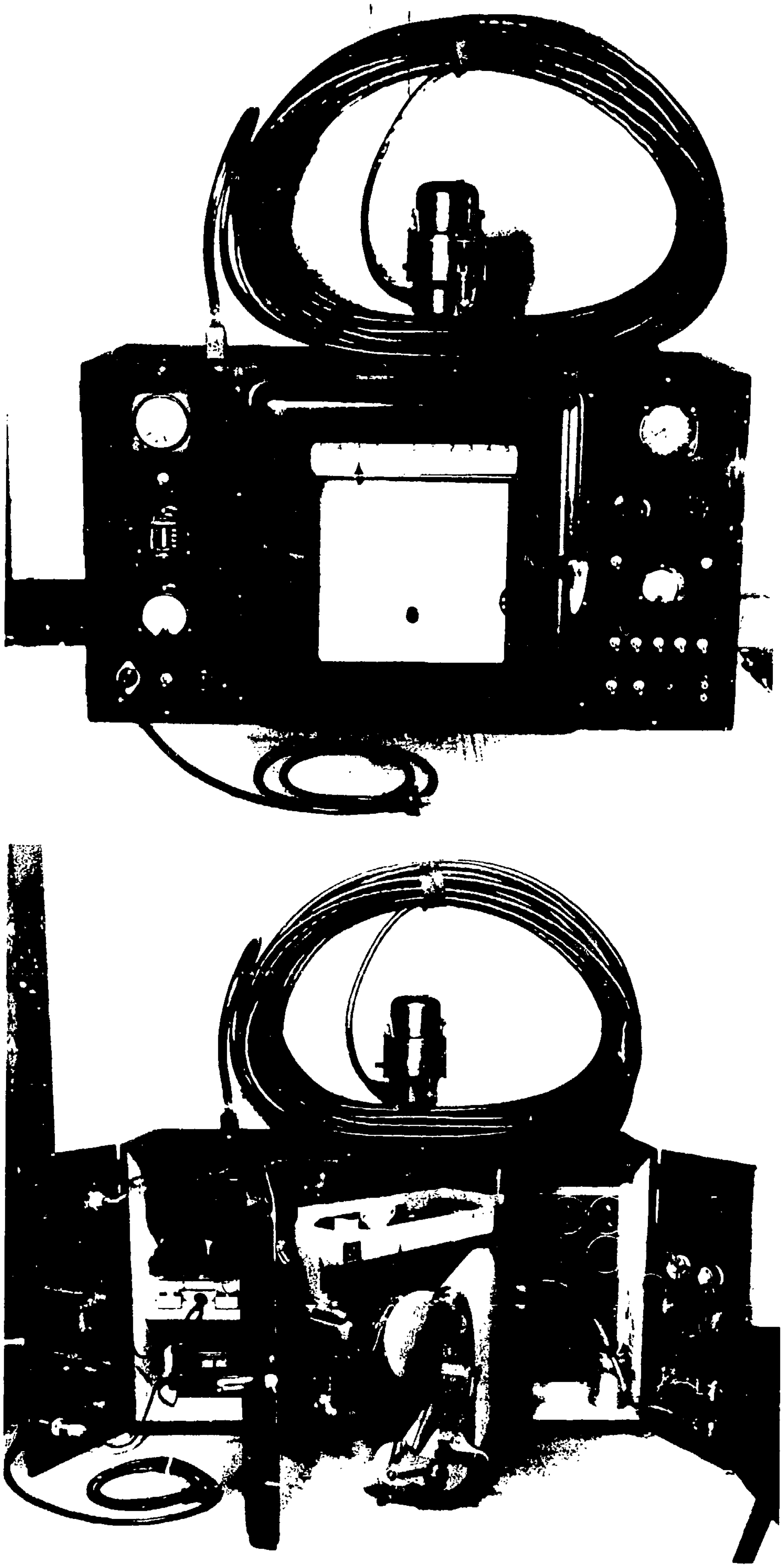


FIG. 2

VI Instrumentation

The first experiment performed to test the principle of the Electrokinetograph was conducted with a simple zero-centered panel type microammeter. Deflections were obtained which could be read reliably enough but because the readings were in microamperes it was necessary to know the resistance of the circuit to compute the voltages observed. Anyone who has tried it can testify that the measurement of the resistance of any circuit containing an electrolyte in any branch is well nigh impossible by direct current methods. The readings obtained are almost meaningless because the resistance (and polarization potential) changes with the application of a voltage needed to make the measurement.

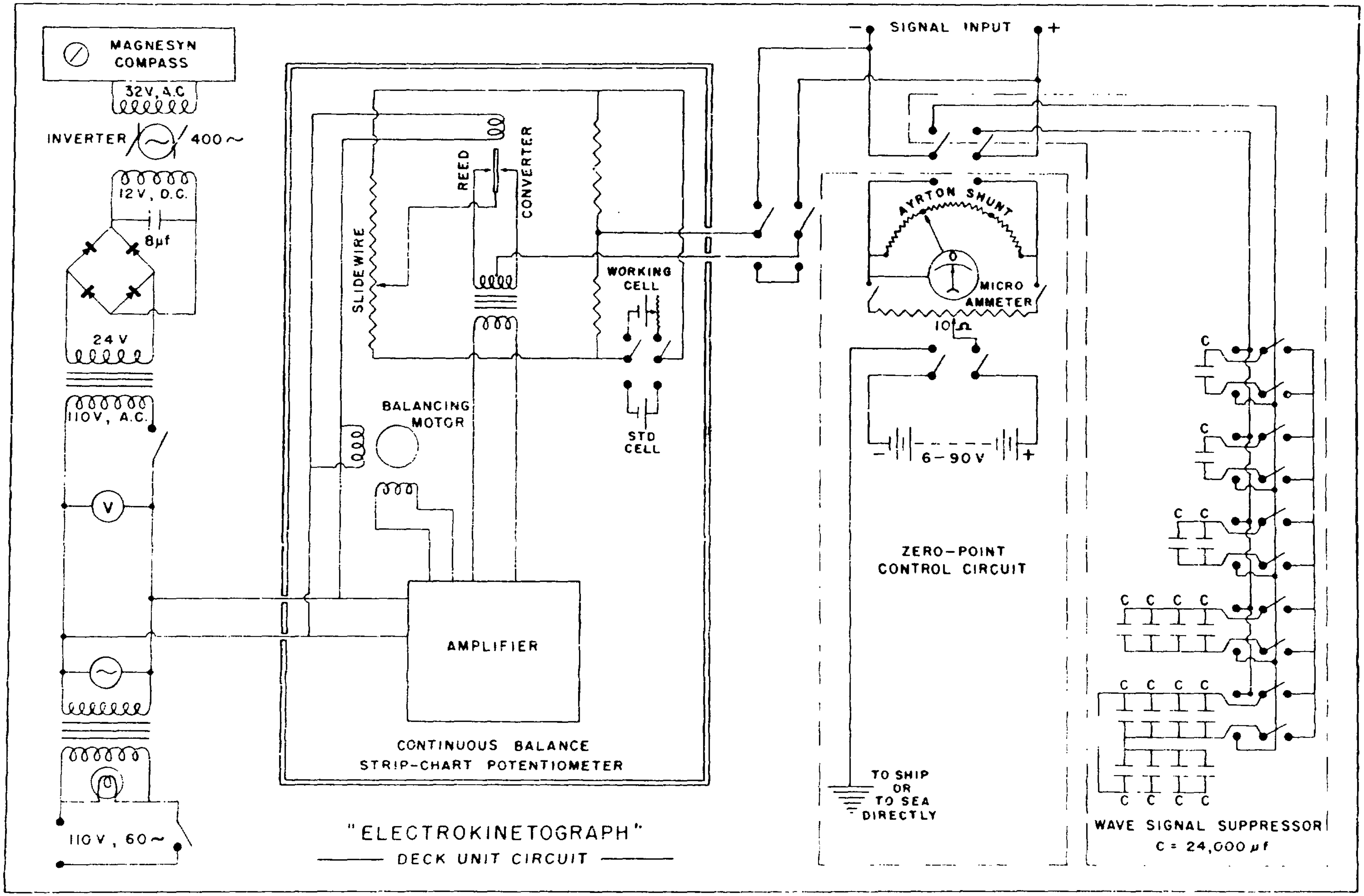
In the second experiment voltages were read directly with a potentiometer. This was accomplished with a Student Type Leeds & Northrup potentiometer coupled to a Brown Instrument Co. chopper amplifier and balancing motor which was mechanically connected to the potentiometer to produce continuously balanced readings. The results were good enough to show that the voltages agreed roughly with those expected from Faraday's theory. Following this a Brown Instrument Company indicating potentiometer pyrometer was modified to read in millivolts on a zero-centered scale. While this instrument indicated the voltages correctly and was rugged enough to withstand the rolling and vibration of small boats it was difficult to judge the average voltages of current signals through the oscillating wave signal voltage and also a problem to determine the zero-point of the electrodes. The number of separate notebook entries per hour of running ran into many hundreds and were confusing to analyse. For this reason a continuous balance strip-chart recorder was purchased and has been used ever since as the nucleus of the Electrokinetograph.

Continuous balance strip-chart potentiometers are relatively expensive (about $500 at present market figures) but their reliability is remarkable. They can be obtained in a number of forms; as multiple point recorders with a repeating stamp wheel, with left hand zero or centered zero scales with spans of from 1 millivolt upward, and by appropriate gear train changes the strip chart can be made to run at practically any desired rate under the pen. Each instrument carries a standard cell to which reference is made automatically at fixed intervals. Provision is also made for standardization at the will of the operator. The minimum signal which these instruments will recognize reliably is of the order of 8 or 10 microvolts, depending upon the make. Because this minimum has a discrete value the record of a slowly changing voltage is often composed of a series of minute steps about a pen's width apart. During more rapid changes of voltage the line is smooth because the recorder balance point lags behind the signal ever so little and does not catch up until the signal becomes constant. Instruments having slow full scale traverse mechanisms lag the signal more than fast traverse instruments. The two principal manufactures of these instruments are the Brown Instrument Company and Leeds & Northrup Company both of whom produce instruments having a "fast" traverse which amounts to about 2 seconds for a full scale sweep of roughly 12 inches. Either of these makes of instrument will withstand continuous violent tilting and heavy vibration without damage or loss of accuracy. They are therefore well suited to use at sea.

The remaining specifications needed to define one of these instruments uniquely are scale span and chart speed. Originally the scale span was chosen to achieve 1 millivolt per knot sensitivity over a range of 5 millivolts either side of a centered zero. This was considered a practical choice both in terms of the interelectrode distance needed to produce this signal and also from the point of view of the ability of the potentiometer to discriminate 1/100th part of a millivolt or knot, and still permit measurement of thwartships currents as swift as 5 knots provided of course the electrode zero and the mechanical zero of the recorder coincide. (Control of this coincidence will be discussed later on.) The strip chart speed was difficult to specify at once and so a number of reasonable chart speeds were provided for the first instrument which ranged between 10 and 120 inches per hour. It has been found that the wave signal is the most complicated of all and that it can be recorded at 60 inches per hour without the pen retracing itself and for ordinary current work 20 to 30 inches per hour will present the signals clearly for all work except detailed studies of waves. If the chart speed is too high it is difficult to take accurate eye-averages consequently in the interests of accuracy and paper economy the slowest practical chart speed is most desirable. Chart speeds of 1/3 or 1/2 inch per minute are considered optimum for survey work on long cruises.

The POWER SUPPLY (see wiring diagram, fig. 3) for these instruments is designed to be 110 volt 60 cycle A.C. The strip-chart drive motor is synchronous and for this reason the frequency of input power must be monitored by a frequency meter of some sort. The Frahm vibrating reed type has been found satisfactory. The sensitivity of the amplifier is affected somewhat by changes in the input voltage and this too must be monitored. Voltage fluctuations of 5 volts can be tolerated without noticeable interference so that an ordinary A.C. panel voltmeter is quite satisfactory. Ship's power usually has provision for voltage control in the engine room but if this is lacking or inaccessible a G.R. Variac can be put in the line to control the input voltage at the instrument. Should the ship's A.C. power be converted D.C. or contain D.C. elements aboard, it is necessary to isolate the power input of the recorder from the ship's power by an isolating transformer. Any D.C. components in the power supply will leak through the chassis of the recorder and through the hull in such a way as to present D.C. potentials at the electrodes. This is ruinous to the electrode surfaces and should be avoided by every possible means. A good quality 1:1 Thordarson 250 watt isolating transformer has been used with success and every precaution has been taken to insulate the recorder and electrode lines from the ship.

The Brown Instrument Company's recorder requires a ground connection for sensitive operation. This poses a problem since the electrodes are essentially measuring differences in ground potential. To add a "third ground" to the system without interfering with the electrodes is difficult. Instead of a separate connection, the instrument ground was made through one of the electrodes. When the power supply and instrument chassis are isolated from the ship this dodge is quite satisfactory. The Leeds & Northrup recorder does not require a ground connection and this problem does not arise. For this reason a choice has been made favoring the L&N



"ELECTROKINETOGRAPH"
DECK UNIT CIRCUIT

FIG. 3

recorder, even though the Brown and L&N instruments are quite comparable in other respects.

On the INPUT side of the Electrokinetograph circuit (see wiring diagram, fig. 3) no special equipment is required, although a number of auxiliary circuits add to its convenience in operation. With zero centered scales there is opportunity for a given signal from the sea to be registered ambiguously as a positive or negative deflection depending upon the manner in which the electrodes are connected. To settle the question of sign an arbitrary convention has been developed for the northern magnetic hemisphere; "THE RECORDER SHOWS THE SIGN AND MAGNITUDE OF THE POTENTIAL AT THE MORE DISTANT ELECTRODE WITH RESPECT TO THE NEARER ONE." The reasoning behind this convention is based on the fact that the motional electromotive force in the sea is counted positive in the sense of direction from plus to minus. Thus, if the farther electrode is more positive than the nearer one the motional EMF in the sea or some component of it is pointed in the same direction as the ship. If the recorder is facing aft so that the observer faces forward to read it, a positive deflection is on the starboard side of zero which is also the direction in which the ship is being set by the current producing the motional EMF. In this way the sign and magnitude of the voltage trace shows the sense of the set while sailing a given heading. Acceptance of this convention reduces confusion enormously. Even if the recorder is facing forward or thwartships the convention is adhered to for the sake of clearness in later interpretation of the records in the laboratory. In this way all records have the same meaning and mental gymnastics are unnecessary during comparison. For similar reasons all written notes on the recorder tape are made perpendicular to the time axis, and "right side up." The chart is driven downward so that time progresses upward on the tape. If all written notes are entered so as to be right side up when the tape is as it was in the recorder the direction of time is established even though the number of time entries is small. The voltage traces are surprisingly ambiguous with respect to time and if the direction progress of time is undetermined so are the signs of the voltages and consequently the directions of the responsible currents by a factor of 180°. To sum up matters concerning the connections made at the recorder input: first determine which binding post made positive will produce a right hand deflection on the recorder and label it (+) and second, connect the wire from the farther electrode to this binding post. This procedure establishes the convention of signs.

Direct connection to the electrodes allows the recorder to receive the total signal from the sea. As has been pointed out in the section on signals, this total signal is composed of the Current, the Turbulence and the Wave signals. The wave signal can be controlled by the wave signal suppressor section of the input control circuit (see wiring diagram, fig. 3). This consists of pure capacitance placed in varying amounts across the input. As shown in the circuit diagram the units of capacitance are large (24,000 microfarads) and their effect is to reduce the response of the recorder to longer and longer period signals as the total capacitance is increased. The subsections of capacitance are in units of 1, 1, 2, 4, and 8 times 24,000 microfarads such that the total capacitance in shunt is doubled as each section of capacitance is added. Switches also may be thrown in such a way as to add 1,2,3,4,5,6,7,8,9,10,11,12,13,14,15, and 16 units at will. Pure capacitance is used so that the constant potential (D.C.) fraction of the total signal is unaffected. The capacitors are Sprague electrolytic condensers rated at 3 volts. Since electrolytic capacitors have an internal potential the condensers are carefully graded and matched against one another so that the potential of one is counteracted by the potential of another which is connected in opposition. This can be done for all but the first two sections which are composed of single condensers. These two are selected from many for their lack of foil potential. All the capacitors are secured by a short circuiting buss bar common to the switches controlling all the sections. In this way any tendancy to develop foil potential is expended by long periods of short circuit rest. No trouble has developed from foil potential thus far. Should foil potentials exist they are immediately apparent as a sharp kick of voltage whenever the condenser bank is put into service. Shorted condensers bring the recorder pen to the instrumental zero point very abruptly and hold it there. No trouble has arisen from this cause either, despite the extraordinary specifications of these capacitors. Only one difficulty has arisen with the condenser banks in that ordinary double-pole - double-throw switches can develop high contact resistance when they are used for low voltage service. Thus it occasionally happens that throwing a fouled switch will not bring in the condenser bank it controls. This is simply remedied by working the switch a few times with 1.5 volts across it. But cleared in this way the condensers may be polarized unless the polarity of the potential is reversed between operations of the switch, then left on "short" for awhile until the condensers recover their equilibrium. If convenient it is best to disconnect the condensers while clearing the switch.

It will be noted from the circuit diagram that the condenser bank enters the circuit by way of a DP-DT switch which automatically cuts out the condensers whenever the ZERO-POINT CONTROL CIRCUIT is being used. This circuit employs voltages in excess of the rating of the condensers and makes such an interlock arrangement imperative.

The ZERO-POINT CONTROL CIRCUIT is a convenience which makes it possible to adjust the contact potentials of the two electrodes with respect to each other without removing them from the sea for chemical treatment as was formerly the case. By this circuit both electrodes are made positive with respect to a separate ground which may be the ship or a piece of metal hung in the water from a wire over the side. The latter procedure is preferred as it avoids miscellaneous potentials from other circuits aboard ship. The positive potential from the battery is lead to the electrodes through the movable center tap of a 10 Ω potentiometer connected ~~through 1000 Ω~~ to the battery. Motion of this center tap puts more resistance in series with one electrode and less in series with the other. Thus one electrode will pass more charge than the other when the circuit is closed. This charge is passed through the sea by reaction of Cl^- ions with the Ag-AgCl of the electrode surface producing more <u>AgCl</u> and Cl^- atmosphere and proportional change in the contact potential of each electrode. Ideally these potentials should be identical. For this reason a microammeter is placed in shunt across the electrode lines so that by adjusting the center tap of the potentiometer the microammeter can be made to read "zero." This condition indicates that equal currents flow in both legs of the circuit and also indicates equal rates of electrode reaction with the sea. The position of the potentiometer center tap changes constantly during this operation because of the inequality of instantaneous reaction rate at the two electrodes and because of slight changes of resistance along the two current paths. In practice the balance point can be refined after rough adjustment by putting the strip-chart recorder in the circuit and setting the circuit dividing potentiometer at such a point that the voltage trace oscillates about zero. Such a treatment lasts only a minute or so if 6 to 22.5 volts are used at the battery. If grounding conditions are bad the voltage may have to be increased to as much as 90 volts to produce enough effect in a short time.

Electrodes so treated will usually show some reaction which may require as much as 5 minutes to expend itself. Usually too the new zero point will not coincide with the mechanical zero of the recorder but will lie a little toward the same side as it originally erred. This can be cured by repeating the zero adjustment procedure with the balance point a little to the opposite side of the instrumental zero as a sort of "straightening a bent twig" operation. It will be found that the result will be closer to mechanical zero than a number of zeroed balance point operations would produce.

The zero-point control circuit has shown itself to be almost indispensable on cruises across long salinity gradients where zero-shift effects are slow but persistent. It is also convenient for shifting the zero point far to the right or left to give an expanded scale for measuring currents larger than the ordinary range of the instrument. It also has an added effect of keeping the electrodes in good condition longer by replacing Cl^- ions flushed out of their atmospheres from the unlimited supply in the sea, rather than from the decomposition of the AgCl coating.

To return to the power supply section of the recorder, a secondary power supply is taken off the input transformer for operating the Magnesyn compass at 12 volts D.C. This power is extracted by a filament transformer which produces about 25 volts and 3.0 amp. max. A.C. at the input of a Selenium bridge-type rectifier the output of which is 12.5 volts D.C. A rather heavy capacitor is placed across this pulsating D.C. to smooth it before it reaches the magnesyn inverter which produces the 32 volt 400 cycle A.C. needed to operate the compass. This is a round-about circuit but it is actually more compact than storage batteries which would be needed otherwise. The Magnesyn Compass has been used to give separate indication of ship's heading up to the present, but when a direction indicator is installed on the interelectrode line it will serve that purpose equally well. Thus the Magnesyn power supply is likely to remain a component of the deck unit unless a better remote indicating direction system can be found. Under good conditions the Magnesyn is accurate to 2 degrees and is equipped with a full set of compensating magnets so that it can be installed practically anywhere. To avoid lengthy compensating procedures the transmitter has been mounted high above the ship on wooden masts or other firm non-magnetic structures where the compensation problem is less acute. When employed on the interelectrode line far from the ship the compensation difficulty should practically vanish.

The ELECTRODES and their CABLE constitute a separate unit of the Electrokinetograph. The cables employed have been two conductor rubber covered varieties such as Demolition Cable, MCOS-2, Tirex, SJ-16, and others. Demolition cable has very high tensile strength but low resistance to abrasion by BT wire. This is also true of SJ-16 which is unshielded. Shielded two conductor cables such as MCOS-2 and Simplex Tirex may be cut through but the shield arrests the BT wire and prevents it from breaking the insulation over the conductors. While this sort of cable is not exceptionally strong the strain on the electrode line is not greater than 100 lbs at 8 knots and no failure has occurred. Light cables have been chosen so that the electrode cable can be handled by one man. Sometimes it is necessary to haul the electrodes in a hurry when again lightness and flexibility are helpful. Fish may attack the cable but so far they have only attacked the electrode cases.

Fitting out the cable with electrodes is accomplished by first measuring off a length from one end roughly 3 times the length of the ship on which the cable is to be used. This point is the location of the first or nearest electrode. The location of the second electrode is determined from the relationship of s̲ the interelectrode length to H_z the strength of the vertical component of the earth's magnetic field (Figure 4) such that for a given value of H_z the value of s̲ can be chosen which will yield a signal strength of 1 millivolt per knot of current. The value H_z is determined by the magnetic latitude in which observations are to be made. Values of H_z for every point on the earth are plotted on Chart H.O. 1702. For work in the region off the east coast of continental United States the modal isodynamic line has the value 500 milligauss (also called 500 millioerstead or 0.500 Oerstead), this by figure 4 corresponds to a value of $s = 38.9$ meters. This length is measured off from the first electrode point and the cable cut.*

At the measured points the outer rubber covering of the cable is cut away and the shield is pierced so as to expose one conductor. The conductors of two conductor cable are commonly coded black and white. By convention the black lead is considered "positive" and is connected to the distant electrode. The white lead is therefore exposed at the first electrode point and the Silver-Silver Chloride electrode soldered to it.

(*) If desired, a length greater than 38.9 meters can be measured off so that s̲ can be altered by taping the distant electrode to the cable after looping it back to the 38.9 meter point. This extra length is called an "s̲ trimmer" and serves as an adjustment of s̲ such that the signal strength can be maintained at 1 millivolt per knot of current even though the ship may work in areas where H_z is lower or higher than the modal value of 500 milligauss. Of course it is also possible to keep s̲ constant and correct the readings by simple proportion. This is more commonly done.

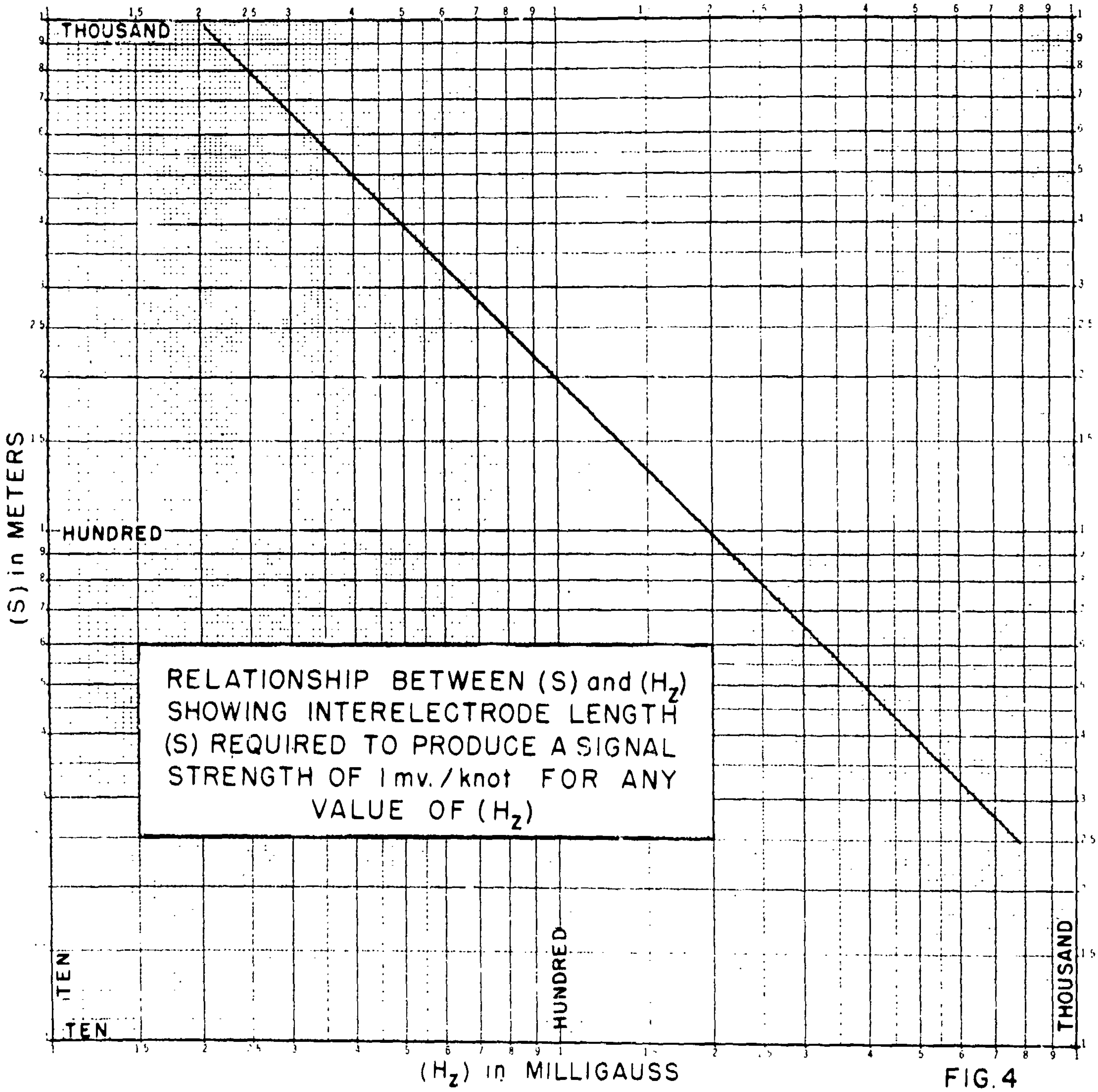

THOUSAND
HUNDRED
TEN
TEN
HUNDRED
THOUSAND
(S) in METERS
(H_z) in MILLIGAUSS
RELATIONSHIP BETWEEN (S) and (H_z) SHOWING INTERELECTRODE LENGTH (S) REQUIRED TO PRODUCE A SIGNAL STRENGTH OF 1 mv./knot FOR ANY VALUE OF (H_z)

FIG. 4

This joint and the whole opening in the cable is then carefully taped up with either Anhydrex or Uskorona rubber tape. With Anhydrex tape one must stretch the black tape until it appears brown and shows striations in order to secure a thoroughly water-tight seal. Uskarona is gray and a much tougher tape but must be pulled very tight to insure an impervious seal. The splicing operation should be done as follows: wrap the soldered joint first with a narrow (half width) of friction tape and then with a half width of rubber tape. Wrap the shield and other conductor of the cable with friction tape and then with rubber tape. Press the soldered splice portion against the unsoldered part of the cable and secure the two together with half-width friction tape: Cover the whole opening in the cable a distance of at least two inches on either side of the opening with rubber tape. At the points where the outer rubber covering of the cable is taped over it is best to clean the cable with CCl_4, but let the solvent cleanser dry thoroughly before taping over. Do not use gasoline or petroleum solvents for this cleaning as they attack natural rubber. A double thickness of rubber tape covered with a single thickness of friction tape completes the splice.

The distant electrode splice is simpler because it is a one-sided splice. To proceed here, cut away two inches of the cable covering, expose the shield and white conductor, and strip the insulation off the black conductor. Put a line of solder around the shield to stiffen it and cut away the excess. Solder the end electrode to the black conductor and tape it with half-width friction tape. Tape over the end of the white conductor with half-width friction tape and run the tape cover back over the shield. Clean the rubber outer covering of the cable and cover with two layers of rubber tape the whole terminus of the cable exposing only the electrode. Complete the splice with a layer of friction tape.

Next the electrode housings are fitted to the cable (figure 5). The barrels of the housings must be slid along the cable to the electrodes but the end pieces can be opened by removing the splines and be slipped over the cable directly. Clamp one end piece (the end closest the ship) at each electrode and secure the barrel. Then pack the barrel very tightly with glass wool. Use as much force as possible in packing so that the glass wool is impenetrable even to rather sharp instruments and then make fast the other cable clamp. In handling glass wool there is some danger of skin and eye irritation from flying particles. To avoid this keep the glass wool wet (with sea water) or wear goggles. It is best to do the packing in the open as particles of glass wool are difficult to sweep up and may fly in the air for weeks after a packing session indoors.

At the terminal electrode only one cable clamp is clamped around the cable, the other is free. If left so it has been found that the terminal electrode yaws violently in the water and may eventually break off the conductors. To steady the motion of this electrode a 15 foot length of manilla line is placed in the grip of the unused cable clamp and allowed to trail behind the electrode as a drogue. This increases the cable strain appreciably but serves to keep the interelectrode line in the horizontal plane as well as to steady the terminal electrode case.

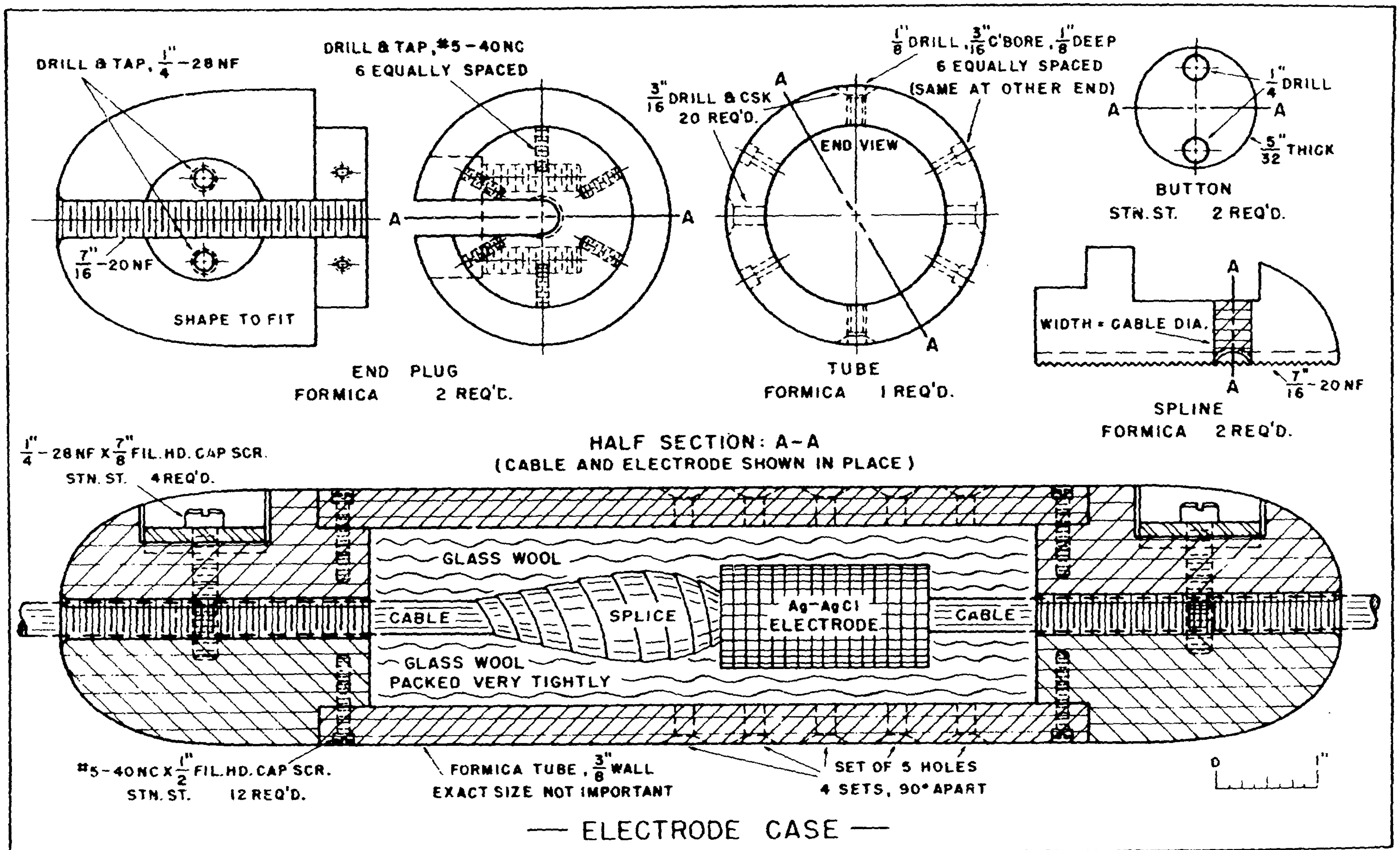

DRILL & TAP, 1/4" - 28 NF
7/16" - 20 NF
SHAPE TO FIT
DRILL & TAP, #5-40NC
6 EQUALLY SPACED
END PLUG
FORMICA 2 REQ'D.
3/16" DRILL & CSK
20 REQ'D.
1/8" DRILL, 3/16" C'BORE, 1/8" DEEP
6 EQUALLY SPACED
(SAME AT OTHER END)
END VIEW
TUBE
FORMICA 1 REQ'D.
1/4" DRILL
5/32" THICK
BUTTON
STN. ST. 2 REQ'D.
WIDTH = CABLE DIA.
7/16" - 20 NF
SPLINE
FORMICA 2 REQ'D.
HALF SECTION: A-A
(CABLE AND ELECTRODE SHOWN IN PLACE)
1/4" - 28 NF X 7/8" FIL. HD. CAP SCR.
STN. ST. 4 REQ'D.
GLASS WOOL
CABLE
SPLICE
Ag-AgCl
ELECTRODE
CABLE
GLASS WOOL
PACKED VERY TIGHTLY
#5-40NC X 1/2" FIL. HD. CAP SCR.
STN. ST. 12 REQ'D.
FORMICA TUBE, 3/8" WALL
EXACT SIZE NOT IMPORTANT
SET OF 5 HOLES
4 SETS, 90° APART
0
1"
— ELECTRODE CASE —

FIG. 5

The design of the electrode housing (Figure 5) is deliberately overdone. They are built of Formica (or Micamold) tubing perforated with 20 1/8-inch holes near the electrode surface and supported at the ends by formica plugs containing splines to clamp the cable. The splines and the slots in the plugs are threaded coarsely so that when the spline is brought snugly against the cable the grip will withstand very large tensile strains. This relieves the splice of external cable tension since the barrel of the electrode housing carries the tension over the electrode and transmits it to the undisturbed part of the cable farther along. The crushing strength of the formica is sufficient to withstand being run over by a 1 ton truck, and has withstood the bite of a shark on one occasion as evidenced by the tooth fragments remaining in the electrode case.

When completed the electrode cable is put into service by simply heaving it over the side drogue first and allowing the drag of the ship's way to pull the remainder off the deck. When about 2.5 times the ship's length of cable is overboard the cable is clamped and the free end run into the laboratory where connections are made to the Electrokinetograph input terminals. The black coded conductor is made fast to the positive terminal and the white to the negative.

The clamp and rig of the overboard portion of the cable is subject to variation depending on the ship. In general it is well to rig the cable well outboard on a light but long boom on the opposite side of the ship from the taff-rail log or BT winch to avoid fouling. A light block at the end of the electrode boom carrying an endless line long enough to reach the deck and be belayed on a cleat makes a convenient rig. The endless line (signal hoist) may carry a dead-eye or wooden sheave through which the electrode cable is reeved and clewed with friction tape served with marline. To haul the electrode cable one has merely to bring the dead eye on deck and haul away. The electrode cable is best stowed by flaking it either on deck or over a pair of pins secured to a convenient bulkhead. The electrodes themselves are stored in sea water. A heavily waxed wooden tub of sea water is best since it insulates the electrodes from the ship and prevents electrochemical damage to them. The water level in the tub should be high enough to cover the electrodes but not so high as to overflow with the roll of the ship. Such overflow will make electrical contact between the electrodes and the deck.

MAGNETOMERTY. On several cruises an NOL-type saturated core magnetometer built by Leeds & Northrup was carried to measured $\underline{H}_z$ at sea. It was found that the values ran erratically around the values given on Chart H.O.1702 and depended a good deal on the heading of the ship. A great amount of time was spent shifting the detector from place to place on the ship in an attempt to secure readings which were independent of the ship's heading. Taking the ship as a dipole one would think a point high and midships would be least affected by ship's field for measurement of the vertical component. Such was not the case. On the <u>Atlantis</u> a long spar was rigged out on the bow as a bow-sprit and the magnetometer head suspended from the tip 20 feet from the ship. Readings were improved but

 [redacted]

still showed variations as great as 10 milligauss on different headings. These experiments in local waters gave no better information than is available on H.O. 1702 and since then this chart has been taken at its face value. It is not known how reliable this and the other magnetic charts are, but for the purposes of the Electrokinetograph, values of H_z to the nearest 5 milligauss in 500 (1%) is within the experimental error of the instrument and sufficiently precise for work in high magnetic latitudes.

The Electrokinetograph is more and more efficient as the value of H_z increases. It is efficient in the sense that the standard signal strength can be received from shorter and shorter interelectrode lines as H_z increases. In the opposite sense the interelectrode distance becomes very large as work extends toward the magnetic equator (where $H_z = 0$) and theoretically becomes infinite at the magnetic equator itself. The practical lower limit of magnetic latitude in which the Electrokinetograph can be used successfully is probably at the 100 milligauss isodyne. At this line the interelectrode distance must be increased to about 200 meters or the 1 mv./knot ratio reduced to some other figure. In low magnetic latitudes the value of H_z must be better known too in order for the percentage error to remain at not more than 2 per cent. Independent magnetometry will doubtless have to be done from the ship if work is attempted in low magnetic latitudes.

VII Theory

The following discussion is divided into two parts; (I) an explanation of the basic physical principles which combine to produce measurable potentials in a wire between two electrodes towed in moving sea water, and (II) a rigorous mathematical treatment by Mr. Henry Stommel of the strength and distribution of residual electric potential fields in the sea which act to reduce the potentials measured in the towed wire to a figure slightly less than the value of the motional Emf obtained from Faraday's Law.

Part I - Basic Relationships

The quantity which is fundamentally responsible for the potentials developed in the towed wire and in the sea itself is the electric field strength $\underline{E}$. This quantity is the driving force which is capable of producing motion when it acts on charged particles. The phenomena accompanying the motions of charges can be measured by ordinary electrical instruments while the electric field itself cannot. Nevertheless the properties of an electric field must be understood if the measurable effects it produces are to be rationalized and predicted.

An electric field is said to exist if a charge placed in a region experiences an electric force. The magnitude of the force $\underline{F}$ depends on both the electric field intensity $\underline{E}$ and the charge $\underline{q}$ on the particle.

$$F = qE \tag{11}$$

By this definition, the electric field intensity at any point is the force exerted by the electric field on a unit (positive) charge at that point. It is counted positive in whatever direction the force $\underline{F}$ acts on that positive charge. If a unit positive charge is moved a distance $\underline{r}$ against the electric field, the work done is $-F\cdot dr$; the minus sign indicating the contrary sense of motion. This work expended, is stored in the position of the particle, the new position being considered to have potential with respect to the old position. The difference in potential between the initial and final points $\underline{dV}$ is equal to the work done $-\underline{F}\cdot\underline{dr}$, and since by (11) $F/q = E$ and $q = 1$ by choice in definition

$$dV = -E\cdot dr \tag{12}$$

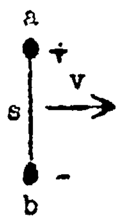
which may also be written

$$E = -\text{grad } V \tag{13}$$

From (13) it may be said, $\underline{E}$ or any component of $\underline{E}$ in a given direction is equal to the space rate of decrease of potential in that direction.

Now the space rate of decrease of potential integrated over a line parallel to the gradient between two arbitrary points yields a quantity which, if no current flows, is the Electromotive Force and is equal to the greatest possible difference in potential between those two points without the action of external agencies. For present purposes it is the case of the electromotive force generated by the motion of a substance with respect to a magnetic field or motional electromotive force that is of greatest interest.

Motional Electromotive Force, Faraday's Law



Let us consider a straight wire $\overline{ab}$ of length $\underline{s}$ having a small metal sphere at each end. The wire is moving with a velocity $\underline{v}$ toward the right through a uniform magnetic field of density B directed into the plane of the paper. The electric force on a free charge in the wire is

$$\underline{E} = (\underline{v} \times \underline{B}) \qquad (14)$$

If $d\underline{s}$ is a vector element of length of the wire, the Motional Emf produced in the wire is

$$\int_0 \underline{E} \cdot d\underline{s} = \int_0 \underline{v} \times \underline{B} \cdot d\underline{s} = - \int_0 \underline{B} \cdot \underline{v} \times d\underline{s} \qquad (15)$$

from which it can be said, the "dot" product of B, the magnetic intensity, and $(\underline{v} \times d\underline{s})$, the time rate of increase of area swept by the wire, yields the motional Emf of this physical situation. This is Faraday's Law.

The existence of the electric field of intensity $\underline{E}$ produces a separation of charge such that for the case described negative charges are driven toward $\underline{b}$ and positive charges toward $\underline{a}$. This separation of charge goes on actively until the quantity of charge collected on the metal spheres is sufficient to produce an opposing difference of potential equal to the motional Emf. Charges of either sign are then in equilibrium and suffer no further motion along the wire.

An Experiment

Suppose this equilibrium is disturbed by allowing the knobs $\underline{a}$ and $\underline{b}$ to slide (making perfect contact) on a pair of conducting rails connected together by a motionless bar to produce a short circuit. The charge separation process is instantly resumed and continues to function so long as the circuit is closed. The rate of charge separation rises as the system attempts to develop a potential difference V between the spheres equal to the Emf, but as fast as charge is separated and collected on one sphere it leaks away into the rail below, flows across the shorting bar and returns by the other rail to the other sphere. The potential difference in the wire never attains the value of the Emf but does reach an equilibrium value determined by the total circuit resistance and the Emf.

$$\text{Emf} = i(R + r) \qquad (16)$$

or

$$iR = \text{Emf} - ir \qquad (17)$$

where R is the resistance of the rails to and including the resistance of the shorting bar, and r is the resistance of the moving wire.

A potentiometer connected across the rails near the moving wire will read the value of iR. If the shorting bar is removed the potentiometer will show a reading equal to the theoretical value of the motional Emf in the wire. Now suppose the potentiometer is made to move with the wire and is connected to the two spheres at the wire's ends. If the shorting bar is removed the potentiometer will read ZERO, quite opposite from the first experiment with the shorting bar removed. This result is zero because the bucking potential (the quantity which a potentiometer indicates) is now exactly supplied by the interaction of the moving potentiometer leads with the magnetic field. The potentiometer leads terminated at the two spheres have an unclosed length s which is exactly the same as the length of wire between the two spheres. Since both branches of the resulting circuit are moving with precisely the same velocity through the same magnetic field, the motional Emf's (by (15)) are identical in magnitude and direction. Having the same direction they oppose each other in the closed circuit.

Next replace the shorting bar. Current immediately flows through the moving wire, the rails and the shorting bar in accordance with equations (16) and (17). The motional Emf in the potentiometer leads is not changed, neither is it changed in the wire, but there is a potential drop ir in the wire which did not exist before. Thus there is a potential difference equal to Emf in the potentiometer leads and a potential difference (Emf - ir) in the wire which is not equal to the value Emf. As a result the potentiometer battery must provide a portion of the bucking potential required to balance it. This portion is V, its reading, and

$$V = Emf - (Emf - ir). \qquad (18)$$

$$V = Emf - \phi \qquad (18')$$

From equation (18) it can be seen that if ir is zero, V is zero, but as ir approaches the value Emf, V also approaches the value Emf. The value of ir approaches the value Emf as the value iR approaches zero. The value of iR can be made to approach zero by increasing the number and total cross-section of the shorting bars between the rails. In so doing the amount by which V differs from the value Emf is diminished.

Thus it can be seen that a practical measurement with a potentiometer can lead to a result numerically equal to the motional Emf provided the motional Emf in the physical system has been shorted out or reduced to a negligible value, while that in the measuring instrument is undisturbed. It is also to be noted that the motional Emf is directly related to the electric field intensity E by the integral of E·ds given in equation (15) and that from a knowledge of the physical situation producing E given in equation (14), Emf may be found. Conversely if Emf or a voltage V which is nearly equal to Emf, is measured the physical situation can be reconstructed. This is the important case insofar as the Electrokinetograph is concerned.

In figure 6 the relationships of the apparent motional Emf in the sea to the water current, the earth's field, and to the observing ship are shown in a cut-away drawing. It must be remembered that the function of the return current lines shown in the water subjacent to the current is to destroy the potential differences resulting from the motion of the sea water, so that the motional Emf in the wire between the electrodes may be measured against as small a background of residual potential difference, (Emf - ir) or (Ø), as the situation will allow. The smaller the resistance of the subjacent water mass the smaller this residual potential difference will be and the more precisely the measured voltage at the potentiometer will match the motional Emf of the drifting interelectrode line as explained in equation (18) and (18'). If nearly all the potential differences in the sea are shorted out it is possible to tow the electrode line at any depth and measure a voltage nearly equal to the electromotive force in it as a result of its drift with the water motion.

In figure 6 and in field work with the Electrokinetograph it has been assumed that the water motions being measured are purely horizontal. In the sea, which is approximately 1/1000th as deep as it is broad, this assumption is not unreasonable. Vertical circulation is known to exist in parts of the ocean. Observations of currents in these areas will yield only the horizontal component of motion for the reason that the electrodes too are horizontal, and for the considerations which follow.

If a water current flows through an inclined magnetic field $\underline{H}$ at a velocity $\underline{v}$ it will produce in itself an electric field $\underline{E}$ given by the vector cross product

$$\underline{E} = (\underline{v} \times \underline{H}) \tag{19}$$

This equation implies that $\underline{v}$, $\underline{H}$, and $\underline{E}$ (all vectors) are mutually perpendicular. The vector $\underline{v}$ or a major component of $\underline{v}$ is parallel to the surface. The vector $\underline{E}$ generates an Emf in the horizontal electrode line which is parallel to the surface and moved with the horizontal component of $\underline{v}$. Thus in this physical situation the only component of $\underline{H}$ that satisfies equation (19) is $\underline{H}_z$ the vertical component. Depending on the sense of direction of $\underline{H}_z$ the vector $\underline{E}$ is directed positively 90° to the right or to the left of the positive sense of $\underline{v}$. $\underline{E}$ has the sense of the direction of advance of a right hand screw perpendicular to the plane common to $\underline{v}$ and $\underline{H}_z$ and rotated from $\underline{v}$ to $\underline{H}_z$ through the smaller of the angles between them. There $\underline{E}$ lies 90° to the right of the direction of $\underline{v}$ in the northern magnetic hemisphere and 90° to the left in the southern. Figure 6 is drawn for the northern magnetic hemisphere.

It is hoped that the foregoing has made clear how the quantities measured by the Electrokinetograph are related to the motions of the sea. It is the conductivity of the sea and its short-circuiting properties that make these measurements possible. Were it not for this, the electric field, which pervades both the moving sea water and the measuring instruments moving with this water, would produce identical effects in the sea and in the instruments with the result that the difference between them would always be zero. In truth the potentials in the sea are not annihilated but they are reduced to small values which are almost negligible for practical situations in the deep sea. In Mr. Stommel's paper the equations for computation of these residuals are developed, and also evaluated for a few special cases in figures 7 and 8.

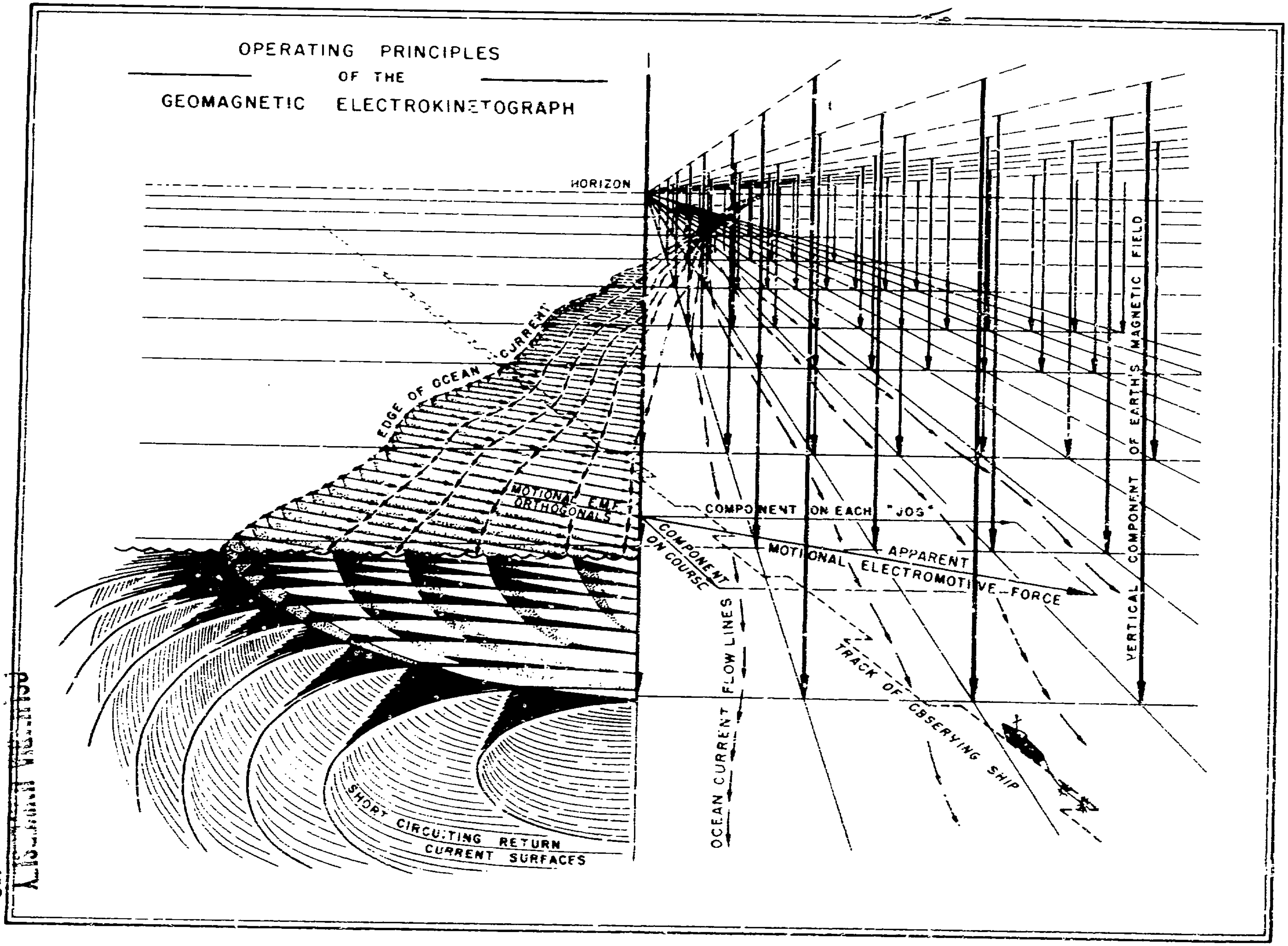

OPERATING PRINCIPLES
OF THE
GEOMAGNETIC ELECTROKINETOGRAPH
HORIZON
EDGE OF OCEAN CURRENT
MOTIONAL EMF ORTHOGONALS
COMPONENT ON EACH "JOG"
COMPONENT ON COURSE
APPARENT
MOTIONAL ELECTROMOTIVE FORCE
VERTICAL COMPONENT OF EARTH'S MAGNETIC FIELD
OCEAN CURRENT FLOW LINES
TRACK OF OBSERVING SHIP
SHORT CIRCUITING RETURN
CURRENT SURFACES

FIG. 6

Part II – The General Theory of the Electric Potential Field Induced in Deep Ocean Currents

By Henry Stommel

"1. The Problem Due to the fact that the water in the ocean is a conductor, and that it is everywhere under the influence of the earth's magnetic field we should expect, by the law of electric induction, that wherever the water is in motion electric potentials and currents will be established. It is the purpose of this paper to discuss the general theory of these phenomena in the deep ocean and to indicate certain analytical solutions of the problem which demonstrate the important physical aspects of electric fields associated with ocean currents.

2. Acknowledgement The author is particularly indebted to Mr. M. S. Longuet-Higgins of the Admiralty Research Laboratory at Teddington for acquainting him with the basic physics involved in section 3.

3. The fundamental equation of the electric field Let $\underline{H}$ be the vector magnetic field intensity, ρ be the scalar resistivity and $\underline{i}$ the electric current vector. Consider a closed curve fixed in the fluid. Let $\underline{v}$ be the fluid velocity vector. The length of arc along the closed curve is given by the vector $\underline{s}$. The element of area of the surface enclosed by the curve is $d\underline{S}$. Faraday's law of induction may then be expressed in the following very general form

$$\frac{d}{dt}\iint \underline{H}\cdot d\underline{S} + \oint \rho\, \underline{i}\cdot d\underline{s} = 0 \qquad (1)^*$$

where the d/dt is to be understood in the manner of the substantial derivative of hydrodynamics. The first term of equation (1)* may be transformed (see Abraham and Becker, "Classical Electricity and Magnetism" pp. 39-40) as follows:

$$\frac{d}{dt}\iint \underline{H}\cdot d\underline{S} = \iint \frac{\partial \underline{H}}{\partial t}\cdot d\underline{S} + \iint (\mathrm{div}\, \underline{H})\underline{v}\cdot d\underline{S} - \iint \left[\mathrm{curl}(\underline{v}\times \underline{H})\right]\cdot d\underline{S} \qquad (2)^*$$

In the ocean a considerable simplification of equation (2)* is possible because over moderately large areas $\underline{H}$ is constant and uniform. Therefore the first two terms of the second member vanish, and by Stokes theorem the third term may be transformed to a line integral.

$$-\iint \left[\mathrm{curl}(\underline{v}\times \underline{H})\right]\cdot d\underline{S} = -\oint (\underline{v}\times\underline{H})\cdot d\underline{s} \qquad (3)^*$$

The equation (1)* may now be written in the following form.

$$\oint (\underline{v}\times\underline{H} - \rho\,\underline{i})\cdot d\underline{s} = 0 \qquad (4)^*$$

The vanishing of this line integral signifies the existence of the electric scalar potential function ϕ, defined in the following way

$$\nabla\phi = \underline{v} \times \underline{H} - \rho \underline{i} \qquad (5)^*$$

The term ρ $\underline{i}$ involving the unknown current vector $\underline{i}$ may be eliminated if ρ is assumed to be uniform, for then the div ρ $\underline{i}$ vanishes, and upon taking the divergence of equation (5)* one obtains

$$\boxed{\nabla^2\phi = \underline{H} \cdot \text{curl } \underline{v}} \qquad (6)^*$$

If $\underline{H}$ and $\underline{v}$ are both regarded as known, which is physically the case, then we simply have here Poisson's equation to solve for the electric potential ϕ. It is desirable to emphasize the complete generality of equation (6)*. This equation defines the electric potential field resulting from <u>any arbitrary velocity field</u> in the ocean.

4. <u>An idealized particular ocean current system and its associated electric potential field</u>. In order to exhibit many of the features of the problem an idealised ocean current system is treated here. Rectangular coordinates are taken with the $\underline{x}$, $\underline{y}$ plane in the surface of the ocean, and the $\underline{z}$ axis pointing vertically upwards. This ocean is supposed to be divided into two layers. The top layer, #1, extends from $z = 0$ to $z = -h_1$. The bottom layer, #2, extends from $z = -h_1$ to $z = -h_2$. The bottom of the ocean, $z = -h_2$, is taken in this discussion as non-conducting.

The velocity in layer #1 is supposed to be given as

$$\begin{Bmatrix} v_x \\ v_y \\ v_z \end{Bmatrix} = \begin{Bmatrix} 0 \\ v_o \cos\frac{\pi}{b}x \\ 0 \end{Bmatrix} \qquad (7)^*$$

Layer #2 is supposed to be at rest. This current system consists of alternate bands of water of breadth $\underline{b}$ moving in the positive and negative $\underline{y}$ direction over a lower layer which does not participate in the motion. This picture is somewhat artificial, but because it is expressed in circular functions may be generalised by means of the Fourier Integral Theorem.

Let us suppose that the magnetic field of the earth is entirely vertical

$$\underline{H} = \begin{Bmatrix} 0 \\ 0 \\ H_z \end{Bmatrix} \qquad (8)^*$$

Substitution of (7)* into equation (6)* gives the following equations

$$\nabla^2\phi_1 = \gamma \sin\beta x \qquad (9)^*$$

$$\nabla^2\phi_2 = 0 \qquad (9')^*$$

Substituting into equation (14)* we obtain

$$\underline{n} \cdot \underline{v} \times \underline{H} - \frac{\partial \phi}{\partial z} = 0 \qquad (16)^*$$

In the particular case we are discussing $\underline{n} \cdot \underline{v} \times \underline{H}$ vanishes so that the boundary condition at the surface $z = 0$ is

$$\frac{\partial \phi}{\partial z} = 0 \qquad (17)^*$$

The boundary condition at the bottom $z = -h_2$ is also one of no current flow so it is the same as equation (17)*.

At the interface between layers 1 and 2, $z = -h_1$, two conditions prevail, for clearly the potential and current must be continuous. Therefore at $z = -h_1$

$$\phi_1 = \phi_2 \qquad (18)^*$$

$$\underline{i}_1 = \underline{i}_2 \qquad (18')^*$$

The second of these equations may be expressed in terms of the potential function

$$\frac{\partial \phi_1}{\partial z} = \frac{\partial \phi_2}{\partial z} \qquad (18'')^*$$

The conditions (17)* at $z = 0$ and $z = -h_2$ and the conditions (18)* and (18")* at $z = -h_1$, suffice to determine the constants of integration.

$$\begin{aligned} A_1 &= \delta \frac{\sinh\beta(h_2 - h_1)}{\sinh\beta h_2} \\ B_1 &= 0 \\ A_2 &= -\delta \frac{\sinh\beta h_1}{\tanh\beta h_2} \\ B_2 &= -\delta \sinh\beta h_1 \end{aligned} \qquad (19)^*$$

Therefore the final solution is

$$\phi_1 = \sin \beta x \left[1 - \frac{\sinh \beta (h_2 - h_1)}{\sinh \beta h_2} \cosh \frac{\pi}{b} z \right] \frac{v_o H_z}{\beta} \qquad (20)^*$$

$$\phi_2 = \sin \beta x \left[\frac{\sinh \beta h_1}{\tanh \beta h_2} \cosh \beta z + \sinh \beta h_1 \sinh \beta z \right] \frac{v_o H_z}{\beta} \qquad (20)^*$$

For purposes of illustration several graphs have been constructed showing lines of equal potential for different values of b, and h_1. Examination of the results shows how sensitive the potential field is to the relative depths of the two layers 1 and 2. When the top moving layer is thin compared to the lower one at rest, the potentials established are very much reduced. The breadth of the current is not a very important factor except for a multiplicative factor directly proportional to breadth.

5. A further particular case of interest The axes are taken as in section 4. The velocity is assumed to be all in the positive and negative y-direction, as before, but according to the following pattern in the x, z plane

$$v_y = v_o \cos \frac{\pi}{b} x \cos \frac{n\pi}{h} z \qquad (21)^*$$

where h is the total depth of the bottom beneath the surface $z = 0$ and n is 0, 1, 2, 3, 4, ...

Substitution of this value of v_y into equation (6)* yields

$$\nabla^2 \phi = -H_z \cdot \frac{v_o \pi}{b} \sin \frac{\pi}{b} x \cos \frac{n\pi}{h} z \qquad (22)^*$$

The solution of this equation which also satisfies the boundary conditions $\partial \phi / \partial z = 0$ at $z = 0$ and $z = -h$ is

$$\phi = \left[\frac{H_z v_o}{\pi} \cdot \frac{bh^2}{h^2 + n^2 b^2} \right] \cdot \sin \frac{\pi}{b} x \cos \frac{n\pi}{h} z \qquad (23)^*$$

$$n = 0, 1, 2, 3, \ldots\ldots\ldots\ldots$$

6. Numerical method of solution A convenient numerical method of solution may be based upon the relaxation methods developed by Sir Richard Southwell ("Relaxation Methods in Theoretical Physics" Oxford, 1946). Any vertical profile can be investigated and the electric potential field computed.

Equation (6)* is expressed in finite difference form. The boundary condition at the bottom and at the free surface is expressed by equation (16)*. The procedure of the solution is then by liquidation of residuals (Southwell, ibid, p. 24). Publication of any of these relaxation solutions is postponed until some simultaneous electric potential measurements and sufficient hydrographic stations for computation of the velocity field are available."

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Note

The values of ϕ over a number of cross-sections of water motion involving shear across the x axis, and across the x and z axes are given in figures 7 and 8 respectively. While these sections do not resemble closely any known oceanographic case they do show how the increase of shear in the water motion improves the results of measurement by reducing the residual potentials in the sea. They also show that both adjacent and subjacent water currents having independent motions with respect to the water current undergoing measurement can replace in effect the properties of a large stationary mass. During examination of these fields it should be remembered that they are fields of residual potential which are subtracted by the sea from the motional Emf in the measuring instruments to yield V the observed motional potential (ref. Equation (18')). The drawings were computed and prepared for drafting by Miss Barbara Allen.

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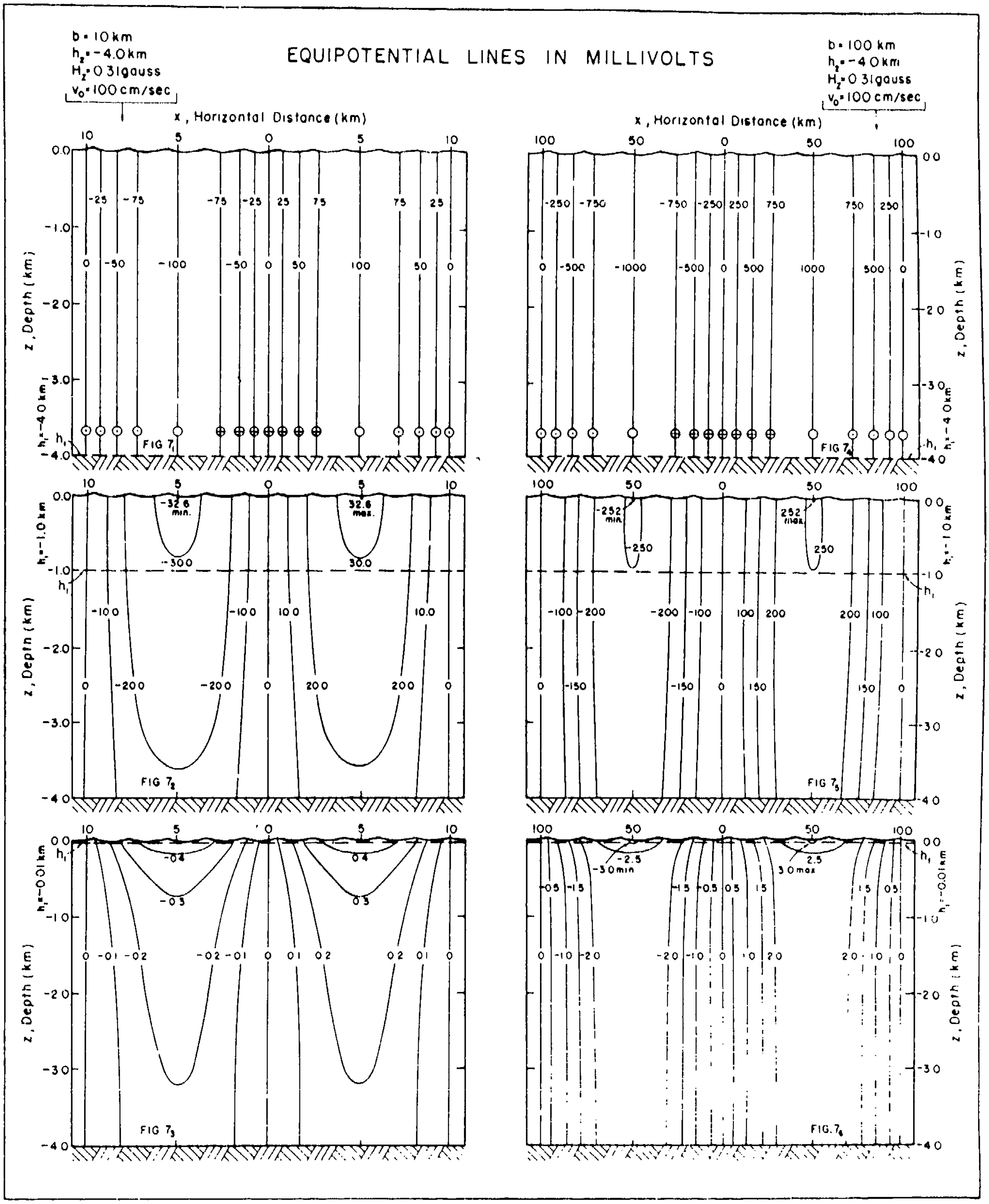
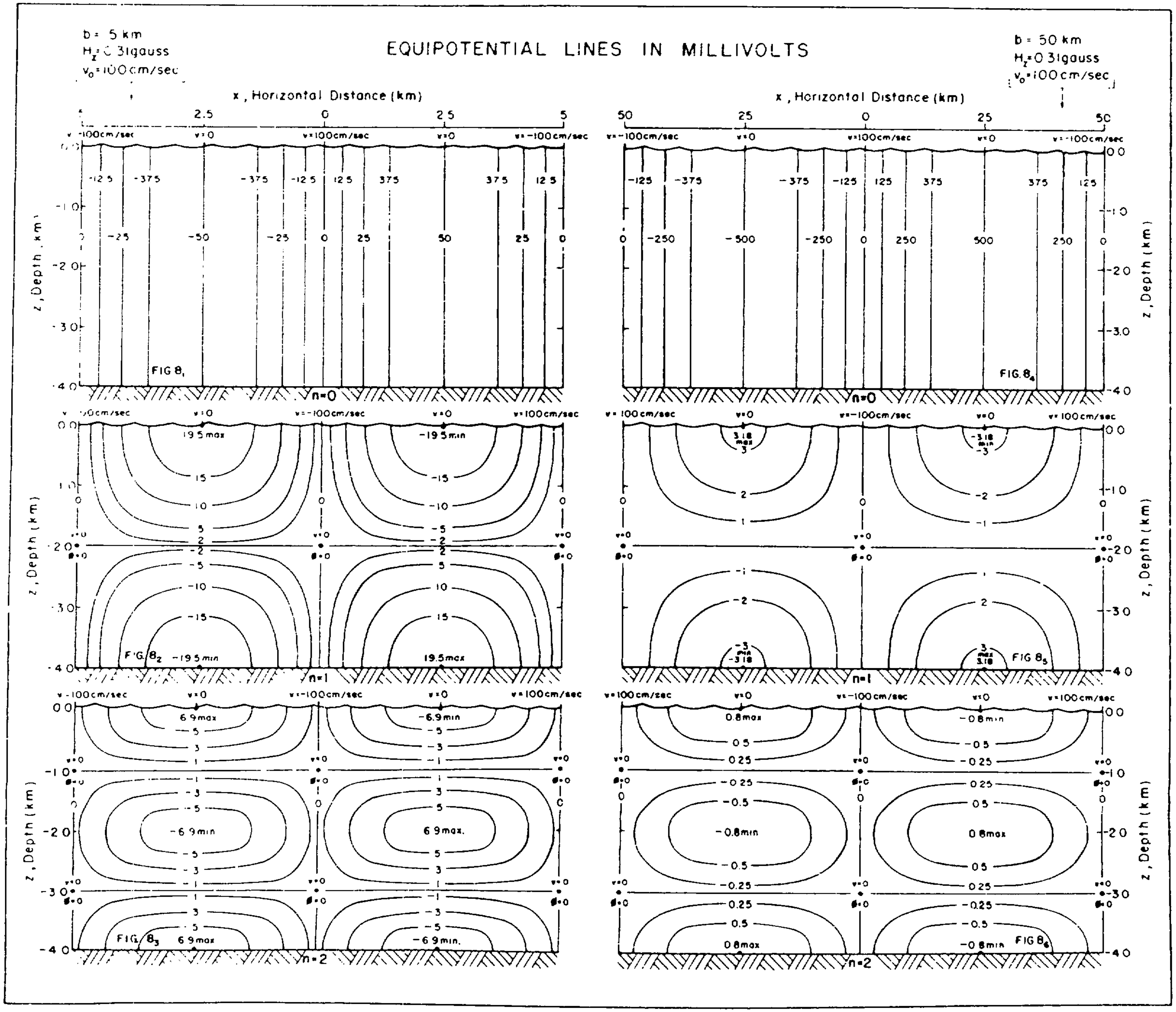


EQUIPOTENTIAL LINES IN MILLIVOLTS
b = 10 km
h_z = -4.0 km
H_z = 0.31 gauss
v_0 = 100 cm/sec
b = 100 km
h_z = -4.0 km
H_z = 0.31 gauss
v_0 = 100 cm/sec
x, Horizontal Distance (km)
z, Depth (km)
h_1 = -4.0 km
h_1 = -1.0 km
h_1 = -0.01 km
FIG 7₁
FIG 7₂
FIG 7₃
FIG 7₄
FIG 7₅
FIG 7₆
-32.6 min.
32.6 max.
-252 min.
252 max.
-3.0 min
3.0 max

FIG.7



EQUIPOTENTIAL LINES IN MILLIVOLTS
b = 5 km
H_z = 0.31 gauss
v_0 = 100 cm/sec
b = 50 km
H_z = 0.31 gauss
v_0 = 100 cm/sec
x, Horizontal Distance (km)
z, Depth (km)
FIG 8₁
FIG 8₂
FIG 8₃
FIG 8₄
FIG 8₅
FIG 8₆
n=0
n=1
n=2

FIG. 8

VIII Ship's Log Experiments

Measurements of the forward speed of a ship are theoretically possible through a slight readjustment of thought concerning the basic principle of the Electrokinetograph. A series of experiments were performed to see how practical such a log would be. Two electrodes were towed equal distances astern on either sides of the ship and separated by 50 feet. The theory is that the wire transverse to the ships way would cut flux and produce a signal proportional to the rate of motion of the ship while the other transverse portion of the loop, closed by the water between the electrodes, does not share this motion and consequently does not cut flux or produce a signal proportional to the ship's speed. This situation should allow measurement of the voltage in the moving segment. It is further argued that the motional EMF signal from moving water filaments between the electrodes would appear with the ship's speed signal and that both wake and current signals would occur. All these theoretical effects were found to exist. On Atlantis Cruise 149 an experiment was run with the ship under sail to avoid the propeller wash present in all previous experiments, and it was found that the recorded voltage changed as the ship's speed changed. But again the problem of electrode zero made it impossible to determine from what point these voltage changes had their origin and therefore, whether or not the changes in voltage were proportional to the change in speed of the ship. Through extrapolation backward toward the origin by means of the theoretical speed-voltage relationship a zero point was calculated which agreed well with the zero point registered by stopping the ship but of course, this is not a practical method. It was thought that exchanging the positions of the electrodes from side to side of the ship would provide the needed zero information, but, to gain the necessary interelectrode distance outriggers were used, and the operation became hopelessly cumbersome. Further work on this problem will be undertaken as new ideas or better electrodes come to light.

TBS and IFF systems are considered to be possible parallel developments to the measurement of voltages in the sea. It is known that both power and potential fields surround an electric dipole in a conducting medium. With suitable detecting circuits it is possible to receive signals emitted from the dipole at some distance. Several experiments have been made to test the range of such a communication system. In one experiment in which two electrodes 2 feet apart were energized by a 1 watt A.F. speech signal it was possible to receive a clearly intelligible signal 30 feet away by means of two other electrodes 2 feet apart. All electrodes were simple brass plates 2 x 6 x 1/32 inches. The received signal was amplified about 120 db and could be heard very well through a speaker. The attenuation over the range was about 90 db. The electrodes in this experiment were arranged to rotate so that it was possible to determine the null pattern of the isopotential lines surrounding the transmitting dipole. The nulls were extremely sharp at short ranges and still sharp enough for homing purposes at extreme ranges. In practical scales using 200 feet between the electrodes of the dipole transmitter and the receiver the maximum range is probably of the order of 1.0 to 1.5 miles for 1000 watts input power, provided code signals are used. Voice or other A.F. transmission would be difficult beyond a range of 0.5 mile. The ranges are short because the input voltage must be increased by the 3/2 power of the geometrical scaling factor. That is, if the interelectrode distance a and the range b is increased by a factor n the voltage must be increased by $nV^{3/2}$. If the interelectrode distance a is kept constant a doubled range is accomplished by cubing the voltage. The cube is a stiff rate of increase consequently the range for reasonable power output is limited to the order of a mile or so.

The rapid attenuation of signal strength has an advantage of security in that the range is so sharply limited that complete confidence can be had in its limits. For short range TBS there is no appreciable electromagnetic radiation developed, and other than that from ignition or generator systems there is no appreciable background noise in the A.F. range of frequency. It was found after these experiments had been performed that more exhaustive trials of the method had been made under full scale conditions by Hardy (1945) and his associates at the Moore School of Electrical Engineering, University of Pennsylvania. His results are in good agreement with those presented here.

The range of the system is also too short for tactical use as SAS-IFF or for use from surface ships with submarine escort. To extend the range to five miles from a transmitting dipole for which a is 200 feet the input power would have to be raised to the order of 1 or more megawatts. With pulsed power this might be feasible without stupendous power packs but Hardy reports poor success with pulsing. His problem was slightly different from the one suggested here in that he was primarily interested in short range communications for landing operations and between swimmers in demolitions crews. Further study of the whole problem might be profitable as the rapid attenuation of the signal with range could be turned to advantage.

(B) Selected Bibliography of papers on motional EMF in liquids Chronologically arranged

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A REPORT ON THE DEVELOPMENT AND BEHAVIOR OF THE GEOMAGNETIC ELECTROKINETOGRAPH

by
W. S. von Arx
Woods Hole Oceanographic Institution
June 1947

Introduction

The Geomagnetic Electrokinetograph is an instrument of great simplicity which is capable of measuring the motions of sea water from a moving vessel. The motions of the sea may result from any cause, wind drift, waves, currents, and their eddies, tides, seiches, tsunamis or artifacts, and still be suitable objects of study. The basic performance of the instrument depends upon Faraday's Law of Electromagnetic Induction, particularly the special case which he mentioned in his Bakerian Lecture to the Royal Society in 1832. This case discussed on page 176 of the Philosophical Transactions 1832 is as follows: "Theoretically, it seems a necessary consequence that where water is flowing, there electric currents should be formed: thus, if a line be imagined passing from Dover to Calais through the sea, and returning through the land beneath the water to Dover, it traces out a circuit of conducting matter, one part of which, when the water moves up or down the channel, is cutting the magnetic curves of the earth, whilst the other is relatively at rest..... Where the lateral extent of the moving water is enormously increased, it does not seem improbable that the effect should become sensible; and the Gulf Stream may thus, perhaps, from electric currents moving across it, by magneto-electric induction from the earth, exert a sensible influence upon the forms of the lines of magnetic variation.* (*footnote Theoretically, even a ship or boat when passing on the surface of the water, in northern or southern latitudes, should have currents of electricity running through it directly across the line of her motion; or if the water is flowing past the ship at anchor, similar currents should occur.)" This is a clear statement of the effect which has subsequently been observed, but which Faraday himself failed to detect through a lack of suitable electrode materials.

The Present Experimental Method

In 1920, Messrs. Young, Gerrard and Jevons of the British Admiralty published the results of preliminary experiments which they performed in Dartmouth Harbor putting Faraday's ideas to a more modern test. They were qualitatively successful and showed that motional electromotive forces (apparently) do exist in the sea and that it is possible to determine the directions of flow causing them. Their experiments were of the sort mentioned by Faraday using moored electrodes on either side of a tidal stream, and also drifting electrodes handled from a boat. In each case the electric current flowing through the circuit was measured rather than the voltage. This leads to a practical difficulty with Ohm's Law which does not hold in electrolytes. To avoid this trouble the Electrokinetograph measures voltage by means of a modified constant balance potentiometer which records continuously on a strip chart. The recorded voltages are those picked up between two Silver-Silver Chloride electrodes either moored, or towed behind a ship in tandem. The magnitude of the voltage is given by the equation

$$kE = H_z sv \times 10^{-8} \quad (1)$$

in practical units, where $\underline{H_z}$ is the vertical component of the earth's magnetic field, $\underline{s}$ is the distance between electrodes, $\underline{v}$ is the speed of the water motion, $\underline{E}$ is the voltage and $\underline{k}$ is a correction factor which depends upon the depth of water and to some extent upon the nature of the bottom. The factor $\underline{k}$ has been determined in water of varying depths and has been found to be roughly 3 in 8 fathoms and 1.0 in depths greater than 1500 fathoms. It may be substantially 1.0 in water only 100 fathoms deep but the existing data are insufficient to establish the point. A program of $\underline{k}$ studies is planned.

Regarding direction, the observed magnitude of $\underline{E}$ varies at any station with the course of the ship. The measured $\underline{E}$ is that along the line between the electrodes and is that induced by the component of water motion at right angles to this line. Thus two measured voltages along two courses at some angle, usually greater than 60° and less than 120°, to eath other and having known geographic bearings, suffice to establish the true direction and magnitude of the motional electromotive force in the sea. This datum is related to the direction and magnitude of the water motion by the vector equation

$$k \cdot \underline{E} = \underline{v} \times \underline{H} \quad (2)$$

in which $\underline{k}$ is the aforementioned scalar correction, $\underline{E}$ is the vectorial voltage produced by the cross product of $\underline{v}$ the water motion vector and $\underline{H}$ the magnetic field vector. Under present circumstances $\underline{E}$ is measured by two horizontally disposed electrodes which therefore detect only the horizontal componen[t o]f $\underline{E}$. This restricts the solution to the horizontal component of $\underline{v}$ and cons[eq]uently the vertical component of $\underline{H_z}$ of $\underline{H}$ the total magnetic field of the earth at the station.

In practice $\underline{H_z}$ is measured from the ship, and ashore a continuous record of the stability of the earth's field is made to establish the state of the "magnetic weather" during observations at sea. Regional magnetic storms are recorded at Woods Hole by means of a pair of electrodes half a mile apart spanning the Hole. A recording galvanometer writes the trace of the electric currents generated by the tidal oscillations and also those earth currents arising from magnetic storms (see figure 1). The validity of this record as an index of magnetic activity has been established through comparison of eight months of continuous tidal Emf trace at Woods Hole with coincident magnetometric traces secured from the Cheltenham Magnetic Observatory. The correlation is nearly perfect, and it is possible to observe the onset and cessation of storms with complete confidence. The effect of magnetic storms upon the measurement of currents at sea is not known at present since the earth's field has been stable during all tests of the method. It is expected that the disturbance will be sufficiently marked to be detected at sea unless observations are being made of violent water motions such as that in the Gulf Stream.

Geophysical magnetic fields due to submarine geologic structures will produce small errors in the observed water motion, but by means of continuous or closely spaced measurements of H_z made currently with a degaussing magnetometer designed by N.O.L., it is possible to allow for such changes. The present instrument reads to better than 10 milligauss at sea, and since H_z in local latitudes ranges from 450 to 500 milligauss, precision of 2 per cent is maintained. This error lies within the experimental error of the Electrokinetograph.

Field Trials of the Electrokinetograph

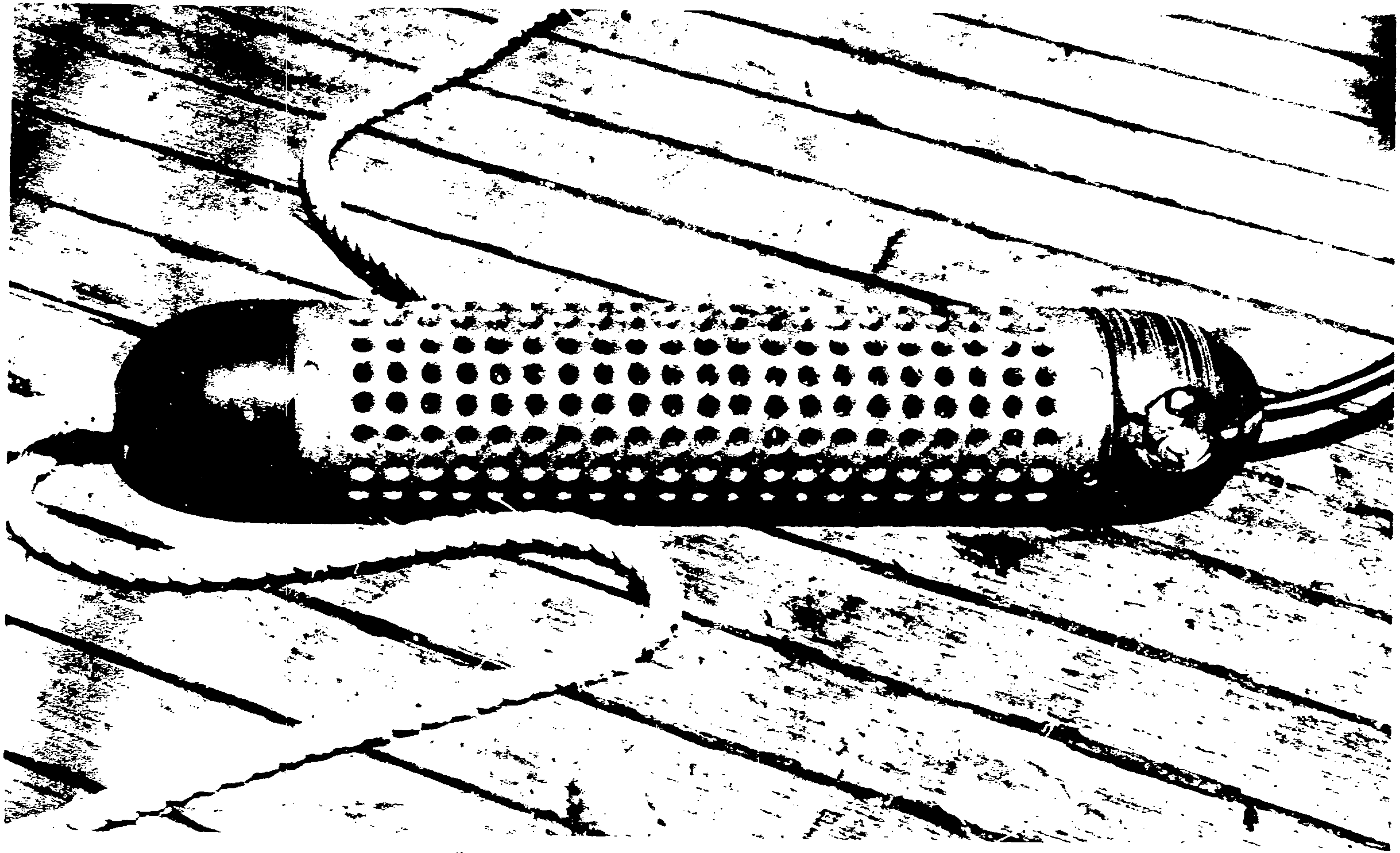
The earliest experiment with the technique was begun 16 November 1946 when the moored electrodes across Woods Hole were installed. These were soon connected to a recording Fluxmeter made by General Electric which was altered to act as a recording galvanometer. This instrument has been in continuous operation ever since. It was noted very early in the experiment that the voltage did not correspond to the current strength in accordance with equation (1), but that k had a value somewhere between 3 and 4.

The first experiment at sea with towed electrodes was performed on 19 March 1947 near the Cox Ledge Gong off Block Island. The results gave the direction of the current in good agreement with the observed direction by visual bearings on the gong and an improved value of the current speed (due to the deeper water) for which k was approximately 2.

Immediately following this experiment a constant balance potentiometer was procured and more suitable equipment built to hold and handle the electrodes. Several cables were fitted with Silver-Silver Chloride electrodes spaced 3×10^3, 4×10^3 and 5×10^3 centimeters apart. The electrodes were housed in "corn cobs" of formica which protect them from damage on deck and attack by fish or the passing BT. The size and surface area of the electrodes is immaterial, the only criterion determining their fitness for use is an identity of skin potential. It has been found that two pieces of silver wire 0.100 in. diameter and 6 in. long wound into pig tails and chlorided for a period of 2 minutes with Conc. HCl and Conc. HNO_3 mixed 1 : 1 have nearly identical skin potentials. Any dissimilarities can be eliminated by shorting the electrodes together in sea water for a few hours. The identity of potential will remain for a period of hours or days depending on the pair and then drift at the rate of 1.0 mv./36 hours or so until the coating is washed away. Renewal of the coating is as simple as its original deposition.

The drift of interelectrode potential does not interfere with the record of the relative potentials in the sea but it does confuse their absolute values by shifting the electrical zero of the recorder with respect to the mechanical zero. For this reason it is necessary to reverse the direction of the ship and the streaming electrodes every four or five hours to reverse the sign of the incoming potential. In steady water currents this method establishes electrical zero along the line of symmetry between the recorded direct and inverse voltages.

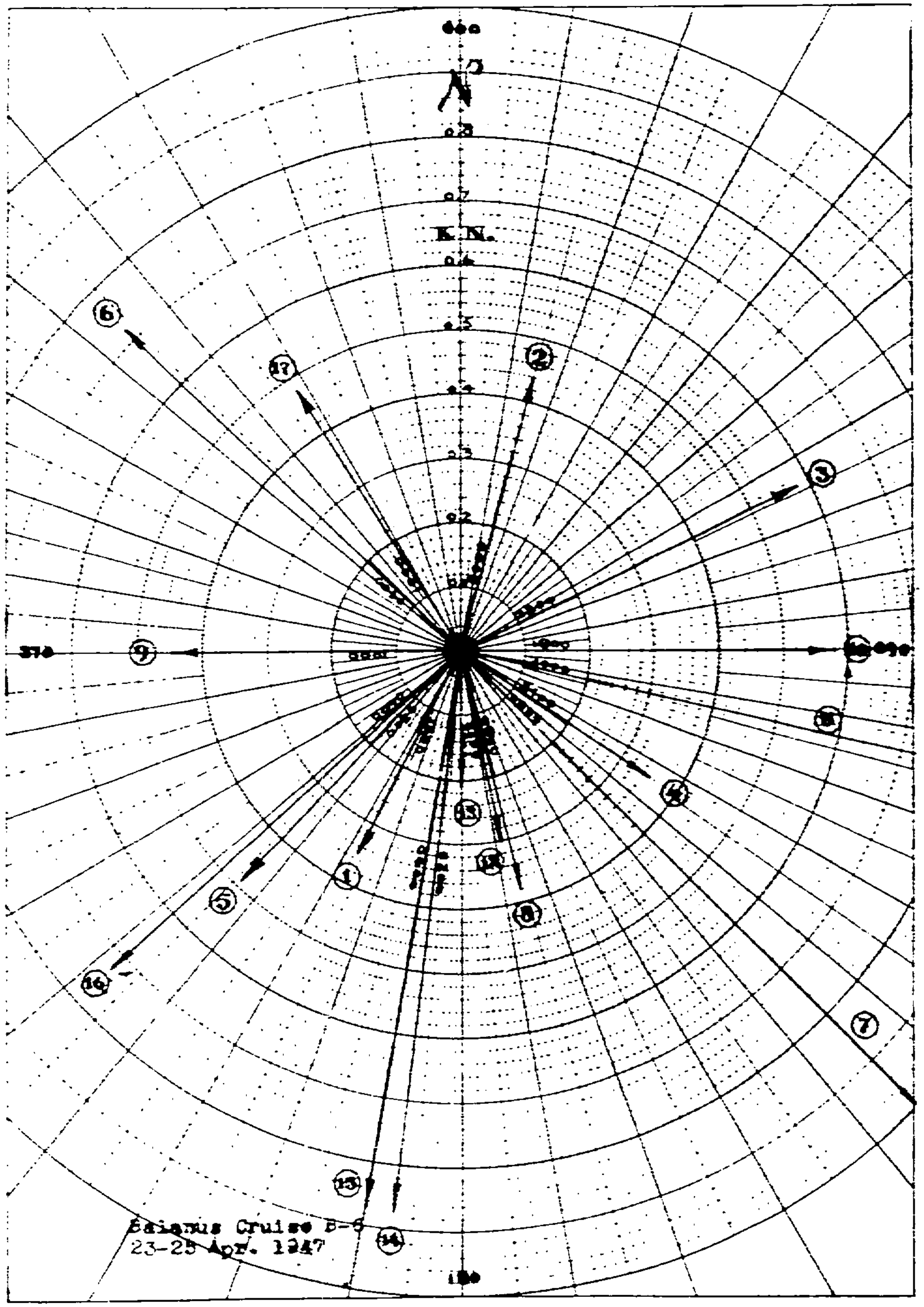
Most of this technique was worked out in the course of a number of



"CORN COB" ELECTRODE CASE

one-day cruises in Vineyard and Nantucket Sounds. These trials were followed by two deep sea cruises B-6 and B-9 of R/V Balanus heading across the shelf from the vicinity of Vineyard Sound lightship. The first cruise was specifically designed to test the Electrokinetograph and the second was an extension of a biological cruise from the edge of the shelf into deep water. The courses sailed and measurements made are plotted on charts included in this report (figures 2 & 3).

Cruise B-6 over the shelf yielded 17 current "fixes" in shelf water and a continuous record of the currents across the line of motion of the ship. It was found almost immediately that the nature of the motion of water over the shelf is far from laminar. The signal shows the occurrence of eddies, one after another, over most of the shelf (figure 4). These have a mean diameter of two-thirds of a mile and a mean angular velocity of approximately 1 radian per hour. In addition there is the rotary tide on the shelf, the data for which are tabulated and reduced in Table 1 (see also figure 2).


K.N.
Balanus Cruise D-6
23-25 Apr. 1947

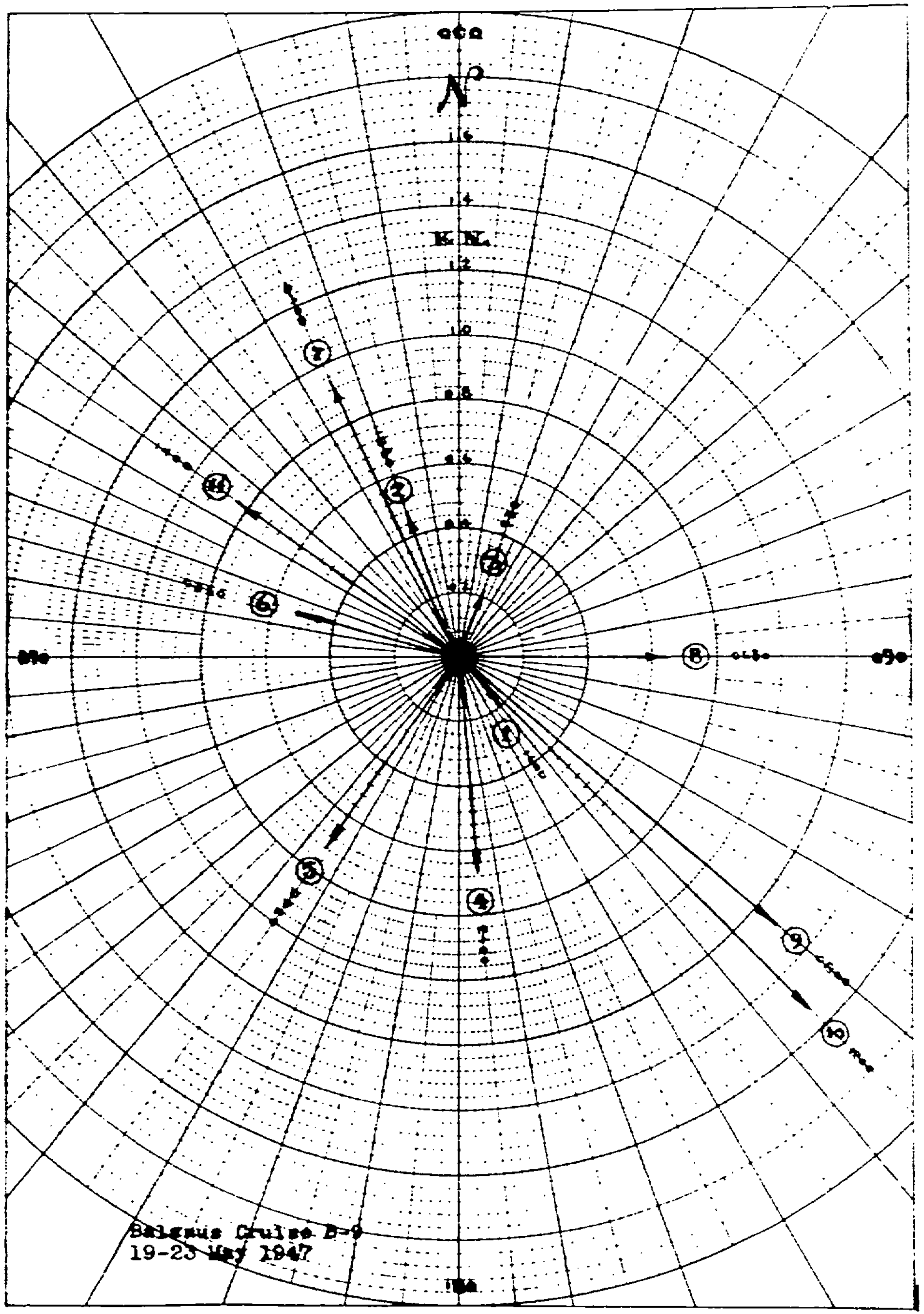

K.N.
Balanus Cruise D-9
19-23 May 1947

TABLE I

Observed Angular Velocity of the Rotary Tides
on the Continental Shelf South of Block Island

Station	θ		T	t	$\frac{d\theta}{dt}$	
1- 2	165°	4h	00m	240m	0.69°/min	
2- 3	49	2	00	120	0.41	
3- 4	60	2	00	120	0.50	
4- 5	98	2	00	120	0.82	outward
5- 6	90	2	00	120	0.75	
6- 7	182	2	00	120	1.52	bound
7- 8	31	2	00	120	0.26	
8- 9	104	2	00	120	0.87	
9-10	180	8	00	480	0.43	
9-10	180	8	00	480	0.43	
10-11	13	2	00	120	0.11	
11-12	64	2	00	120	0.53	
12-13	12	2	00	120	0.10	homeward
13-14	7	2	00	120	0.06	
14-15	4	2	00	120	0.03	bound
15-16	38	2	00	120	0.32	
16-17	100	4	00	240	0.42	

outward bound sub total $\frac{6.25}{9} = 0.697°$/min.

homeward bound sub total $\frac{2.00}{8} = 0.250°$/min.

2) 0.947
0.474°/min

0.474) 360°
760 minutes / tidal revolution

or 12.67 hours / tidal revolution

This value is compensated for the progress of the ship across cotidal lines by the distribution of stations on both legs of the cruise. These are not equal in number but are weighted out in the calculation and are limited to the same geographic zone. The value obtained is close to the period of the mean tidal day of 12.83 hours.

On the basis of these figures it is possible to calculate the rate of progress of a given tidal phase. The ship's mean rate of progress was close to 7.5 knots, which motion altered the value of $d\Theta/dt$ by $\pm 0.223^{\circ}$/min. from the average value 0.47°/min. Thus it may be concluded that the velocity of propagation of a tidal phase is

$$\frac{0.474}{0.223} \times 7.5 \text{ knots} = 16.0 \text{ knots approx.}$$

At this velocity a given tidal phase could progress landward from the edge of the continental shelf to the beach (roughly 100 mi.) in 6.25 hours and return to the edge in the same time 12.50 hours later to be in phase with the next incoming tide.

These numbers then represent the period of the forced oscillation of water on the shelf off Block Island and the velocity of phase propagation.

* * * * * * * *

[redacted]

The sailing plan employed on Cruise B-6 was straightaway on course with a calibration square composed of four cardinal legs 2400 feet long sailed every two hours. Thus a continuous record of the currents transverse to the course was obtained together with a measure of the true direction and magnitude of the current every 15 miles. It was found that the leeway of the ship did not correspond very well with the action of the observed currents. Wind and waves, both of which were of force 4 to 5 throughout most of the cruise, had an overpowering effect upon the motion of the ship through the relatively weak current system. The voltage record shows the waves as well as the currents and eddies. It is possible to determine the period, internal velocity, and direction of the waves from the calibration squares. An attempt was made to measure the change of internal velocity of the waves with depth by sinking the electrodes deeper in the sea, but insufficient weight of suitable shape was at hand to carry the measurements very far down.

It was also noted that there is a very rigid correlation between changes in the temperature and salinity of the sea with the appearance of new current vectors. The STD recorder running continuously along with the Electrokinetograph showed the ship's entrance into and departure from warmer more saline water.

On Cruise B-9 which was devoted to the Electrokinetograph experiments from the 1000 fathom line to the Gulf Stream and return, the edge of the Gulf Stream was crossed four times. In each case the mature value of the current was observed within a mile of the first indicated crossing. Of the four crossings, the two entering crossings are illustrated in figures 5 and 6. It will be noted that both the period and amplitude of the eddy structure is changed as well as the mean speed of the current. The sudden changes in recorded voltage which are bracketed are those measured by 90° jogs in the ship's course. Jogs were sailed for four minutes every half hour, alternately right and left so that the current could be fixed upon every 4 miles and the zero drift checked every hour. This was found to be a much more satisfactory procedure than calibration squares in complex velocity structures because the ship covers less ground and takes less time during which changes in the current might occur. Even so the best values are only approximations since the eddying current structure is so variable in detail (see figures 7, 8, and 9). There is indeed more information on the record tapes than we are presently prepared to understand. As field work progresses new techniques will doubtless come to mind which will simplify the records and their interpretation.

On Cruise B-9 the recorder was fitted with a 60,000 microfarad capacitor across the input so that the amplitude of the wave signal could be reduced. Figure 10 shows the effect of the capacitor in the circuit. Even so large a value as 60,000 microfarads is insufficient to damp out the wave signal, and so 500,000 microfarads have been made ready for the next cruise. This should increase the accuracy of measurement of the relatively slow alternations of potential due to eddies. Extraordinarily large capacitors can be used to damp out the eddy signal for measurements of the mean current but this would discard useful data. It is obvious that the term current must be qualified by subdivision into at least two categories:

[redacted]

perhaps eddy or instantaneous current, and mean or transport velocity could be used. The flow mechanism by which water is moved from one place to another in the sea is only rarely laminar. By the existing method eddies smaller than 100 feet across are lost, as are those having a differential voltage of less than 0.1 millivolt due to their slow rate of rotation. With the increased sensitivity planned for the Electrokinetograph it should be possible to measure details 100 or possibly 1000 times smaller. There may be a practical limit determined by the necessity of damping out the wave signal to make accurate measurements of current. If the details of detectable eddy motion begin to come into the frequency range of waves the two signals could not be separated. Indeed, the cycloidal motion of water parcels in waves is different from eddy motion only in its plane of movement.

As a wave recorder the Electrokinetograph measures, in its present form, only the horizontal component of wave motion. It is conceivable that a two or even three component electrode system could be devised to study their motions in three dimensions. Such studies at a variety of depths would provide entirely new information which would be of great value. The case of the breaking wave near shore as it "feels bottom" would be particularly exciting. With the increased sensitivity expected from the microvolt recorder model it may be possible to study the slow oscillations of internal waves although there are many practical difficulties in that direction.

As a current measuring device it has been proven accurate insofar as direction is concerned under all circumstances, and with a little more work the magnitudes of currents should be quite reliable. In deep water the method seems to work without correction. At the 1200 position of the Balanus shown in figure 11 she was hove to for a series of hydrographic lowerings and biological observations. The current observed by the Electrokinetograph at this station was measured at 4.83 knots setting 143°T. She drifted 3.25 hours to the 1515 Loran fix covering a distance of 13.8 miles into another current measured at 4.55 knots setting 160°T. and made leeway under a southwest wind at the rate of 1.0 knot. Extracting her leeway, her rate of drift was 4.25 knots and direction of drift 145°T. In view of the extreme complexity of the current in this part of the ocean and the uncertainty, due to leeway, of remaining in fairly constant current conditions, this drift station is considered a good check.

Reliability thus established for the other B-9 values of current direction in deep water the peculiar direction of the Gulf Stream motion is apparently real. Tank experiments employing what are believed to be identical Reynolds numbers yield a meandering sort of motion for the Gulf Stream. These observations may be taken as confirmation of the existence of such motions. The mass motion of the stream is probably given by the positions of the first and fourth crossings. A more extensive cruise is planned during which the entire Gulf Stream will be crossed at least twice and the eddies on the northwest flank studied as intensively as possible with all available means. It is interesting to contemplate the data that might be secured by several ships sailing abreast through the Gulf Stream, making systematic sorties at different latitudes.

Woods Hole Oceanographic Institution
15 June 1947

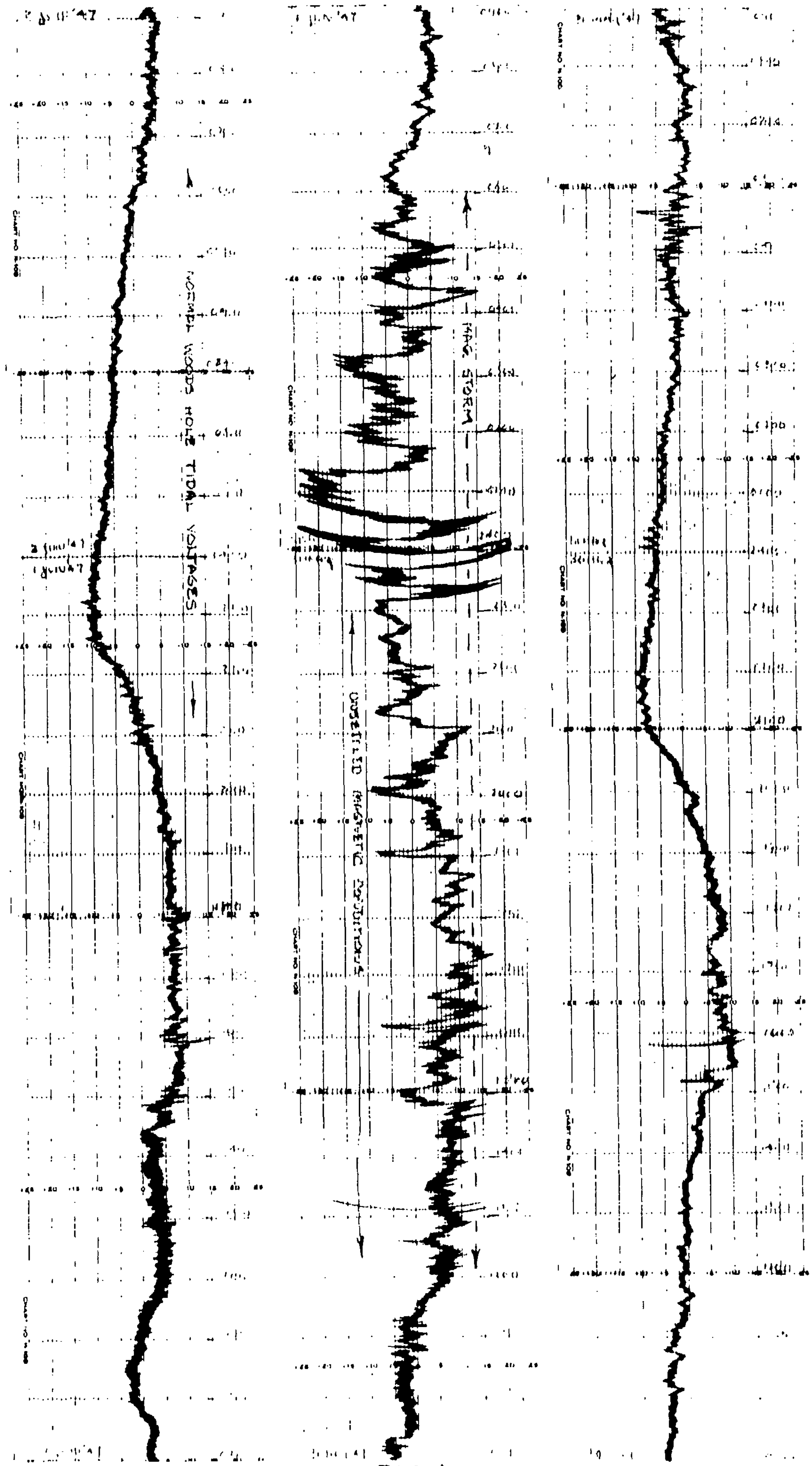

NORMAL WOODS HOLE TIDAL VOLTAGES
MAG STORM
UNSETTLED MAGNETIC CONDITIONS

FIG. 1

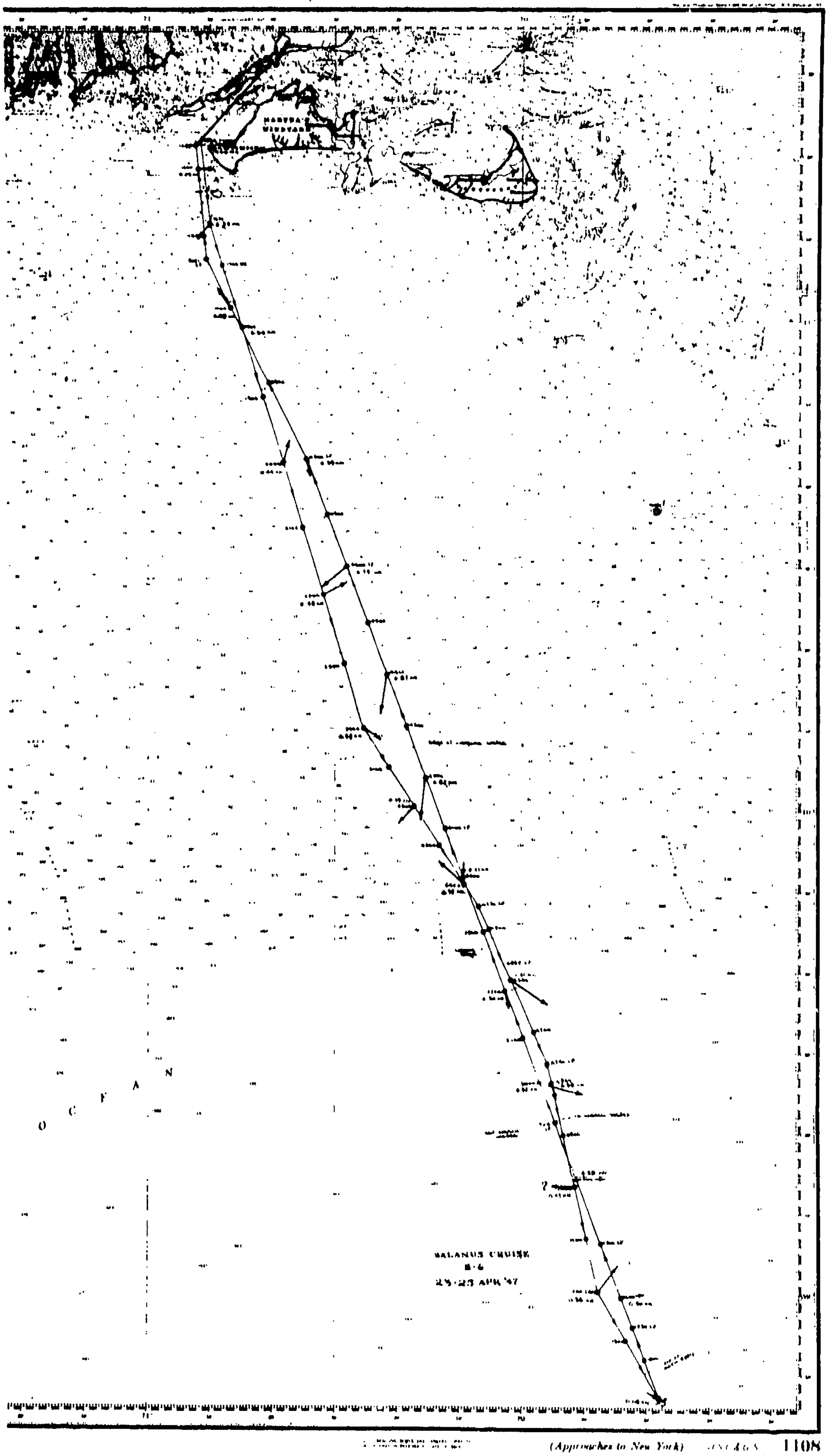


FIG. 2

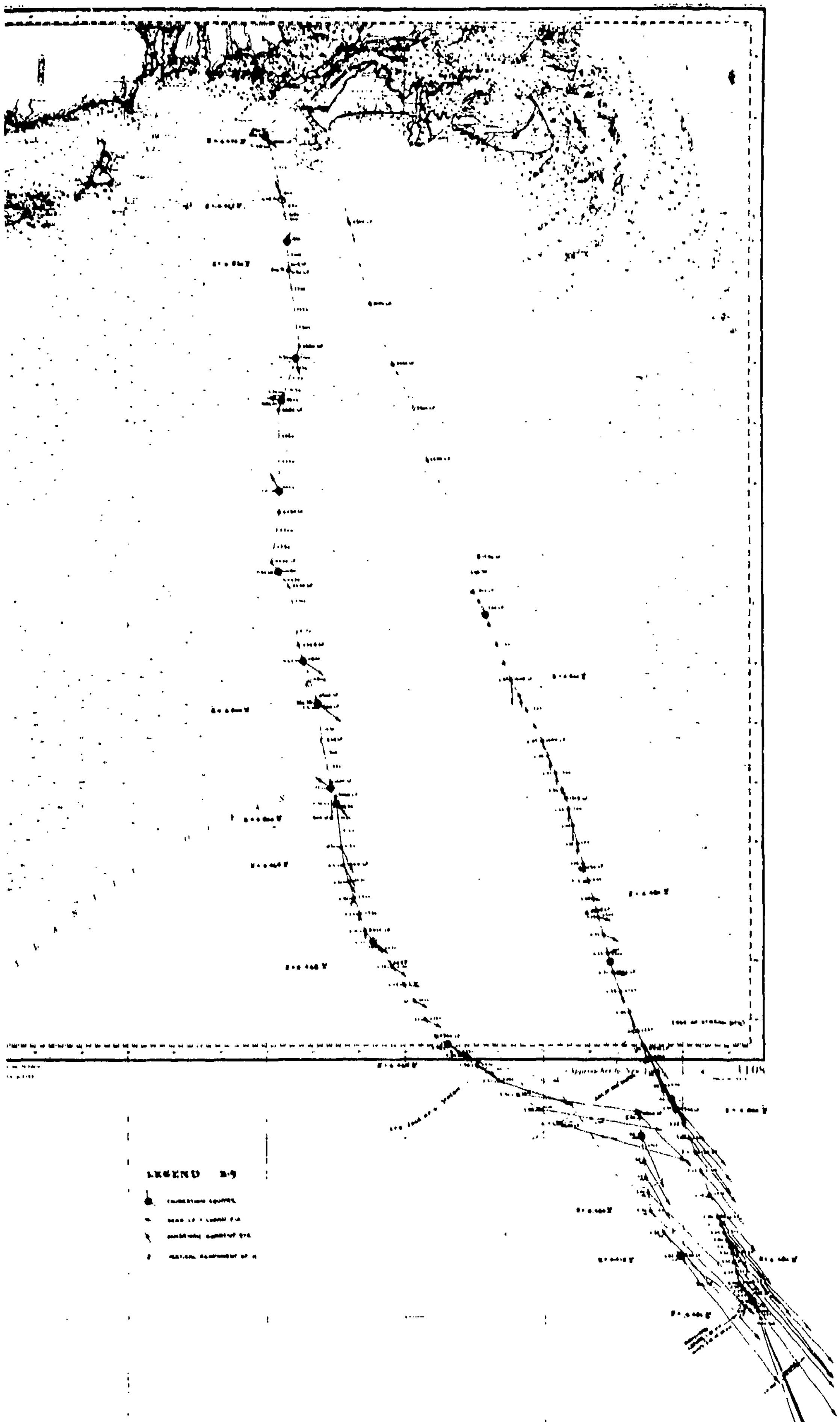


FIG.3

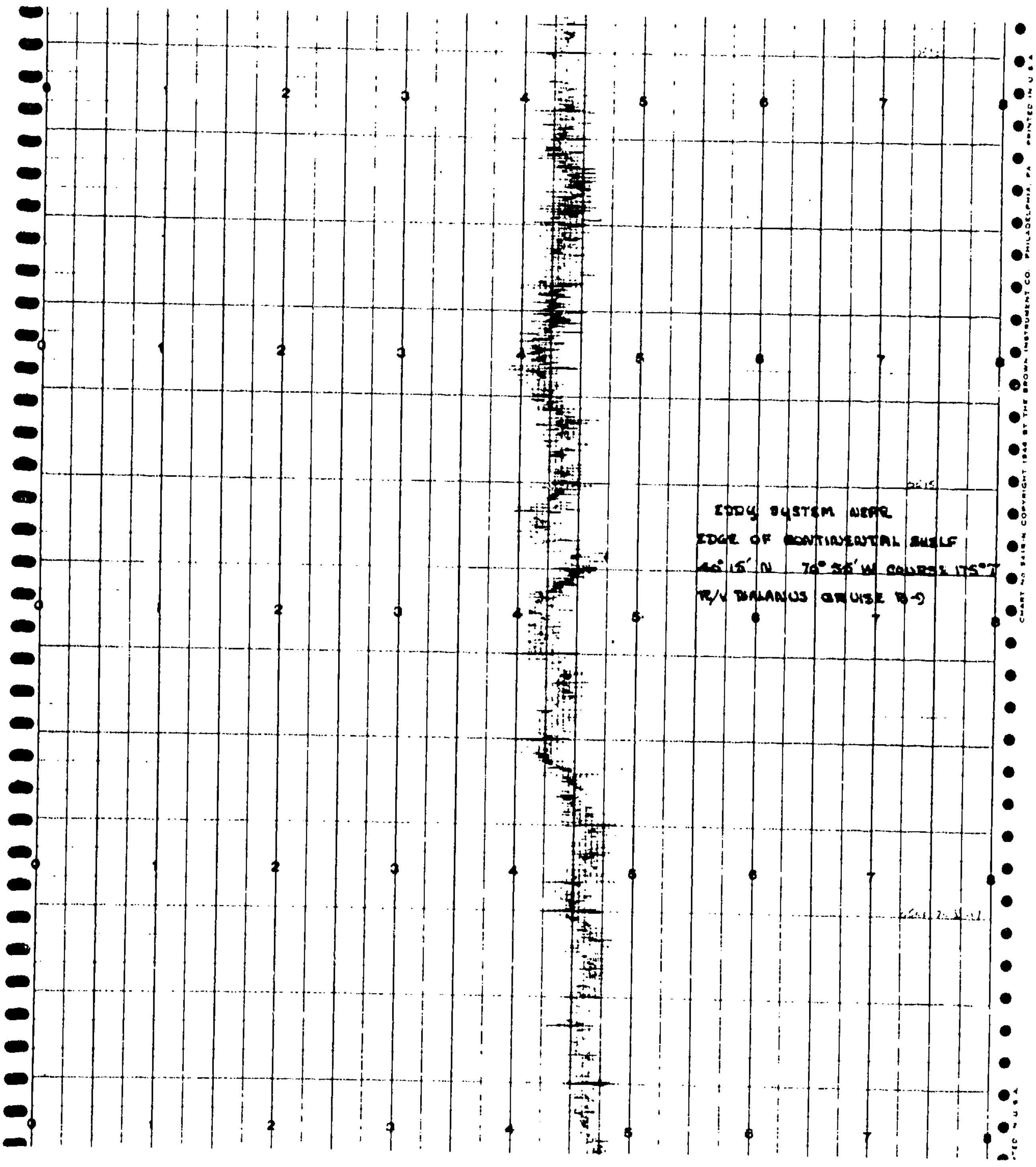

EDDY SYSTEM NEAR
EDGE OF CONTINENTAL SHELF
R/V BALANUS CRUISE

FIG. 4

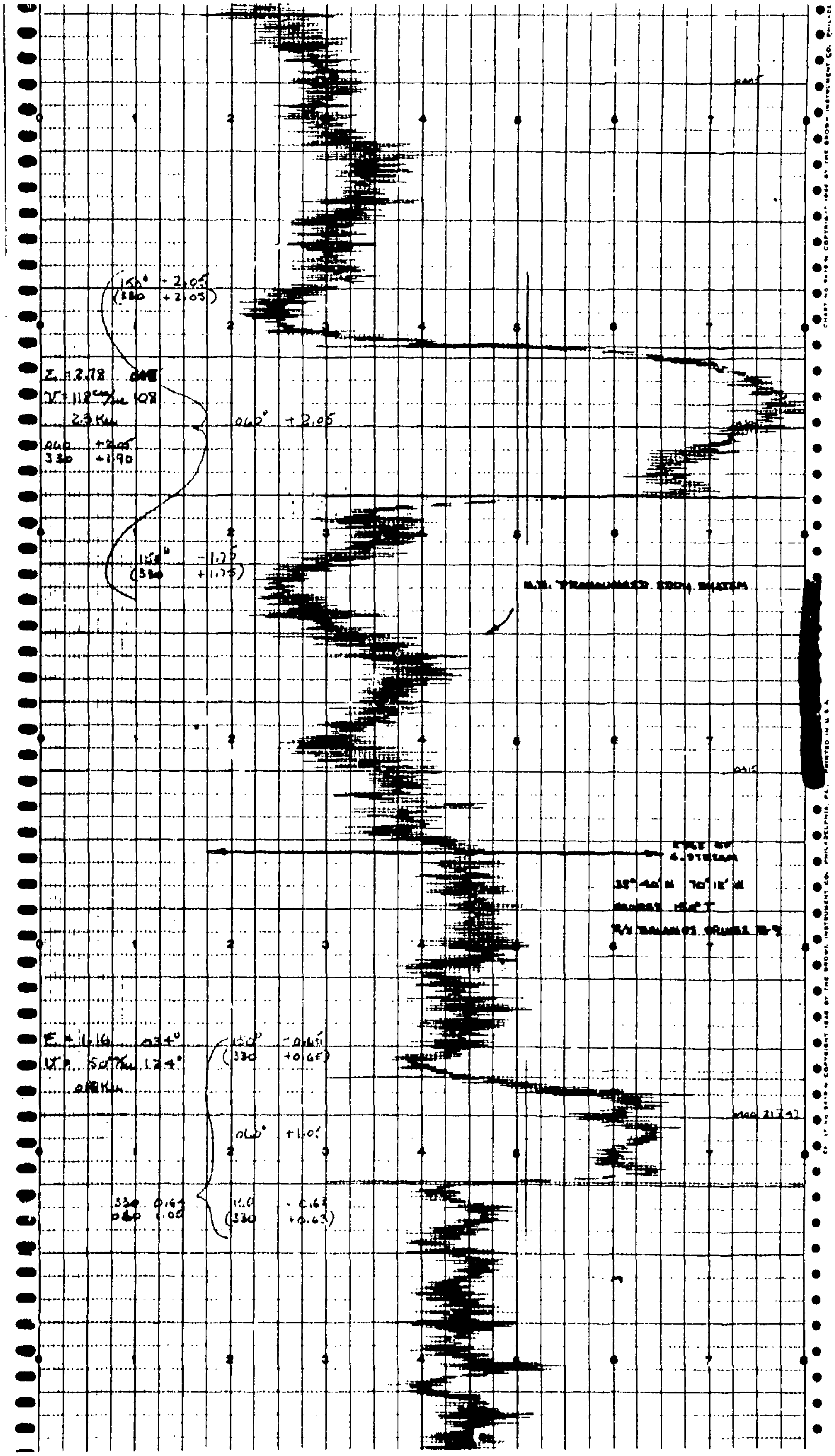


FIG. 5

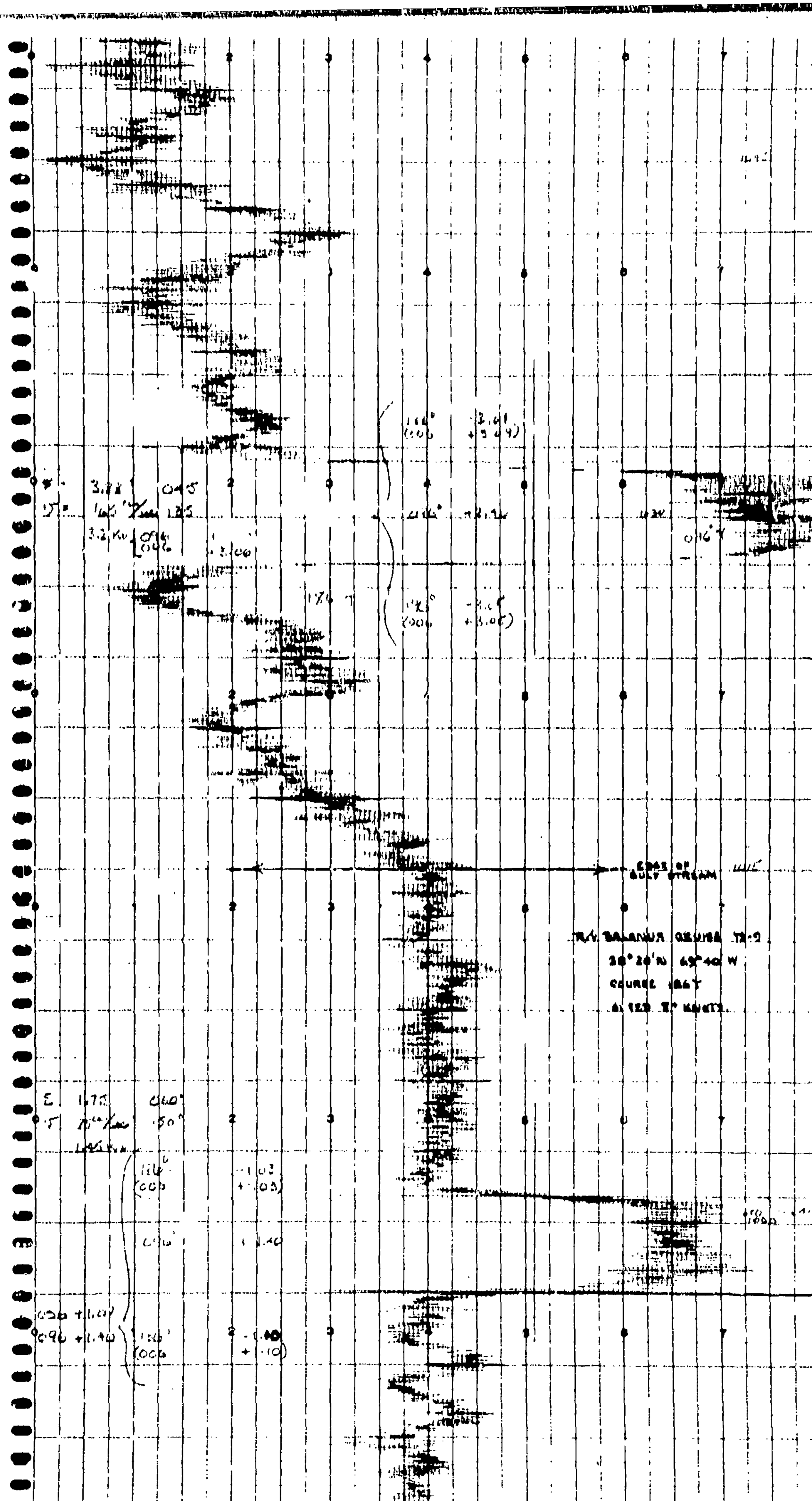


FIG. 6

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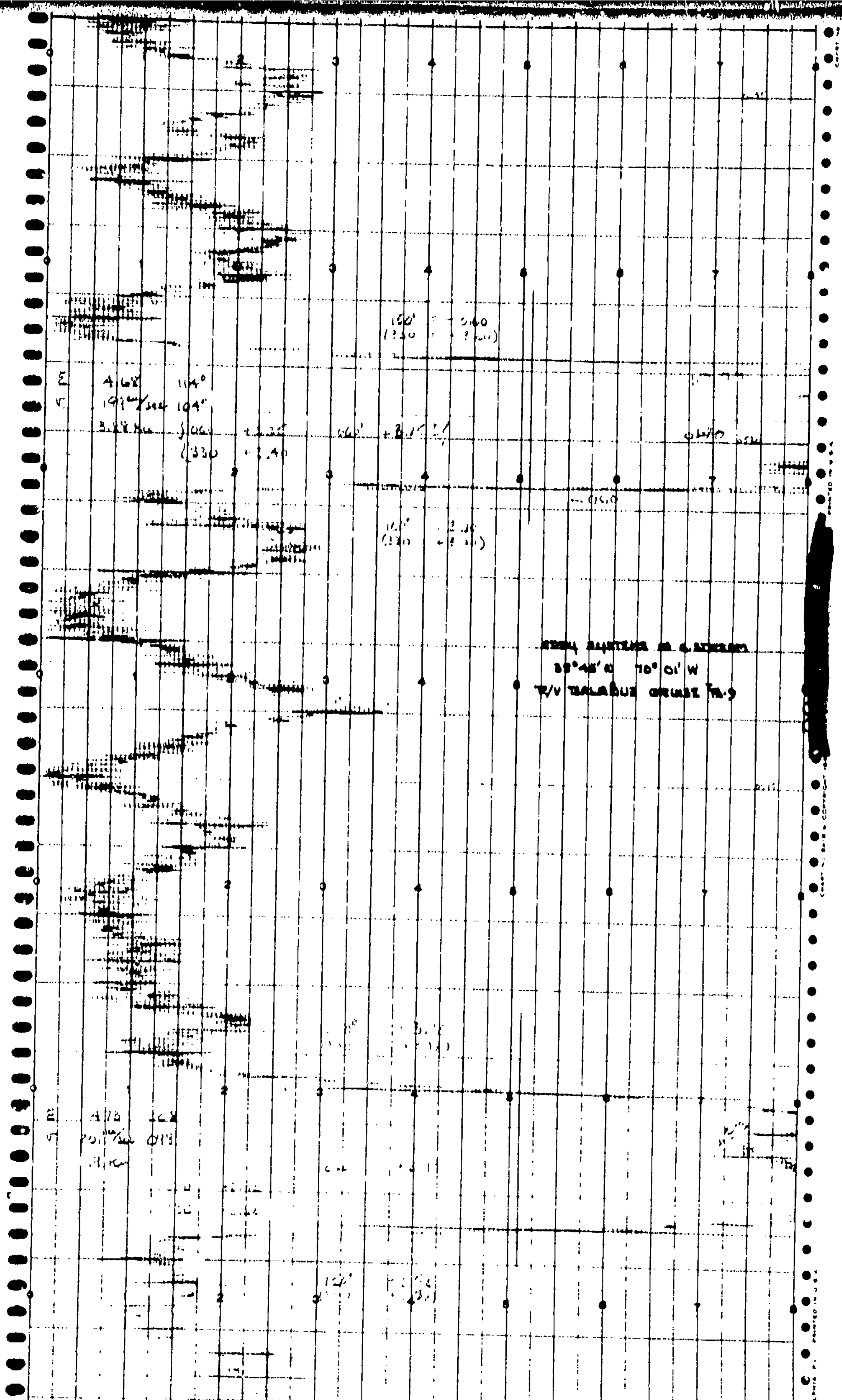

FIG.7

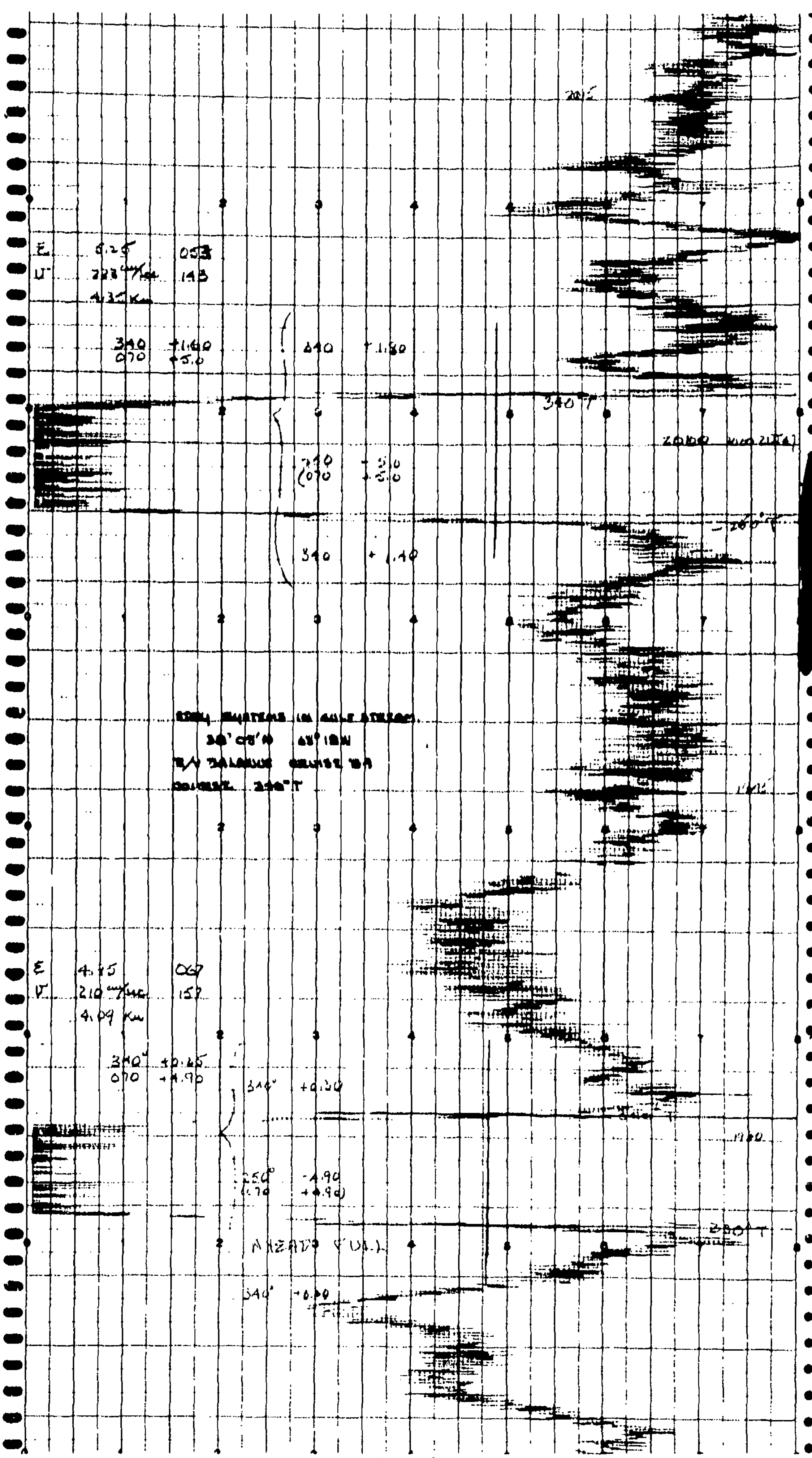

FIG.8

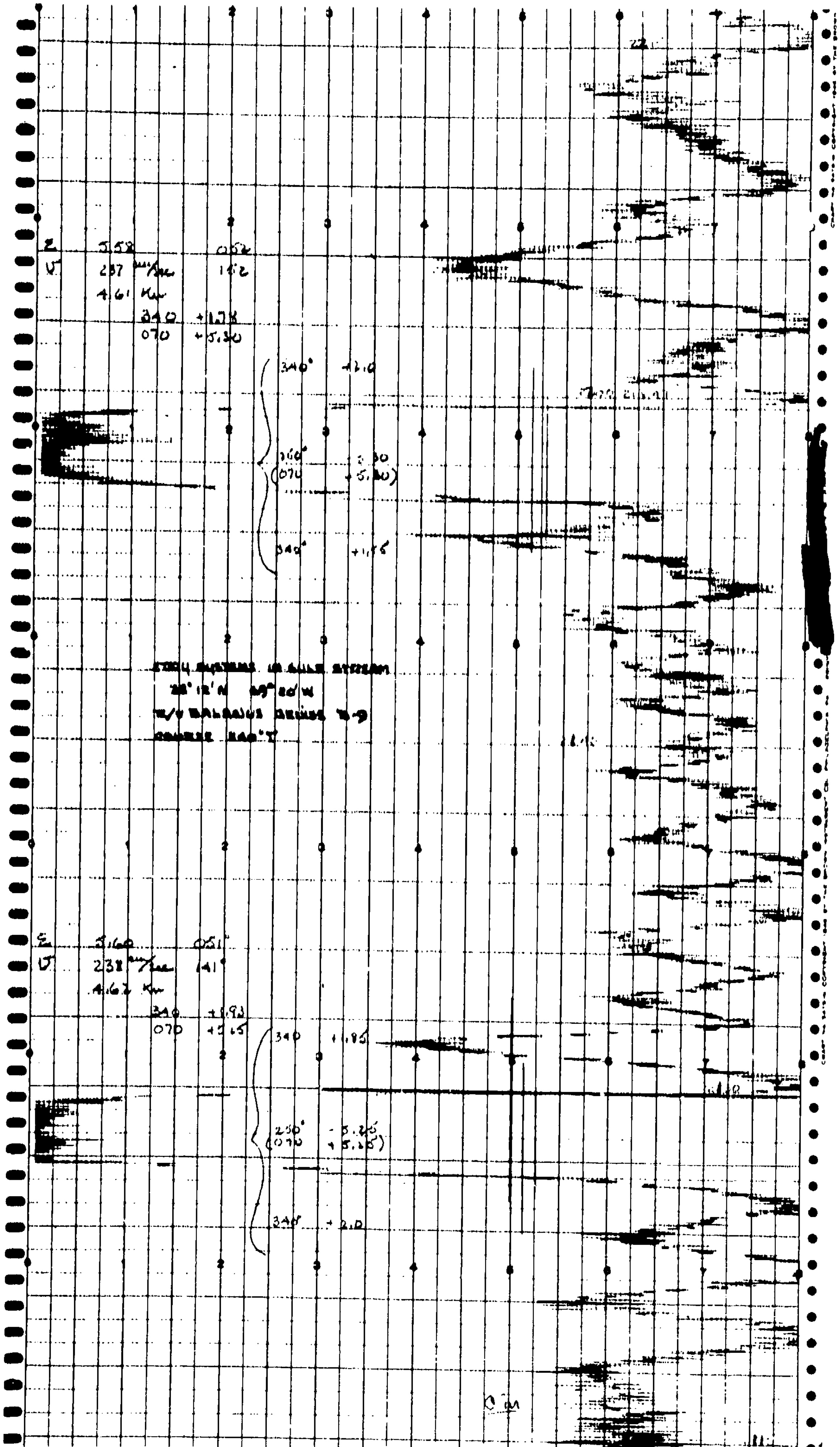

FIG.9

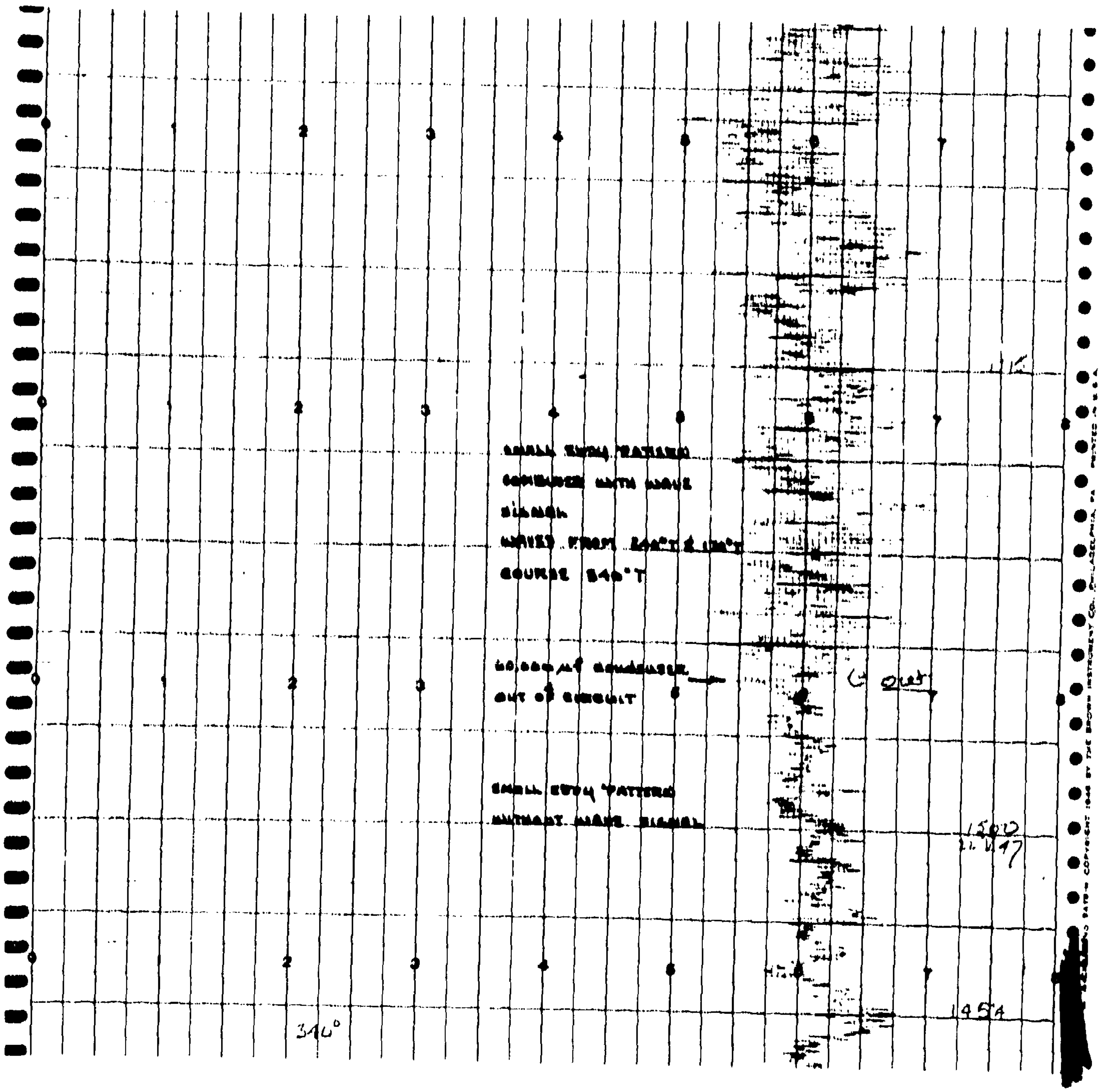

FIG.10

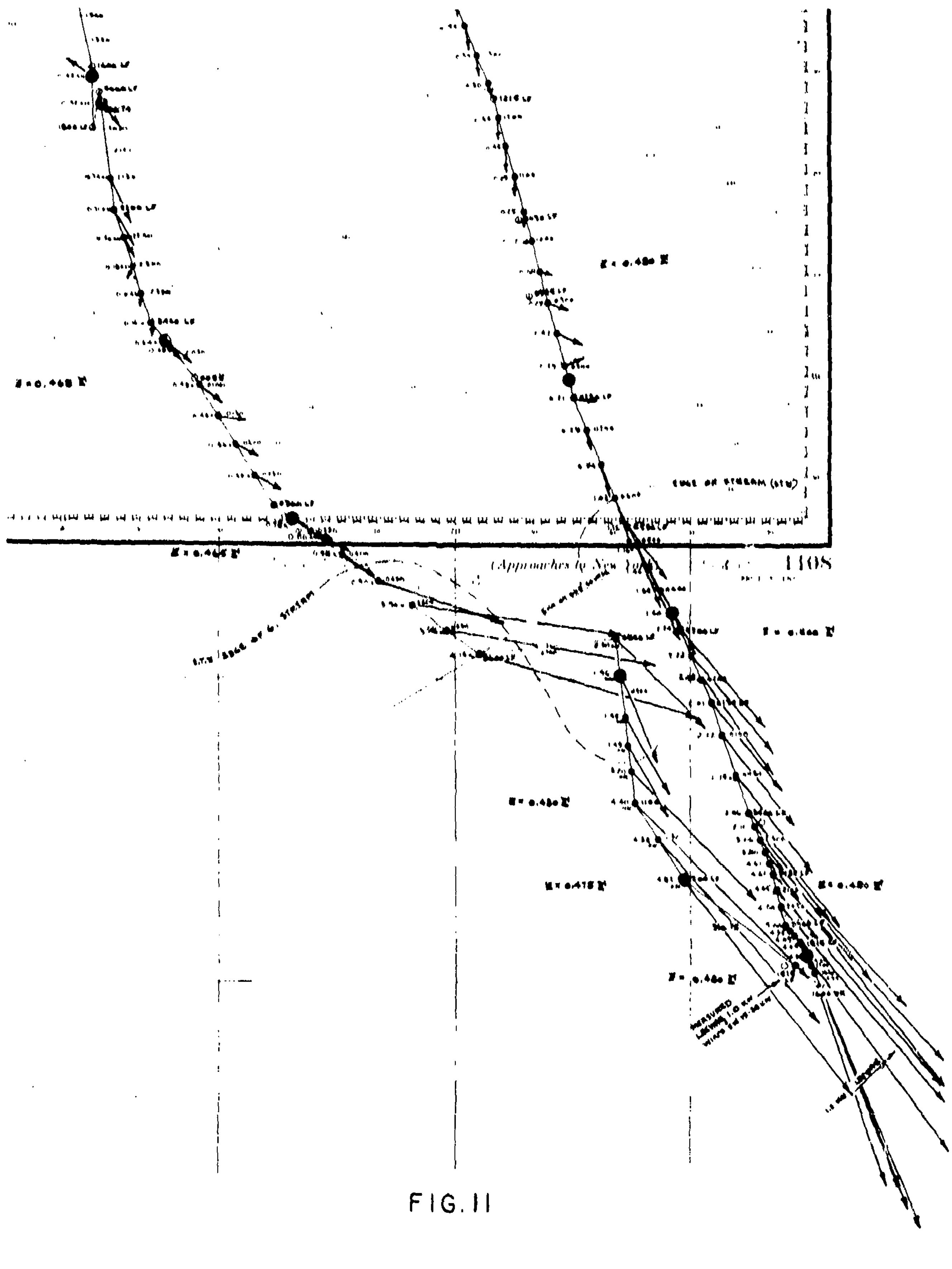

FIG. 11