MOORING OF SHIPS IN DEEP WATER FOR THE DIRECT MEASUREMENT OF CURRENTS.

by

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Accurate knowledge of the direction and strength of currents at the surface of the sea and at various depths down to the bottom is of great importance for the understanding of the circulation and tides of the ocean. Whilst the surface currents and those in the shallow depths of the coastal waters and inland seas mostly could be measured accurately from fixed stations on land, by means of bearings and distances of objects floating in the current, or from ships at anchor provided with current recorders, and the general character of the surface currents in the high seas on the lanes of navigation is known on account of the numerous astronomical observations taken by ships, research in connection with the movements of water in great depths has, until now, depended upon the indirect method of observation of temperatures and salinities at different points and on the calculation of the speed of the circulation from the static state of the fields of mass and pressure which result from the distribution of temperature and salinity. This calculation, based on hydrodynamic laws, can only be applied under certain definite hypotheses, the validity of which must be more closely investigated. Direct accurate measurement of currents in deep waters is ever more required by modern quantitative sea-research . Every improvement in this method is an advance in the knowledge of the most important problems of the ocean.

Every accurate current measurement requires the least possible movement of the floating body from which the observation is taken, *i.e.*, a fixed mooring and, at the same time, an anchorage of the research ship with the least possible cable, and with this begins the difficulty of the method in deep water. Between the first successful work of PILLSBURY in the Gulf Stream and the latest deep sea anchorage of the *Meteor* and the *Willebrord Snellius* there is a span of 40 years during which this method, at least as far as big ships are concerned, has not been substantially developed ; this may well indicate the difficulty of anchoring in deep water and justify the doubts which have been cast on the results of the measurement of currents in deep water owing to the irregular movements of the ship while observations are being taken. Without going into the details of these results, some information is given below with regard to the methods of anchoring in deep water so far employed, the arrangement of the anchoring installations in the *Blake*, *Meteor* and *Willebrord Snellius*, and with regard to the experiences at the anchor stations of the *Meteor* during the German Atlantic Expedition of 1925-1927, relative to the influence on the measurement of currents of the movement of the ship as a result of long anchor cable and, finally, with regard to the practical suggestions which may be deduced therefrom for future use.

MEASUREMENT OF CURRENTS IN SHALLOW WATER.

Many attempts have already been made to solve the problem of the direct measurement of currents near the coast and in shallow water. Though these have usually been made by anchoring small ships, boats or buoys, they have given important data from which the value of current measurement may be judged and which may give noteworthy information for this kind of measurement from bigger ships anchored in deep water. Therefore, the most important researches and experiments will be mentioned :

The principal requirement for the purpose of measuring currents with a self-registering current-meter, such as the EKMAN screw-propeller apparatus which has been mostly used, is to provide a vertical from a floating body, with the least possible movement, to which the observations can be referred. Many and successful are the measurements made by surveying vessels and lightships, which were mostly anchored near the coast and in shallow water (the latter moored particularly firmly by means of mushroom anchors), and, when there were strong surface currents, mainly tidal currents, these vessels took up a nearly steady position, less influenced by wind, during the observations. These observations, carried out from many points off the coast, have given a fairly comprehensive picture of the tidal currents which everywhere govern the shallow seas.

Difficulties in measuring currents began with the deeper seas, with greater distance from land and with less marked surface currents.

In 1903 Fr. NANSEN (1) and V. W. EKMAN, with an EKMAN current meter, undertook researches in the Skagerrak from the vessel *Michael Sars* at anchor. These researches, made from a vessel 39 metres (128 ft.) long, of 226 gross tons, were not very satisfactory.

In 1904, Fr. NANSEN obtained more satisfactory measurements from the yacht *Veslemoy*. This was a vessel of 32 tons nett, fifty feet long and had for mooring gear 3 hand-winches, each holding 1000 metres (547 fms.) of steel wire. The following trials were carried out in various fjords at depths to about 100 metres (54 fms.) and in the Skagerrak at depths to about 150 metres (82 fms.). The vessel was first moored with 2 bower anchors, 2 grapnels being used with satisfactory results ; the branches of the grapnels were united by a thick plate of iron and thus a firmly holding mushroom anchor, with flukes at its periphery, was formed. Nevertheless, NANSEN found that the ship swung about considerably in shifting winds, which entirely falsified the current observations. He then tried anchoring bow and stern with the cable shortened as much as possible, but the vessel still swung and easily dragged. NANSEN therefore advised against taking current observations from a moored vessel unless strong and regular surface currents prevail which will hold the ship in position, or unless very accurate observation of the ship's movements at anchor, both as to their direction and their velocity, can be made. With a weak current, NANSEN deduced from his observations that the current meter merely registered the irregular movements of the ship caused

(1) NANSEN, F. *Methods for Measuring Direction and Velocity of Currents in the Sea.* Publ. de Circonstance N° 34, Copenhagen, 1906.

by wind. To determine these movements he recommended lowering a meter to a great depth where, mostly, very weak currents are the rule. This meter would make it possible to determine the effect of the ship's movements on the observations of current which are recorded at the same time by a second apparatus in the upper layers. NANSEN further recommended that, in shallow water, the movement of the ship should be observed in the following simple manner: A heavy lead with a marked line should be dropped as far as possible from the ship, where note is taken of the amount of line paid out and hauled in again in order to keep the line continually taut. At the same time the changes in bearing of the lead-line must be noted. From the depth of the sea, the length of line out and the changes in the line's azimuth, the horizontal movements of the ship while swinging can easily be worked out by simple geometrical construction (which NANSEN gives). This method must of necessity lose some of its value in deep water, as the considerable sag of the line (curve of the lead-line between lead and ship) must be taken into consideration, though this is not measurable, and further the lead is easily dragged in keeping the line taut.

NANSEN continued observing the current from a boat anchored nearby and not from the vessel; for this purpose he was in favour of using a keelless flat-bottomed boat (pram). HELLAND-HANSEN also made successful observations in this manner in 1906, in the North Sea (1). The boat was anchored bow and stern, the cables were of either hemp or steel. These cables, for this purpose divided into lengths of about 50 metres (27 fms.) and shackled together, were passed to the boat after the anchors had been let go and were passed back to the ship and there hove in for weighing the anchors. A small boat riding at short moorings will have decidedly less movement than a big vessel, but it is very difficult to determine such movements from the boat. In *deep* water this method is difficult and takes time, as the cables must be larger if the boat is not to drag apart from the fact that the fitting and working of a heavy winch, which is necessary for current measurement in deep water, is difficult, if not impossible, in a small boat.

NANSEN finally tried to carry out the observations by means of a moored buoy. This submerged buoy holds a line vertically up and down, to which the measuring apparatus is attached at the desired depth. As the buoy floats under water, it must stand considerable pressure if it is lowered to a great depth. NANSEN recommanded an arrangement of several (from 20 to 40) glass balls, such as fishermen use on their nets, in an open canvas bag of such form as to offer the least resistance to the current. The construction of this buoy is seriously complicated by the fact that it must either have a clockwork which releases the messenger of the current meter, or by the provision of a brass tube so arranged that a messenger dropped to the buoy releases a second which brings the meter into action. The first trials were again made from the vessel at anchor from which the buoy was sunk and the messenger sent down a surface line attached to the buoy. As however the ship

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(1) HELLAND-HANSEN, B. *Current Measurements in* 1906. Bergens Museum Aarborg, N° 15, 1907.

swung too far from the buoy, a pulling-boat had to be sent along the surface line to a position vertically above the buoy in order to drop the messenger. This method gave unsatisfactory results. Further trials were made from the vessel adrift. A pulling-boat proceeded in the direction of the current, with the buoy's anchor (consisting of two sounding leads) attached by a line to the vessel, and the buoy's mooring-line, sank the buoy's anchor and the buoy and then remained as nearly as possible vertically above the buoy, to which she was attached by a thin line. The messenger was dropped down this thin line, and set the meter in action, at the same time releasing the thin line from the buoy. After the observation the buoy was weighed by the ship. (See Fig. 1).

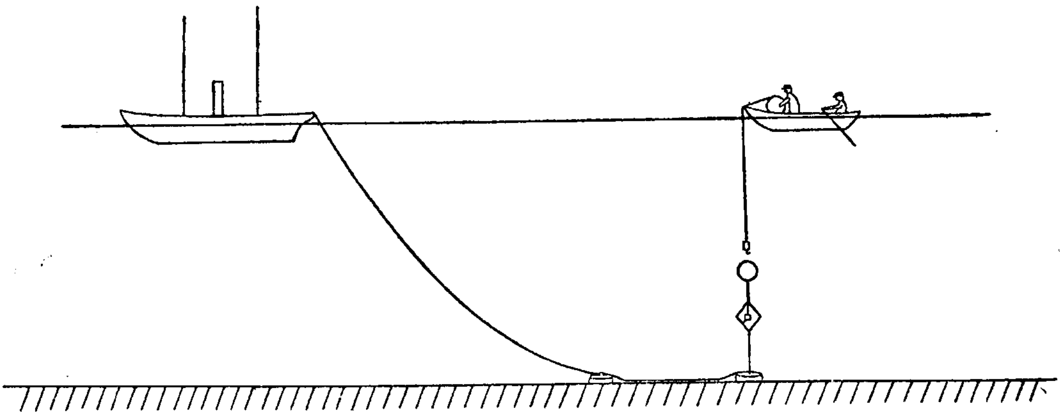

FIG. 1
Current Observation from a drifting ship by means of a moored buoy (NANSEN).

Undoubtedly this method contains the source of defect that the buoy does not always hold the meter cable vertical. Even in weak currents, it executes swaying movements which it is not possible to determine. Besides, in deep water, the above-described mooring of the buoy, previous preparation and weighing after each single observation, more especially in a rough sea, take so much time and are so difficult that but very few observations can be completed.

In this method also the same difficulty remains, *i.e.*, of determining the movements of the floating body, and this is the main point. Then the currents produced by the movements of the ship — called by R. J. WITTING the "Schiffsstrom" — will not infrequently be of the same order of magnitude as the true current to be measured. WITTING, in his treatise: *Etliches über Strommessung* (1), gives differential equations by which he calculates the true current from the observed velocity when the ship swings, *i.e.*, the velocity with which the ship moves in azimuth in a given period of time, and from the velocity of the observed current during the same period. On the basis of practical research he has arrived at the conclusion that "observations of currents are utilisable not only when the ship's movements are small or, which

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(1) WITTING, R. J. *Etliches über Strommessung*, Publication de Circonstance N° 31, Copenhagen 1905.

is often the same, when the currents are very strong, but also when the data of current observations, even though the ship's movements have been taken into account, cannot be made homogeneous. Accurate and inaccurate data will be mixed up with each other. However, the accuracy of each separate figure can be discussed and the magnitude of the probable error be determined without very great trouble. The utility of such data is indisputable".

During the Finnish research cruises, in 1905, WITTING tried to measure the movement of the vessel in the following manner :

To the anchor to which the vessel is riding, a buoy is attached by a short line. A light line from the buoy is led to the ship, where it runs over a metre-registering sheave. When this line, which is generally slack, has reached a certain tension, the metre-recorder is read and, at the same time, the relative bearing of the vessel and buoy is read off from the compass. This method has the disadvantage that, should the anchor drag, the buoy drags with it, and thus does not allow the consequent displacement of the ship to be known. It would be better to moor a buoy to its own anchor and not to measure the distance from the ship by a line attached to the buoy which may very well drag the buoy as it tautens, but by running out a marked line from the ship to the buoy by means of a rowing-boat or still better, to measure the distance from the buoy optically, *e.g.*, by measuring the vertical angle between the buoy and the horizon from the masthead of the ship. In *great* depths it is extremely difficult to moor a buoy in such a manner that 1) it does not swing too much, 2) it does not dip in the current, and 3) it does not drag. Only by laying out moorings in various directions can these conditions be fulfilled, and this again meets with considerable difficulties in deep water. Also the method recommended by WITTING of mooring two buoys, which are attached to each other by means of a line of definite length, which renders measurements of distance unnecessary, if their reciprocal bearing has been ascertained when they were laid out, is much too troublesome in deep water.

In view of the above-mentioned difficulties, Kl. GREIN (1) (as also had NANSEN (2) with a sea-anchor, using two current meters) entirely gave up the idea of anchoring the ship during his current observations in 1911, off the west coast of Sardinia, and employed with success an EKMAN current-meter suspended from a buoy, whilst the vessel drifted, to depths of 400 metres (220 fms.). The buoy was in the form of a torpedo, flattened top and bottom ; it had a fixed rudder aft and, in the middle, an opening through which the line suspending the meter passed and which allowed free passage for the messenger. Though the buoy, on account of the slight resistance which it offered to the wind and of the set of the rudder, took up a fairly steady position in the current, yet it, and also the ship, to which it was attached by means of a slack line, must drift. For this reason the measurements must be erroneous if the drift had not been ascertained by bearings of objects on land. GREIN came to the following conclusion : "There is no doubt that the data

(1) GREIN, Kl. *Ein Hilfsmittel für direkte Strommessungen in grossen Meerestiefen*, Bulletin du Musée Océanogr. de Monaco N° 235, 1912.

(2) NANSEN, Fr. *Observations from a drifting Ship*, Publ. de Circonstance N° 34, Copenhagen 1906.

as to velocity obtained by this method are affected by errors, the magnitude of which in the open sea cannot be ascertained, but which, in any case, are only a fraction of the quantity observed, and it is debatable whether henceforward the ability, thus obtained, to make direct measurements of currents in open sea and at any desired depth without large apparatus, would not to a great extent outweigh the disadvantage of the want of accuracy".

Moreover a large number of current measurements have been carried out with success in shallow water. Reference will be made to but a few here, particularly to the accurate measurements made by SVERDRUP during the *Maud* Expedition in the Arctic Ocean on the continental shelf north of Siberia (1). Also to the measurements made by the Dutch members of the Central Commission for the International Exploration of the Sea, ROOSENDAAL and WIND (2), in the North Sea in the Research Ship *Wodan* and several lightships, and those by DALHUISEN and RINGER (3) in 1905-06 during the Dutch research cruise in the North Sea, and finally to the systematic Tide investigations carried out by the German Navy in collaboration with the INSTITUT FÜR MEERESKUNDE of Berlin and the DEUTSCHE SEEWARTE of Hamburg, in the surveying vessels *Triton* and *Panther* and several sounding boats in the North Sea (4) during 1921 and 1922; besides making observations for the measurement of currents and tidal amplitude, these vessels investigated the errors of the EKMAN current-meter (5). Similar investigations were undertaken in the North Sea by the steamer *Poseidon* in 1920 for the German Scientific Commission for the Exploration of the Sea. No important experience was gained during these cruises with regard to anchoring for the purpose of measuring currents at sea (6).

CURRENT MEASUREMENT ON THE HIGH SEAS AND IN GREAT DEPTHS.

As opposed to the numerous stations at anchor in the neighbourhood of coasts and in shallow water, those in deep water and in the open ocean are but rare up to the present. Apart from the stations made by PILLSBURY in the Gulf Stream, to which we shall refer later, HELLAND-HANSEN, in 1910, attempted current measurements from a ship at anchor in the North Atlantic in the research vessel *Michael Sars* (226 tons gross) already mentioned (two profiles: Strait of Gibraltar to the Sargasso Sea to the Gulf Stream and Newfoundland to Iceland) (7). In the Strait of Gibraltar observations were

(1) SVERDRUP, H. U. *Maud-expeditionens videnskabelige arbeide,* 1918-19. S. A. Naturen, Jan.-Apr. 1922, Bergen.

(2) ROOSENDAAL, A. M. VAN u. WIND, C. H. *Prüfung von Strommessern und Strommessungsversuche in der Nordsee.* Publ. de Circonstance N° 26, Copenhagen 1905.

(3) DALHUISEN, A. F. H. und W. E. RINGER. *Fortgesetzte Strommessungsversuche in der Nordsee.* Publ. de Circonstance N° 36, Copenhagen 1907.

(4) MERZ, A. *Gezeitenuntersuchungen in der Nordsee,* Ann. d. Hydr. u. maritim. Meteorologie, Dec. 1921, page 397.

(5) MÖLLER, L. *Die Deviation bei Strommessungen im Meere,* Veröffentlichungen des Inst. Meereskunde, Berlin. Neue Folge, Reihe A, Heft 13.

(6) SCHULZ, Br. *Hydrographische Beobachtungen auf Poseidon.* Ann d. Hydr. u. maritim. Meteorologie, Jahrgang 1921, Heft III, page 74.

(7) HELLAND-HANSEN, B. *Neue Forschungen im nördlichen Atlantischen Ozean,* Zeitschrift der Ges. f. Erdkunde zu Berlin, Jahrgang 1911.

made down to a depth of 400 metres (220 fms.) and, at a depth of about 300 metres (164 fms.), a current of four knots was measured without the ship dragging. South of the Azores the ship was anchored in a depth of about 900 metres (492 fms.) and a fairly strong current was observed also at a depth of 730 metres (400 fms).. Mooring with one anchor thereby passed the test. In 1913-14 and 1922 HELLAND-HANSEN undertook three long cruises in the Atlantic in the *Armaur Hansen* (1), a ship of only 57 tons gross, length 24 metres (78 ft. 9 in.), beam 6 metres (19 ft. 8 ins.). For anchoring in deep water a winch was provided which ordinarily was used for hauling a trawl, and which carried 8000 metres (4375 fms.) of steel cable, of 11-9 m/m (1/2 —1/3 in.) diameter. The ship's 40 H. P. motor could be used directly for weighing the anchor. This installation allowed the ship to anchor in depths of from 5000 to 6000 metres (2735 to 3280 fms.). In 1923 and 1924 HELLAND-HANSEN and EKMAN undertook a series of trials of deep sea anchoring in the North Sea, in the Norwegian Sea and in the channel between the Faroes and Shetlands, during which the EKMAN Repeating Current Meter was tested and many technical experiments in connection with anchoring were undertaken, concerning the outcome of which the writer has no details. In 1925 these trials were continued in the North Atlantic as far as the Canary Islands to depths of 4000 metres (2187 fms.). With the exception of the work of the *Meteor* in the South Atlantic these are the only direct current observations which have been undertaken in the open seas of the Atlantic. If, in spite of these very isolated direct current observations in the Atlantic Ocean, a fairly comprehensive picture of the surface currents is available, this is due to the fact that, during the last decades, in this ocean so full of traffic, by international agreements, the condition of the surface currents has been established by means of innumerable ship observations and, so to speak, as a by-product of the necessary daily observations at sea. This condition of the currents still remains to a great extent in the form of observational data, covering all seas, which mostly have not yet been worked out. But it is recognised that this material is affected by the uncertainty of the errors in astronomical observations, by errors in course and speed and, above all, by the drift caused by wind, which affects every ship differently. However the modern methods of study of these crude drifts caused by currents, based on careful analysis of current areas according to the theoretical investigations of BJERKNES and SANDSTRÖM, such, for example, as Hans H. F. MEYER employed for his chart: *Die Oberflächenströmungen des Atlantischen Ozeans im Februar* (The Surface Currents of the Atlantic Ocean in February) (2), give, contrary to the more generalised and statistical current charts produced until now, a very complicated representation of currents in the whole ocean; certainly the larger ones, known since HUMBOLDT's time, appear, such as the Equatorial currents, the Gulf Stream, the West Wind drifts and the Polar currents; but besides these, convergence areas filled with currents are displayed, where, until now, large cur-

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(1) HELLAND-HANSEN, B. *Meeresforschungen mit kleinen Forschungsschiffen*, Zeitschrift der Ges. f. Erdkunde zu Berlin, 1928, Erg. Heft III.

(2) MEYER, Hans H. F. *Die Oberflächenströmungen des Atlantischen Ozeans im Februar*. Veröffentlichungen des Inst. f. Meereskunde zu Berlin, Neue Folge, Reihe A, Heft II.

rent-free areas had been assumed diagrammatically on current charts. Above all, detailed analysis of the drifts caused by currents shows that a periodical variation in the various individual currents takes place monthly and yearly. It is apparent that first of all a systematic, direct measurement of the currents throughout the ocean at various depths undertaken, if possible, by means of synoptic observations carried out by several vessels anchored in great depths for a considerable period of time and suitably distributed in the characteristic individual currents, would introduce complete clarity into the picture of the surface and deep currents. To obtain knowledge of the share taken by tidal currents in producing the picture of the surface currents, it would be desirable to have current observations covering, not merely semi-diurnal and diurnal periods, but a complete month. Besides, investigation of the drift currents caused by the wind, and of the circulation currents brought about by diffe-rences in density would necessitate lengthy periods at anchor, in order to determine not only the short and long period, but also the aperiodic variations in the representation of the surface and deep currents.

INVESTIGATIONS IN THE GULF STREAM.

It is not by chance that, of the great currents of the Atlantic Ocean, the Gulf Stream was the first to attract the attention of mariners since the age of discoveries, as a mighty natural phenomenon of the surface of the sea. It formed, with its strong 4 knot current, an almost insuperable hindrance to the old sailing ships in their beat along the East Coast of North America to the South and through Florida Strait. No ocean current in the history of oceanography has stimulated investigators as much as this "River in the Sea", which was investigated thermometrically and charted for the first time by B. FRANKLIN. A. VON HUMBOLDT pointed out its connection with the Equatorial Current and, later, the Gulf Stream became the classical region of systematic deep sea research and the first area of accurate current measurements; it contributed substantially to the development of oceanography as an independent branch of the science of geography. The names SIGSBEE, BARTLETT, and PILLSBURY, the Commanders of the *Blake*, are closely bound up with this important epoch.

These researches throughout the American Mediterranean and the Gulf Stream as far as Cape Hatteras in the years 1845 to 1860 and 1867 to 1889, were carried out under the U. S. Coast and Geodetic Survey. Whereas SIGSBEE and BARTLETT sought to determine the bed of the Gulf Stream and its thermic constitution, by means of many hundreds of soundings and of temperature observations at different depths, it is to PILLSBURY that great seamanlike and scientific merit is due in that he carried out, for the first time from a ship at anchor in the open sea, in a strong current, and in depths to 1000 metres (547 fms.) — and once even in 4000 metres (2187 fms.) — systematic and accurate measurements of the current from the surface down, generally to a depth of 238 metres (130 fms.), with an instrument constructed by himself. Thus he originated the method by means of which reliable current measurements at sea may be expected. The first current measurements in the Gulf Stream from a ship at anchor were made from the schooner *Drift* in

1883 at five observation stations, but in the vicinity of the 100 fathom line, though once in 400 fathoms.

During the years 1888 and 1889 alone PILLSBURY carried out hours, days and even weeks of observations at 39 stations, taking 2577 current and 2535 temperature observations, 6 transverse sections of the Gulf Stream, 10 through the passages through the Greater and the Lesser Antilles and several in the Equatorial and Antilles Currents (1). On the basis of these current observations PILLSBURY drew up diagrams of the horizontal and vertical distribution of velocity in the Florida and Antilles Currents, in which the individual values were represented graphically as functions of time in an endeavour to establish a relation between the oscillations of the current and the declination of the moon. His claim of such relation, and the unexpected results obtained, aroused the criticism of oceanographers and cast doubt on the utility of these current observations. However, G. WÜST, in his work *Florida- und Antillenstrom* (The Florida and Antilles Current) (2), demonstrated that PILLSBURY'S results agreed, to a great extent, with the distribution of velocity which WÜST himself had calculated theoretically for several sections on the basis of the distribution of density and pressure by means of the temperature observations made by BARTLETT in the *Blake* and of the new salinity and temperature observations taken by the *Bache* in 1914.

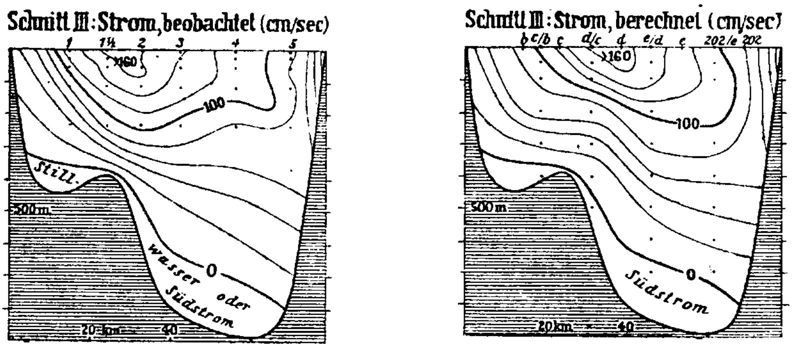

FIG. 2

Comparison of the distribution of vertical velocity in the Florida Current according to PILLSBURY'S *Observations* (left) *and according to calculation by* WÜST (right).

As an example, comparison of the velocity of the currents observed by PILLSBURY in cross-section III, from Cape Florida towards Gun Cay, with the velocity calculated theoretically by WÜST for the same section (see Fig. 2) will show quite close agreement. In both sections, the strength of current is given by lines of equal velocity in cm/sec. The numbers 1, 1 ½, 2, 3, 4, 5 show the positions of PILLSBURY'S current observation stations, the letters *b*, *c*, *d*, *e* indicate BARTLETT'S temperature observations, and the number 202 gives the position of a station of the *Bache* with salinity and temperature values. In his inves-

(1) PILLSBURY, J. E. *The Gulf Stream*, Report of the Superintendent of the C. & G. Survey 1890, Appendix N° 10, Washington 1891.

(2) WÜST, G. *Florida-und Antillenstrom*, Veröffentlichungen des Instituts f. Meereskunde, Berlin, Neue Folge, Reihe A, Heft 12.

tigation : *Der Golfstrom* (The Gulf Stream), G. WÜST gave the following information concerning the transport of water by the Gulf Stream :

"The quantity of water and heat which the Gulf Stream carries from the Gulf of Mexico into the North Atlantic is prodigious. In three sections we obtain an average water transport of 85 cubic kilometres (13.5 cub. miles) per hour or 24 million cubic metres (847.55 million cub. ft.) per second. An idea of the immensity of this can be gained by recalling that the outflow into the sea of the mightiest of all continental rivers, the Amazon, is on an average only 1/10 of a million cubic metres per second and that the entire discharge of waters from the land, *i.e.*, the mean outflow of all the streams, rivers, and glaciers of the earth is, in round figures, 1.2 million cubic metres per second. This shows that the Florida Current transports, in any time unit, on an average, roughly 22 times as much water as is discharged by all the rivers of the world taken together."

In this powerful stream, PILLSBURY lay for days on end in the open sea in depths to 4000 metres (2187 fms.) in a ship at anchor and measured current velocities up to 4.6 knots without dragging. We can appreciate this great feat of seamanship when we recall the peculiar impression which we experienced at the mouth of the Amazon near the Salinas Lighthouse, when for the purpose of taking the pilot on board from the pilot boat which was at anchor far from the land in the very strong current of 5 knots, we had to mark time in the vicinity steaming up at almost the normal speed of the *Meteor* so as to get the pilot boat to leeward in the current. We feel that we can understand PILLSBURY's sensation when, in his vivid manner, he describes the deep impression made on him by the rapidly moving stream of which, when on board a ship drifting with it, one sees nothing : "But to be anchored in its depth far out of the sight of land, and to see the mighty torrent rushing past at a speed of miles per hour, day after day and day after day, one begins to think that all the wonders of the earth combined cannot equal this one river in the ocean." (1).

And yet G. WÜST rightly points out that, as a current, the Gulf Stream in no way merits the very exceptional position which it has been given on charts hitherto ever since the time of FRANKLIN. "It is but a modest member of the surface circulation and, as such, falls considerably below the Equatorial Currents which, over an enormous breadth, with considerable strength and with remarkably great regularity set, as drift currents, through the ocean from east to west. It is but in the Florida Strait that the Gulf Stream can compare with it in strength and regularity". Direct and systematic current observations within the range of other great currents of the Atlantic Ocean would give just as surprising results as did the observations of PILLSBURY in the Gulf Stream in their time.

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(1) PILLSBURY, J. E. *The Gulf Stream.* loc. cit

OUTFIT OF THE "BLAKE" FOR ANCHORING IN DEEP WATER.

The most surprising point of PILLSBURY's method in the *Blake* (even a vessel 45 metres (147 ft. 6 ins) long, 218 reg. tons) anchored in deep water — and this is the principal point of interest in this article — is the simplicity of the equipment and the seamanlike ingenuity of the arrangements by which he sought to overcome the insufficiency of the material which was inherent to the time, and particularly steel wire cables. Quite apart from this, in view of economy he used existing fittings in the *Blake* which were originally intended for trawling. PILLSBURY had spent two years testing the deep sea anchoring outfit, continually trying to improve it. Thereafter, for three years, he used it during the above-mentioned current observations with great success and without any serious failure. If now-a-days such outfit can be constructed more simply thanks to the quality of the materials, PILLSBURY's invention contains so many noteworthy features that a short description of the final fittings in the *Blake* appears to be justified (See Fig. 3). It is taken from PILLSBURY's report, to be found in the above-mentioned Annual Report of the C. & G. Survey (1).

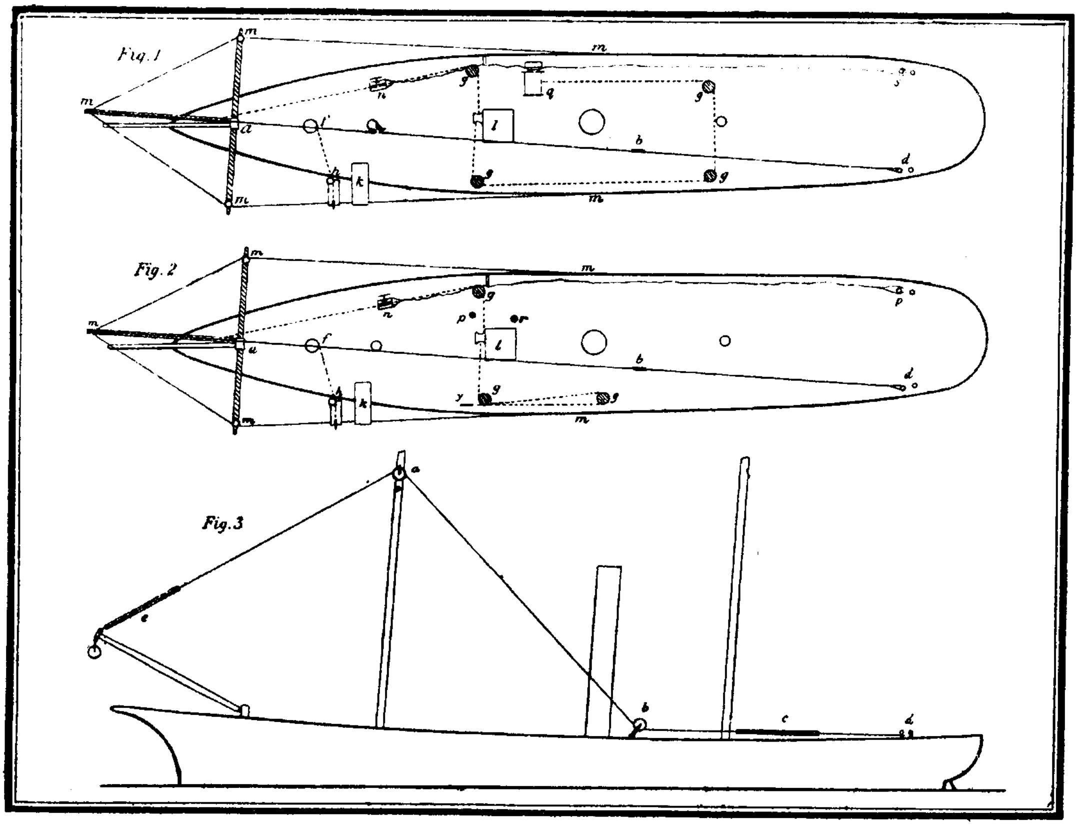

FIG. 3.
Arrangement of the Anchoring Gear on board the Blake *according to* PILLSBURY.

(1) PILLSBURY, J. E. *Outfit of the* "Blake" *for Anchoring at Sea*, etc., C. & G. Survey Ann. Rep. 1891, Chap. IV, App. 10, and KNIPPING, E. *Die Ausrüstung des Vermessungs-dampfers* "Blake" *zum Ankern in See und zu Strombeobachtungen*, Annalen der Hydrographie und Maritimen Meteorologie, Jahrgang 1896, Heft VI.

The arrangement of the anchoring gear was designed with the primary object of reducing, as far as possible, the jerking of the cable when the ship pitched in a seaway. This was done by introducing a strong spring (Accumulator, Fig. 3, *e*.) in the topping-lift of the anchoring boom. Further, the topping-lift was led over the foremast head down to the waist and along the deck aft, so that the anchoring boom and the foremast took the greatest strain lengthwise (*e*, *a*, *b*, *d*, Fig. 3). The anchoring boom which projected, over and beyond the short bowsprit, 11 degrees on the starboard bow and, with no load other than its own weight, was 45 degrees above the horizontal, was about 9 metres (30 ft.) long and 33 c/m (13 ins.) greatest diameter, slightly tapering towards both ends and was strengthened at intervals of 1 metre (3 ft.) by iron bands. Under the outer end was shackled the pulley for the anchor cable, the topping-lift was shackled on above, and on each side a steel wire guy. At the inboard end of the boom there was a ball-and-socket joint, the socket being placed on the pawl-bitt (Figs. 1 & 2, *a*.). Two spars 20 cms. (8 ins.) in diameter extended herefrom which projected over both sides of the ship, to give the guys the necessary spread (Figs. 1 & 2, *m*, *m*, *m*). The axis of these spars passed through the ball and socket and was at right angles to the plane in which the anchoring boom moved up and down. The outboard ends of both spars and of the anchoring boom thus formed a right-angled triangle with the boom perpendicular to the base formed by the two spars. The two spreaders were held in position by strops at their heels and lashings at the rail. Steel-wire rope jumperstays were led from the outboard ends to heavy eyebolts in the ship's side near the water-line. The guys were set up by heavy turn buckles to wire-rope strops at the warping chocks on the main deck. The spreaders lay at the same angle (11 degrees) from athwartships as the anchoring boom did from the centre-line of the ship and kept the boom clear of the fore-stay.

The boom topping-lift was a steel-wire rope 25 m/m (1 in.) thick; it was composed of two parts which ran from an iron tye (Fig. 3,*a*) on the port side of the foremast head by means of a pendant with a little fore and aft play. The fore leg of the topping-lift ran from this pendant to the anchoring boom, the accumulator (*e*) (which in the first trial was interposed in the position *c*, Fig. 3) being inserted therein ; the after leg to a snatch-block (*b*) on deck and then to a bollard in the stern (*d*), where it was belayed. The anchoring boom and the topping-lift lay in exactly the same plane. The position of the snatch-block on the port side abaft the foremast was such that, at greatest load on the anchoring boom and the accumulator, the foremast bisected the angle between the two legs of the topping-lift, the strain on the iron pendant and the mast was therefore exactly in the line of the mast.

The accumulator, which was primarily intended to lessen the jerking strains when the ship was pitching, was a powerful built-up spring. It consisted of an open frame, made of two long side rods 25 m/m (1 in.) thick, of the best tool-steel, with strong connecting-plates at the uper and lower ends. Through an opening in the lower connecting-plate of the frame a heavy middle rod, a slide bar 32 m/m (1 1/4 ins.) in diameter, was passed on which were threaded 70 rubberdiscs 6 c/m (2 1/2 ins.) thick. Each disc was separated from the next by a brass washer; these washers prevented contact between rubber and slide-bar, being of greater diameter than the rubber-discs, and by an increase in the thickness of the metal at the middle giving a bearing surface as they slid on the rod. The last free brass washer in the frame was firmly attached to the slide-bar. Then, the frame being fixed, if a strain were brought on to the free outer end of the slide-bar, the rubber discs were compressed between the inner end of the slide-bar and the lower connecting piece of the frame. When the strain was eased they expanded again. Under very heavy strain the movement of the slide-bar amounted to 1.5 $^{m}/_{m}$ (5 ft.). The accumulator required constant watching, all metal parts in contact had to be kept well greased, the rubber discs deteriorated mostly from the effects of irradiation by the sun and of excessive strain. To prevent an inordinate strain on the accumulator, a second topping-lift ran from the anchoring boom to the pendant at the masthead with such slack that it only came into play when the accumulator had stretched to the limit of safety.

As anchor cable, steel wire from the WARRINGTON Works, England, was used. The cable had to have the greatest breaking strain for the size, with no indication of brittleness in splicing, and the galvanizing had to be clean and smooth. Great pliability was not necessary. The breaking strain guaranteed for 9 1/2 $^{m}/_{m}$ (0.37 in.) diameter was never under 6 1/2 tons, for 11 1/2 $^{m}/_{m}$. (0.45 in.) it amounted to 8 1/2 tons, for 13 1/2 $^{m}/_{m}$ (0.53 in.) 11 1/2 tons, for 16 $^{m}/_{m}$ (0.63 in.) never under 15 1/2 tons. A tapered cable, 13 $^{m}/_{m}$ (0.51 in.) inboard, 11 1/2 $^{m}/_{m}$ (0.45 in.) and 9 1/2 $^{m}/_{m}$ (0.37 in.) outboard, with a rather heavier end 180 metres (100 fms.) long close up to the anchor, proved the best. The steel cable was coiled on a reel in lengths of 2000 fathoms, the splices in the cable, made on board, were 6 metres (20 ft.) long and only visible under careful examination. "The 9 1/2 $^{m}/_{m}$ was perhaps a trifle small for all conditions, but it always held the ship unless it was badly kinked." When heaving in, the cable acted like a screw in the water, after long use it kinked in the opposite direction to a new cable and then broke easily.

As anchor, the *Blake* used in every case the so-called "Cape-Ann" anchor with a very long shank, fairly large palms and a long hard-wood stock. It weighed from 200 to 250 kgs. (4 to 5 cwt.).

The cable-blocks, all of iron, were all on the starboard side, were provided with suitable wooden sheaves and were fitted so that the cable always lay exactly in the plane of the sheaves. The cable ran from the block of the anchoring boom, along this to another at the ball and socket, then along the starboard side of the deck and through a third block (Figs. 1 and 2, *g*) to the winch amidships (*l*). This was an extremely compact steam engine of 30 H.P. driving a winch head (by means of gearing) 1.4 m. (4 ½ ft.) in diameter and a revolution counter. When anchoring, the winch first raised the cable from between decks, ran it out free and finally acted as a brake if the cable ran out too quickly. The cable drum was at the bottom of the hold firmly secured to the keelson. It consisted of a boiler-iron barrel 66 $^{c}/_{m}$ (2 ft.) in diameter and 1.2 metres (4 ft.) long with flanges 1.2 metres (4 ft.) in diameter. The barrel was protected from being crushed by the cable by two oak diaphragms. On one side it had the usual strop brake, lined with oak, which was worked from the upper deck; on the other side a compact double-cylinder engine, the throttle governing the latter likewise was placed on the deck.

From the drum the cable passed first to starboard, then upwards to between-decks, across to port, upwards to the upper deck, thence aft, back forward and finally amidships to the anchor winch. When using the two engines great care had to be taken that the cable was always kept at the right tension between the winch and the drum. If this were not done, kinks formed between the drum and the winch, causing trouble and even breakage of the cable. (The *Meteor* had the same difficulty to contend with. In modern trawlers the improvement has been introduced that the two machines automatically maintain the correct tension or else re-establish it immediately).

When anchoring, the anchor and cable were lowered at a speed of from 90 to 150 metres (50 to 80 fms.) per minute, but as the vicinity of the bottom was reached this was reduced. The change in the direction of the cable from the drifting ship, was the first indication that the anchor had bitten. If the anchor was surely on the bottom and the current were strong this was noticed by the speed of the water alongside and the movement of the boom and the ship's engines were started at once in order to relieve the accumulator. In depths of 1000 metres (550 fms.) and less, two or three times this amount of cable was run out; at 3600 metres (2000 fms.) and less, about one and a half times the depth of water was veered. In order to ease the winch after anchoring, the cable was put into a long brass-jawed vice, the jaws of which were shaped to fit the cable, *i.e.*, a cable-stopper (*n*), which was attached by a long steel wire pendant to a bollard (*s*) on the side of the afterdeck and kept off the deck by a purchase in the fore shrouds. Every day one metre (3 ft.) of cable was veered in order that it should not be weakened by constant strain on the same place.

When the ship was at anchor at sea, the ship was steered to the cable day and night. Steam was continuously kept up and the engines ready for immediate movement. With the wind at force 6 and above it was still possible to remain at anchor, except when there was a heavy sea and the wind was against the current. It was possible to tell by the movements of the accumulator and of the boom and by the humming of the cable, whether the anchor held, was dragging or was foul. The humming of the cable in a current when the anchor held was quite different to the hum when the anchor dragged. The greatest depth at which the ship was anchored was 3986 metres (2013 fms.).

When weighing the anchor, the cable was hove in slow at first, 15 to 18 metres (50 to 60 ft.) a minute, and required the help of the main engines. As soon as it was noticed that the anchor was away the winch was immediately run as fast as possible, heaving in from 90 to 150 metres (300 to 500 f.) of cable per minute, so that the anchor should not bite again. The anchor was hauled up to the end of the starboard spar by means of a snatch-block put on to the cable, and then catted along it and fished. The longest time during which the *Blake* remained at anchor at the same station at sea was 166 hours, nearly 7 days. The total number of hours at the six stations of Section *A* through Florida Strait alone was 1100, *i.e.* nearly 46 days.

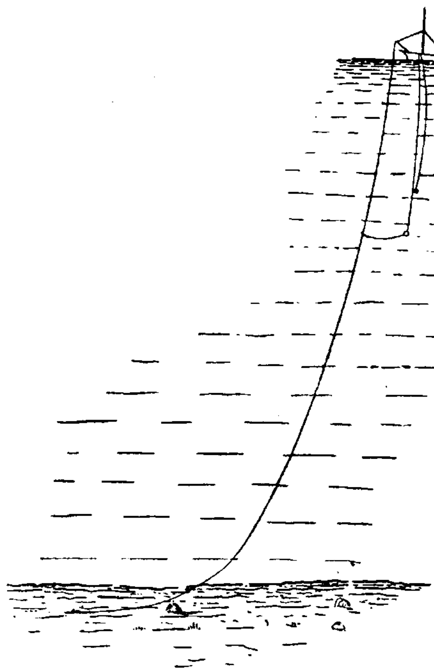

FIG. 4.
Current Observations on board the Blake *by means of a guide wire and distance line, according to* PILLSBURY.

As to the current-meter, into a description of which we will not go here, the chief difficulty was to keep it always up and down in deep water and also in a strong current. For this purpose the help of the anchor cable was called in as follows : — A jackstay or guiding wire was used and, in spite of the current, was lowered vertically (See Fig. 4). The guide-wire was weighted with 100 kgs. (220 lbs.) and had at its lower end a distance line, the length of which had to be adapted to the depth of the water, the strength of the current and the depth to which the current-meter was to be lowered. The other end of the distance line was secured to the anchor cable, and then both the anchor cable and the guide-wire, with the distance line between them, were run out simultaneously as far as was necessary. If the guide-wire was up and down, it was placed between two guide-rollers on an horizontal arm which projected laterally from the frame of the current-meter. In depths of 550 to 750 metres (300 to 400 fms.) and in a strong current, 180 metres (100 fms.) of distance-line were necessary in order to be able to lower the meter to a depth of 270 metres (150 fms.). In a depth of 2700 metres (1500 fms.) and a strong current, for lowering the meter to the same depth, 45 to 55 metres (25 to 30 fms.) of line sufficed. The meter was left at each observation depth for 30 minutes and had to be hauled up after each observation. In a 5 knot current 335 metres (183 fms.) of the meter wire had to be run out in order to attain an observation depth of 240 metres (130 fms.). In a 5 knot current the meter could not possibly be lowered to 360 metres (200 fms.) by the above-described means.

THE MOVEMENTS OF A SHIP RIDING TO A LONG ANCHOR-CABLE.

When one considers that, on one occasion, PILLSBURY lay at anchor for nearly a week, on another with a wind of force 6, on another in a depth of 4000 metres (2200 fms.), and yet again with the current increasing within 50 minutes from 3.3. to 4.6 knots without dragging or carrying away his cable, proof is provided of the suitability of his method in any circumstances that may occur in the open ocean, except heavy weather. If, in spite of this, the results which he obtained in measuring currents, as stated above, roused the criticism of specialists and caused doubts as to whether they could be used, this is due less to the assumption that the dragging of the ship during the observations may have falsified them, than to consideration of the irregular pendular movements to which a ship riding to a long stay is subject. First the fore and aft movements to and from the anchor, the "*over-riding*", and then the sideways swaying of the ship, the "*swing*", which is caused by the fact that generally the cable is not led inboard exactly amidships through the stem of the ship, but slightly on one side through the hawsepipe or, as in the case of the *Meteor*, the knight-head roller and, in the case of the *Blake*, the anchor-derrick, and thus part of the force of the wind and current can act sideways on the ship and make the vessel swing. Besides these sideways movements with the position of the anchor as centre there are, as was determined in the *Meteor* by careful observation, sideways movements of the vessel with the point as centre where the cable reaches the bow, *i.e.*, somewhere about the vertical axis of the stem, which, in order to differentiate them from the swing, we will call "*yaw*". These three pendular movements of the vessel, which the current-meter suspended therefrom must necessarily make with her to some degree at the same time, falsify the results. The longer the cable and the weaker the surface current, the longer will be the periods of these movements and from fractions of an hour these periods may even reach over an hour, whereas, with modern current-meters, an observation takes only 5 to 10 minutes. During the observations in the Gulf Stream, the over-riding movements, in spite of the large amount of cable out, were very small for the strong current held the cable fairly evenly taut, and swinging was limited, as the ship could be kept to her course by means of the helm.

The difficulties due to the movement of the ship affect, more or less, all observations undertaken from an anchored vessel and all modern current measuring appliances. Thus, theoretically, the taking of current measurements which are free from objection is not possible to carry out, as the basic requirement — complete immobility of the vessel at single anchor — is unobtainable. To attain this triple moorings would be necessary, say two well spread anchors forward and one stern anchor. In great depths such mooring is an extremely difficult and lengthy, if not impossible, operation. Therefore the degree to which these movements of over-riding, swinging and yawing affect the direct measurements of current must be studied as well as the extent to which analytical treatment can be applied to them.

Whilst the pendular movements of the ship in swinging and yawing can be followed accurately by careful observation of the compass and of the changes in the bearing on which the cable grows, it is impossible to gauge the period and amplitude of the over-riding without some other help, unless objects on land are visible and bearings of them can be taken.

Mark-buoys, anchored in the open sea in the vicinity of the vessel, as was stated in connection with the researches of R. WITTING, can only be used in the open sea and great depths for taking bearings if they themselves have triple moorings, which is a very difficult matter. The only possible check on the over-riding movements in the open sea is astronomical determination of position, and it will be left till later to investigate whether their degree of accuracy will allow this.

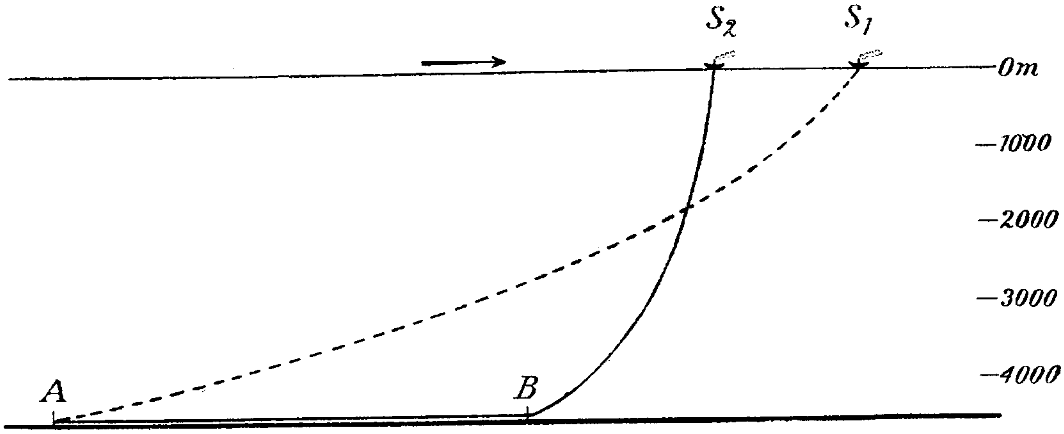

FIG. 5.

Diagram of the over-riding movements of a ship riding to a long stay, according to KRÜMMEL.

In his critical reflections on current observations in the open sea from a ship at anchor, with reference to the amplitude of the over-riding, KRÜMMEL takes a rather exaggerated case, by which he explains how the influence of the over-riding movement must affect the results of current observations; therefore this case is quoted below (1) (See Fig. 5):

"The research vessel allowed, for a depth of 4,500 metres (2460 fms.), about three times that length of cable, *i.e.*, 13,000 metres (7100 fms.). Under the action of the wind and surface current the ship is so strongly driven to leeward (S_1) that the whole length of the cable from the anchor (A) is lifted from the bottom and hangs in a catenary in the water. The tension of the cable together with its weight (2000 to 3000 kgs. (2 to 3 tons) in water, if a wire be used) are now too great for the vessel to sag further to leeward; further she will begin to ride up against the wind and current on account of the tension and weight of the cable; this occurs slowly at first, later at a gradually increasing speed, until such part of the cable lies on the bottom that the ship comes up to windward but slowly and finally not at all (Position $A\ B\ S_2$ in the figure). Meanwhile wind and current gain the upperhand and force the vessel to leeward towards S_1, whereupon the performance begins again. Supposing that the time taken to cover the distance S_1 to S_2 = 2000 metres (2187 yds.), is about 2 hours (an arbitrary assump-

(1) KRÜMMEL. *Handbuch der Ozeanographie*, Bd. II, page 425.

tion, as observations are lacking), the ship thus moves at an average velocity of 28 $^c/_m$ (11 ins.) per second or, in round numbers, 0.5 mile per hour. If the current at the surface has a velocity of 1 knot, the measurement will give 1 ± 0.5 knots according to the phase of the over-riding movement. If observations are taken at a depth where the current is weaker, it may occur that the current-meter, which is dragged along with the ship, may record a direction which is exactly opposite to the true direction or a far too great velocity in the true direction. If observations were carried out at different depths during several hours, the result may be a confused distribution of directions and strengths of current, and even for certain distributions of the times of observation, with reference to the phases of the over-riding movements, a periodic change in the direction and increase and decrease in the strength of the current may be found, over which theorists may well puzzle!

The movement is greatly increased if, as PILLSBURY did, the meter be lowered to various depths along the cable. If, in the above example, it be assumed that the cable run out was only 6000 metres (3280 fms.), the over-riding movement would act on the disturbing "ship's current" with not quite half of its value, but as we know nothing of the period of the movement during over-riding, it is safer not to assert anything".

Moreover, KRÜMMEL considered that an analytical treatment is possible. How is such analytical examination of a ship's movements to be carried out? At the deep sea anchor stations of the *Meteor* account was taken of the influence of this factor from the first, and very accurate observations were provided for, in order to follow the movements continuously. (These, for all stations, are collated in Table I.). As the method of anchoring with the least possible cable and some of the arrangements of the anchor gear differed from those of the *Blake* described above, a description of the deep sea anchoring arrangements of the *Meteor* will now be given.

THE DEEP SEA ANCHORING ARRANGEMENTS OF THE "METEOR".

(See Fig. 6).

The principal mission of the German Atlantic Expedition was not the observation of currents, but the investigation of the stratification and circulation throughout the area of the South Atlantic Ocean by means of about 9000 serial temperature and salinity observations at an average of 27 different depths at 310 observation stations on 14 transverse sections running approximately along parallels of latitude. In addition to making the hydrodynamic calculation of the movement of the water caused by thermo-haline differences, direct serial current measurements were to be made as a check, if possible, once in every section, at deep-sea anchor stations, in the depths of the principal currents. It was recognised beforehand that the stormy weather prevailing in the *higher* latitudes might render anchoring of the ship in the open sea impossible, and this was the case. Added to this, on the long southern sections, the steaming radius of the vessel did not permit full advantage to be taken of the few days of fine weather for anchoring. The anchor stations of the *Meteor* lay between 24° N. and 28° S. latitude (see Table I,4). Direct current measurements were particularly important however in the *lower* latitu-

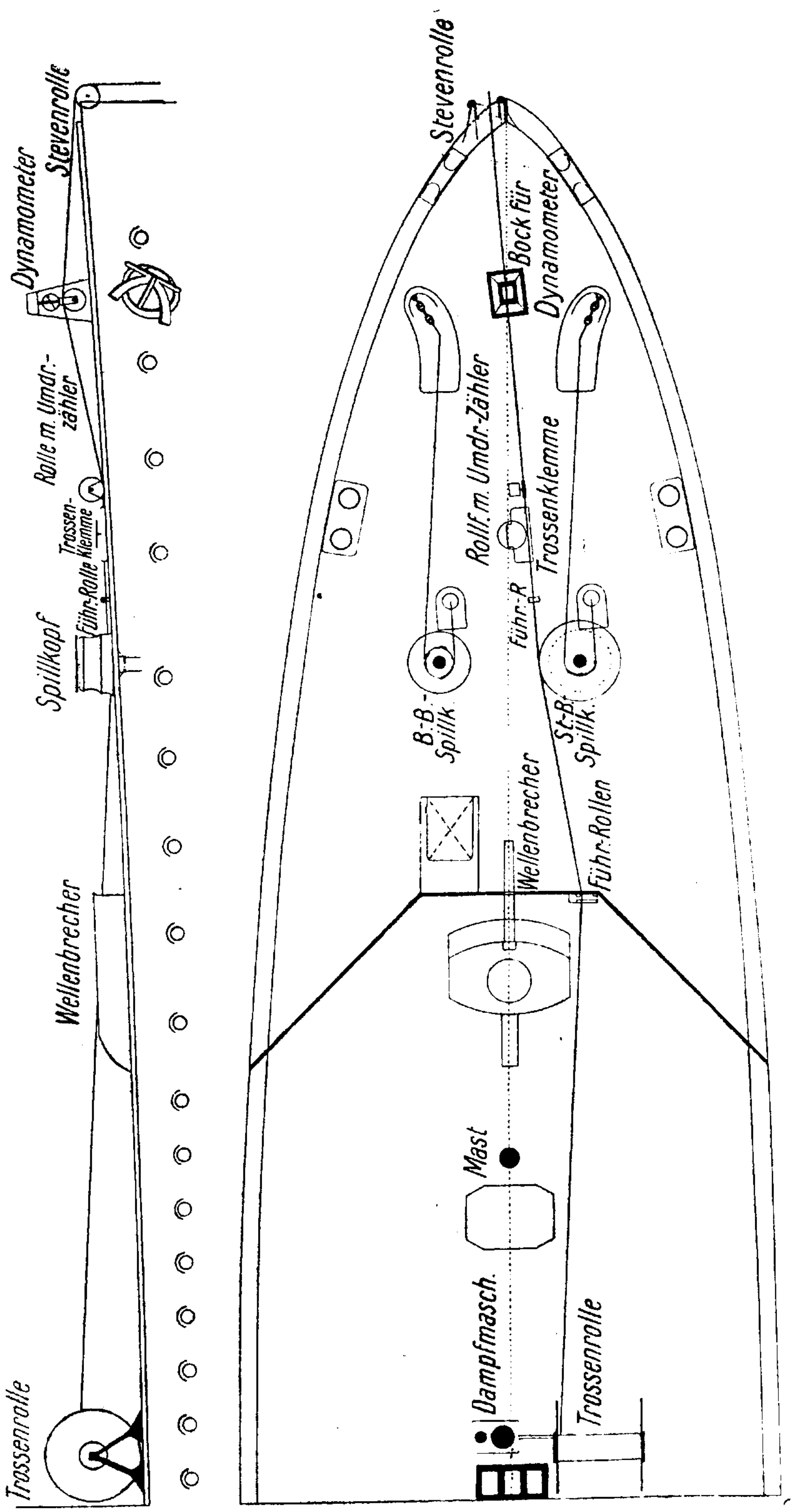

FIG. 6. *Deep-sea Anchor Gear on board the Meteor.*

Trossenrolle = Cable reel.		Stevenrolle = Knight-head roller.	
Wellenbrecher = Breakwater.		Dampfmasch. = Steam engine.	
Spillkopf = Capstan.		B.-B.-Spillk = Port capstan.	
Führ-Rolle = Guide roller.		St.-B.-Spillk = Starboard capstan.	
Trossen-Klemme = Cable stopper.		Bock für Dynamometer = Dynamometer trestle.	
Rolle m. Umdr.-zähler = Block with revolution counter.			

des as in the vicinity of the Equator, the indirect hydrodynamic methods are least reliable, in that there enters, in the formula for calculating the velocity of circulation between two points by specific volumes and increase of pressure, the factor of the influence of the rotation of the earth on the acceleration of circulation, which increases with the sine of the geographical latitude.

As it was a question for the *Meteor* of anchoring in depths down to 6000 metres (3280 fms.) and as the displacement (designed displacement = 1180 tons) and the ship's length (67 m. = 220 ft.) were considerably greater than those of the *Blake*, the requirements as to deep sea anchorage were higher. Relying on the resistance and elasticity of the modern steel cables as supplied by German firms, a cable in *one* piece, 7500 metres (4100 fms.) in length and weighing 5700 kgs. (5.6 tons) of galvanised cast-steel wire, was provided. With the object of attaining greater strength the cable was made without splice, the ends of each wire in every strand being welded together in different places. Seven wire strands each consisting of 24 wires were laid up round a hemp heart. The cable was tapered, the end to which the anchor was to be shackled had a circumference of 3.6 $^{c}/_{m}$ (1.4 ins.) and the end which was fastened to the cable-reel 5 $^{c}/_{m}$ (2 ins.).

Compared with the weakest cable of the *Blake*, 9 1/2 $^{m}/_{m}$ (0.37 in.) and the strongest, 16 $^{m}/_{m}$ (0.63 in.) in diameter, the *Meteor's* cable had a diameter of 11,5 $^{m}/_{m}$ (0.45 in.) outboard and of 15,9 $^{m}/_{m}$ (0.63 in.) inboard. The tapering was attained by gradually lessening the number of wires. As in the case of the tapered cable in the *Blake*, this took into account the gradually increasing load on the cable, owing to its own weight, corresponding to the increase in the depth of the water.

The cable was wound on a strong flanged cast-iron reel, 1 ½ metres (5 ft.) long and 1 ½ m. (5 ft.) in diameter. The reel was held by solid supports bolted to the deck on the forecastle abaft the starboard anchor capstan, slightly to starboard of amidships. The shaft of the reel had, outside and to starboard, a ratchet wheel into which pawls dropped for holding the reel, and also a plate compressor worked by a hand-lever for braking the reel. At both ends the shaft of the reel was squared to take crank handles for reeling up the cable by hand. From the cable-reel the cable ran over a horizontal and two vertical guide-rollers in the breakwater to the barrel of the starboard anchor capstan. A special enlarged capstan-rim 1 ½ m. (5 ft.) in diameter was placed on the barrel when anchoring in greath depths ; it was composed of two parts and provided with vertical whelps and 4 or 5 turns of the cable were passed round it. It was found necessary to extend it down to the deck for, at the fourth anchor station, the cable, as the result of a sudden slacking, jumped from the capstan-rim and got jambed in the sprocket-wheel. When anchoring, from the very beginning, the cable was hove out by the windlass engine and not run out by easing the capstan brakes, in order to avoid the possibility of the cable jumping off the capstan-rim and fouling.

From the capstan the cable ran over a small horizontal guide-roller screwed directly on to the deck, the object of which was to prevent the cable from slipping *upwards* off the capstan-head, and, from there, between the two slightly *S*-shaped jaws of an external screw block-brake worked by a hand-wheel. This brake, when the operation of anchoring was completed, was used for stoppering the cable. The cable then remained on the capstan and further was belayed to the starboard bollard. The cable ran from the block-brake over a guide-roller, exactly 1 m. in circumference, provided with a revolution counter which made it possible to read off directly, in metres, the length of cable paid-out. From here the cable was passed over the roller of a spring dynamometer which hung freely in the midship line from an iron frame 3 m. (10 ft.) from the stem, and on which the tension on the cable could be constantly read off while lying at anchor and weighing it.

For this cable, weighing 7.5 tons and of 13.7 m/m (0.54 in.) mean diameter, the breaking strain is 19.3 tons, thus about 4 tons higher than that of the strongest 16 m/m (0.63 in.) cable of the *Blake*. Finally, from the dynamometer the cable passed over a knight-head roller 30 c/m (1 ft.) wide and 25 to 30 c/m (10 to 12 ins.) in diameter immediately on the port side of the stem, in such a way that the cable ran in a straight line from the capstan-rim to the knight-head roller and thence to the water.

The deep-sea anchor was a "Normal", or "Admiralty" anchor, with a long shank and iron stock. It was only 100 kgs. (2 cwt.) in weight and had a 1.5 m. (5 ft.) length of chain and a 20 m. (11 fms.) wire pendant shackled to the thimble of the cable with a swivel piece. After some trials, the first anchor was backed by a second anchor, a "Stockless-bower (Wasteneys Smiths patent)" of the same weight, by means of a 50 m. (27 fms.) wire pendant. The anchor with a stock was lowered first and then the patent anchor. In depths between 2100 and 5500 m. (1150 and 3000 fms.), between 2700 and 6500 m. (1475 and 3555 fms.) of cable was paid out (See Table I, columns 5 & 6), which, corresponds to about 1 1/3 times the depth of water. This short stay — in comparison with the usual method of the *Blake*, of allowing 1 ½ to 2, and even three times the depth — was intended to reduce the over-riding and swinging movements as far as possible, even with the risk of dragging temporarily during heavy squalls. Besides, it must be noted that the *Meteor* had not such great speeds of current to deal with as those of the Gulf Stream. During the paying-out of the last part of the cable, the ship moved the engines slowly astern to prevent the cable falling in bights over the anchor or on to the bottom and forming kinks.

The *Meteor* did not have, as did the *Blake*, two years in which to test the anchor gear, but only made two anchor stations in the Atlantic Ocean, during a four weeks' trial-cruise to the Canary Islands. During the first trial on 26th January, 1925, in the latitude of Lisbon, in a depth of about 4800 m. (2625 fms.) and with a length of 5500 m. (3000 fms.) of cable out, several defects became apparent, which necessitated some considerable modifications. On account of the repeated heating of the endless-screw of the windlass drive and the resulting interruptions, anchoring took 4 ½ hours. This time was reduced later to less than half (Column 8 of Table). After some 2000 m. (1100 fms.) of cable had been hove out, the cable twisted itself continually to the left outside the ship in the water (experienced also by the *Blake*) until the end of the heaving out.

During the weighing of the anchor, the windlass engine, which moreover was not constructed for use in deep sea anchoring, was barely capable of lifting the weight of the 5500 m. (3000 fms.) cable and break the anchor out of the ground, and thus changes were necessary in it also. The windlass engine, which worked both of the capstan heads on the forecastle, was a vertical two-cylinder expansion, non-condensing engine, intalled on the upper deck, which could be controlled either from the forecastle or directly on the spot; it was fitted with reversing gear, which caused the engine to turn in the direction in which the starting-gear was moved and stopped it when the gear was centred. This had the advantages that, when any trouble of any sort (*e.g.*, kinks) occurred, the capstan-engine could be stopped immediately from the forecastle, and that the rate of heaving could be regulated at will.

The capstan-engine was calculated to raise a 1.3 ton anchor and 100 m. (55 fms.) of chain cable at a velocity of 12 m. (40 ft.) per minute. The starboard capstan only was fitted for deep sea anchoring. As the heaving in and out of the deep-sea anchor at a speed of 30 to 60 m. (100 to 200 ft.) per minute lasted for several hours, special attention had to be paid to the proper working of the transmission members of the engine. Besides a single-block thrust-bearing (MITCHELL system) on the shaft of the endless-screw, a spheroidal worm was adopted after the two experimental anchorings on the trial cruise and this produced a better distribution of pressure on the teeth of the worm-wheel than a cylindrical worm. The worm and worm-wheel were enclosed in an oil-tight oil-bath. Further, from an oil pump geared to the engine, oil was sprayed by several jets on to the teeth actually in gear. An oil-cooler, cooled by sea-water, kept the oil at a temperature as low as possible. For this purpose, a mixture of lubricating-oil, cylinder-oil and soap was necessary. In weighing the anchor, the main engines were used for the purpose of easing the windlass and the cable.

At the first trial, immediately the weighing of the anchor was commenced, the cable showed so strong a propensity to kink in the part between the windlass and the cable-reel, that it was impossible to resist it even by keeping the cable tauter while reeling it up. As a result, in some 5000 m. (2700 fms.) the cable was unusable in certain places. Likewise the last 600 m. (330 fms.) down to the anchor, *i.e.*, the portion that had rested on the bottom, came up so heavily kinked that its solidity was considerably impaired, although the strain on the cable in weighing had never exceeded 4000 kgs. (4 tons). After these experiments the cable was replaced by a strong twist-and kink-free cable, supplied by the firm of G. KOCKS, Mühlheim a. d. Ruhr, such as is used in mines (so-called "Tetragonal cable"). This cable, likewise tapered, had the same measurements and properties as the first cable. Freedom from twist was attained by means of laying the outer four wire strands right-handed, the inner three left-handed. The cable was satisfactory in every way and never formed kinks. The test-load of 19.3 tons was exceeded once, at anchor station N° 147 during a rough sea which rose suddenly, as the result of heavy pitching of the vessel during the weighing of the anchor. It broke at its most critical point, namely, the sharp bend at the knight-head roller, which had a diameter of only 25 to 30 c/m (10 to 12 ins.). The dynanometer had oscillated very heavily during the weighing of the anchor and it reached its limit of

TABLE I.

SUMMARY OF THE OBSERVATIONS MADE AT THE DEEP SEA ANCHOR STATIONS OF THE **METEOR.**

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
													SURFACE CURRENT.											
Nª	*Designation.*	*Date.*	*Mean Position.*	*Echo Depth from......... to......*	*Length of anchor cable.*	*Nature of bottom.*	*Time anchoring.*	*Time weighing.*	*Time at Anchor.*	*Duration & Depths of Current Observations.*	*Mean wind.*	*State of Sea.*	*Mean.*	*Min.*	*Max.*	*Direction.*	*Relative bearing of cable.*	*Angle of cable.*	*Tension.*	*Amplitude of swing.*	*Method of fixing position.*	*Greatest difference in position.*	*Drag.*	*Special Events.*
I	Test anchor Station.	26. I. to 27. I. 25	40°19' N. 10° 50' W.	4900 m. 4770 m.	5500 m. 1 anchor	—	4 hrs. 30 mins.	5 hrs. 15 mins.	16 hrs. 14 h. 30 m. 26. I. to 6 h. 30 m. 27. I.	6 hrs. Test at various depths.	S.W. 2	Light swell.	—	—	—	—	—	—	—	—	3 Astronomical Observations.	O. M.	—	Cable kinked seriously.
II	Test anchor Station.	31. I. to 1. II. 25	Cape Anaga 269°5 true Lighthouse Isleta 159° Pico de Teyde 257° true	3570 m. 3660 m.	4300 m. 1 anchor	Volcanic mud & sand.	1 hr. 36 mins.	2 hrs. 30 mins.	20 hrs. 7 h. 31. I. to 3 h. 1. II.	16 hrs. Test at various depths.	E. – E.S.E. 1	0 – 1	TIDAL CURRENT.				—	—	—	180°	Half-hourly bearings.	O. M.	—	—
III	Test anchor Station on leaving.	29. IV. to 30. IV. 25	24°31'5 N. 26°58'2 W.	5510 m. 5595 m.	6170 m. 1 anchor	Globigerina ooze.	1 hr. 45 mins.	2 hrs.	13 hrs. 15 h. 30 m. 29. IV. to 5 h. 30. IV.	11 hrs. Test at various depths.	S.W. – S.S.W. 0 – 1	1	0.4 knot.	—	—	Tidal Current 180°	—	—	—	180°	4 Astronomical Observations	O. M.	—	Bight of Cable round stock of anchor.
1	Anchor Station 36 Section II.	13. VIII. to 15. VIII. 25	28° 7'5 S. 19°20'8 W.	4353 m. 4488 m.	5100 m. 2 anchors	Red clay over hard bottom	5 hrs. 30 mins. (3 hrs. interruption).	2 hrs. 30 mins.	43 hrs. 11 h. 50 m. 13. VIII. to 6 h. 40 m. 15. VIII.	42 hrs. 0, 30, 500, 2.500 m.	N.W. – W. — S.W. 1 – 3	1 – 2	S.S.W. true. 0.3 knot.	0.2	0.5	E. – S.E.	0° to -5°	0° to +7°	2100 kgs. to 2900 kgs.	220° to 358° true.	5 Astronomical Observations. 16 Position lines.	0.9 M. Lat. 1.1 M. Long.	Probably between 18 h. 15 m. 13. VIII. & 6 h. 38 m. 14. VIII. 1.3 M. to N.E.	Cable jumped the capstan head while heaving out.
2	147 Section VI.	9. V. to 11. V. 26	14°57'2 S. 0° 6'6 W.	5196 m. 5489 m.	6500 m. 2 anchors	Globigerina ooze.	2 hrs. 5 mins.	Cable broken while weighing.	49 hrs. 11 h. 35 m. 9. IV. to 12 h. 23 m. 11. IV.	48 hrs. 0, 30, 700, 2,500 m.	S.E. 4 – 5 finally 6 (7)	3 – 4 finally 5 – 6	N.W. ½ W. 0.71 knot.	0.18	1.22	N.W. – N.W. bW.	-2° to +3°	0° to +11°	3000 kgs. to 5700 kgs. weighing: 10000 kgs.	87° to 153° true.	4 Astronomical Observations. 16 Position lines.	0.6 M. Long. 0 M. Lat.	After anchoring 12 h. – 14 h. 9. V. 2.4 M. to N.W.	Cable carried away while weighing on account of pitching in a seaway.
3	176 Section VII.	17. VII. to 18. VII. 26	21°29'8 S. 11°41'5 W.	2160 m. 2377 m.	2708 m. 2 anchors	Pteropod ooze.	48 mins.	1 hr. 30 mins.	30 hrs. 16 h. 55 m. 17. VII. to 23 h. 18. VII.	26 hrs. 30 mins. 0, 50, 100, 150, 200, 300, 500 m.	S.E. bS. to E.S.E. 2 – 3	1 – 3	W. bN. 0.4 knot.	0.2	0.6	W. – N.W.	-6° to +5°	+2° to +10°	1100 kgs. to 2500 kgs.	73° to 150° true.	3 Astronomical Observations. 10 Position lines.	0.1 M. Lat. 0.9 M. Long.	—	21 h. 18. VII. Ship dragged in heavy squall; weighed, stock of anchor broken.
4	186 Section VIII.	29. VIII. to 31. VIII. 26	8°57'2 S. 10°53' E.	3062 m. 3257 m.	3500 m. then 4000 m. 2 anchors	Gray ooze.	1 hr.	1 hr. 30 mins.	51 hrs. 13 h. 40 m. 29. VIII. to 16 h. 46 m. 31. VIII.	50 hrs. 0, 50, 700, 1100, 2200 m.	W.S.W. – S.W. 1	0 – 1	N. 0.44 knot.	0	0.75	N.N.E. — N.N.W.	—15° to +4°	0° to +10°	1000 kgs. tp 1600 kgs.	150° to 249° true.	4 Astronomical Observations. 20 Position lines.	0.5 M. Lat. 1.1 M. Long.	—	6 h. 30. VIII. veered 500 m. more cable.
5	214 Section IX.	21. X. to 23. X. 26	Commencement; 3°26'6 N. 25°54'8 W. End: 3°33'1 N. 25°58'3 W.	3927 m. 4069 m.	5000 m. 2 anchors	Globigerina ooze.	1 hr. 50 mins.	2 hrs.	43 hrs. 19 h. 20 m. 21. X. to 14 h. 30 m. 23. X.	42 hrs 30 mins 0, 25, 50, 100, 200, 400, 700, 1000, 2000 m.	S.E. bE. — S.S.W. 2	1 – 2	N. 0.43 knot.	0	0.90	N.N.E. – N.W. bN.	—5° to +3°	0° to +5°	1100 kgs. to 1300 kgs.	126° to 233° true.	3 Astronomical Observations. 9 Position lines.	6.5 M. Lat. 3.5 M. Long.	Between 13 h. 30 m. 22. X. & 12 h. 23 m. 23. X. 6.6 M to N.W bN.	—
6	229 Section X.	22. XI. to 23. XI. 26	Commencement: 3°57'8 N. 0°57'8 W. End: 4° 1'2 N. 0°53'9 W.	4586 m. 4687 m.	6241 m. 2 anchors	Gray-brown clay.	2 hrs.	2 hrs. 30 mins.	29 hrs. 30 mins. 10 h. 35 m. 22. XI. to 16 h. 11 m. 23. XI.	28 hrs. 30 mins. 0, 25, 50, 100, 200, 400, 700 m.	S.S.W. 3	2 – 3	N.E. ½ N. 0.84 knot.	0.52	1.22	N.E. bE. — N.E. bN.	—5° to +10°	0° to +15°	1400 kgs. to 1700 kgs.	208° to 233° true.	4 Astronomical Observations. 17 Position lines.	3 M. Lat. 3 M. Long.	Between 18 h. 18 m. 22. XI. & 5 h. 30 m. 23. XI. 5.1 M. to N.E.	—
7	241 Section XI.	22. XII. to 25. XII. 26	3°50'3 S. 1° 5'1 E.	3881 m. 4151 m.	5547 m. 2 anchors	Globigerina ooze.	1 hr. 30 mins.	2 hrs. 10 mins.	65 hrs. 16 h. 7 m. 22. XII. to 9 h. 7 m. 25. XII.	64 hrs. 0, 25, 50, 2000 m.	S.E. – S. bW. 3 – 4	2 – 3	N.W. 0:81 knot.	0	1.33	N.W. bW. — N. bE.	—10° to +7°	0° to +12°	1500 kgs. to 2000 kgs.	124° to 230° true.	6 Astronomical Observations. 29 Position lines.	1.6 M. Lat. 1.7 M. Long.	—	—
8	254 Section XII.	31. I. to 2. II. 27	2°27'9 S. 34°57'3 W.	3845 m. 3886 m.	6000 m. 2 anchors	id.	3 hrs. 20 mins.	2 hrs. 30 mins.	42 hrs. 30 mins. 12 h. 15 m. 31. I. to 6 h. 38 m. 2. II.	42 hrs. 0, 25, 50, 2000 m.	S.E. – E.S.E. 4	3 – 4	W. bN 0.97 knot	0.52	1.38	W.N.W. – W.	—2° to +8°	+5° to +20°	1800 kgs. to 2200 kgs.	85° to 124° true.	6 Astronomical Observations. 28 Position lines.	1.5 M. Lat. 1.5 M. Long.	Between 12 h. 15 m. & 15 h. 50 m. 31. I. 2.4 M. to N.W.	Admiralty anchor lost, the shackle joining it to the patent anchor having carried away.
9	288 Section XIII.	27. III. to 29. III. 27	12°37'6 N. 47°36'1 W.	4413 m. 4518 m.	6003 m. 2 anchors	id.	2 hrs.	2 hrs.	39 hrs. 30 mins. 16 h. 27 m. 27. III. to 7 h. 30 m. 29. III.	38 hrs. 0, 25, 50, 100, 200, 500, 800, 1100, 1500, 2000, 3000 m.	E. bN — E.N.E. 5 – 6	5	W. bS. 0.44 knot.	0.25	0.61	S.W. bW. – W. bN.	—5° to +10°	+10° to +20°	2200 kgs. to 2900 kgs.	40° to 100° true.	5 Astronomical Observations. 21 Position lines.	0.6 M. Lat. 2.5 M. Long.	Between 21 h. 45 m. 27. III. & 8 h. 54 m. 23. III. 2.5 M. to W.	—

10 tons several times; a spare cable ordered from home was shipped at Rio de Janeiro.

The reeling up of the cable on the cable-reel by hand was very laborious and required four men on each crank, who, on account of the enormous exertion, had to be relieved every hour. For this reason a small two cylinder compound engine, formerly a steam pinnace engine, was set up on the port side, the crankshaft of which could be coupled to the axle of the reel by means of a geared coupling for the purpose of reeling up the cable. There still remained the difficulty, as in the *Blake*, of working this engine in step with the windlass engine, so that the cable would be kept at equal tension between the windlass and the cable reel. On account of the above-described changes after the trial-cruise, the time required for weighing the anchor from a depth of 4000 (2200 fms.) was reduced from 5 to 2 hours (See Column 9 of the Table).

OBSERVATIONS AT THE ANCHOR STATIONS OF THE "METEOR".

At the anchor stations of the *Meteor*, the following observations were taken continuously for the accurate determination of the movements of the vessel riding to a long cable, which are important for the analysis of the factors which influence current observations :—

1) Astronomical determination of position as often as possible;

2) Reading of the direction of the ship's head every ten minutes;

3) Determination of depth by echo-sounding every 20 minutes;

4) Observations of the wind and state of the sea and of the direction and force of the swell every 30 minutes;

5) Measurements of the direction and strength of the surface current with the taffrail-log every hour. Simple small wooden boards served as logs;

6) Estimation of the angle of the cable, *i.e.*, the angle between the cable and the vertical (Cable grows forward = +; aft = —) every thirty minutes;

7) Estimation of the relative bearing of the cable, *i.e.*, the horizontal angle between the cable and the ship's head (cable grows to starboard = +, to port = —) every thirty minutes;

8) Reading from the dynamometer of the tension of the cable in kgs. every thirty minutes;

9) Commencement of anchoring, weighing, special happenings, squalls, etc.;

10) Name of the observer.

In the accompanying synopsis (Table I) the data for each anchor station are given in tabular form in mean or maximum and minimum values.

From the synopsis it will be seen that the *Meteor* always lay at anchor in very light winds and sea (Columns 12 and 13), except at Station 147, where she finally encountered bad weather, wind 6 to 7, sea 5 to 6, which led to the cable carrying away while weighing the anchor, and at Station 288, wind 5 to 6 and sea 5, where no damage occurred, though the limit for working with the sensitive MERZ-EKMAN current meters was reached. Likewise the surface current was weak throughout (Columns 14 to 16) reaching a maximum of 1.33 knots. If, in spite of this, the ship dragged temporarily at 6 of the 12 stations, this was due to the short stay at which she rode and probably because the anchors were too light, as is shown moreover by the damage done to them. The dragging occurred each time either shortly after anchoring, until the anchor finally held, as at Station 147, 2.4 miles and at Station 254, 2.4 miles, or else after squalls set in, when the only thing to be done was to determine the total drift of the ship by the next astronomical position, as at Station 36, in twelve hours of the night, 1.3 miles; at Station 214, in 23 hours (during which no observations were possible), 6.6 miles; at Station 229, in 11 hours of the night, 5.1 miles and at Station 288, in 11 night hours, 2.5 miles. Further check on the amount of drift is provided by measurement of the surface current, and observations of the cable as to bearing, angle and tension (Columns 18 to 20), and the bearing of the ship's head. Finally, the sudden changes of the depths by echo-sounding gave an idea as to the duration of the drift. The other movements of the ship were noted as follows :

Swinging, by reading the bearing of the ship's head and the relative bearing of the cable, as also was *yawing.* *Over-riding* was observed by the angle and tension of the cable, and its amplitude by the difference in the astronomical positions.

ASTRONOMICAL DETERMINATION OF POSITION OF ANCHOR STATIONS. (See Fig. 7).

The astronomical determination of position was carried out in the following manner :

At daybreak 3 to 5 position-lines were determined by altitudes of fixed stars or planets. This position-line polygon gave the "morning position". During forenoons and afternoons several hour-angles of the sun were observed, which, together with the meridian altitude or circum-meridian altitude gave the "noon-position". In the evening 3 to 5 fixed stars or planets were again observed for the "evening position". Thus daily, on an average, three satisfactory positions were available, which were plotted graphically on a large scale by drawing the position-lines on squared paper.

Fig. 7 is an example of such position-line plot for Anchor Station 254. The vessel, riding to two anchors and 6000 m. (3280 fms.) of cable, in 3950 m. (2160 fms.) by echo-sounding, took current observations during 42 hours, with an average SE to ESE wind, force 4 and a mean surface current running to W. b. N, 0.97 knots. The astronomical determination of position consisted of the following observations :—

31st January, 1927, noon and afternoon, three sun position-lines, 1, 2 & 3.
31st January, 1927, evening, five fixed star position-lines, I, II, III, IV & V.
1st February, 1927, morning, 5 fixed star position-lines, VI, VII, VIII, IX & X.
1st February, 1927, forenoon, noon and afternoon, 5 sun position-lines, 4, 5, 6, 7 & 8.
1st February, 1927, evening, 5 fixed star position-lines, XI, XII, XIII, XIV & XV.
2nd February, 1927, morning, 5 fixed star position-lines, XVI, XVII, XVIII, XIX & XX.

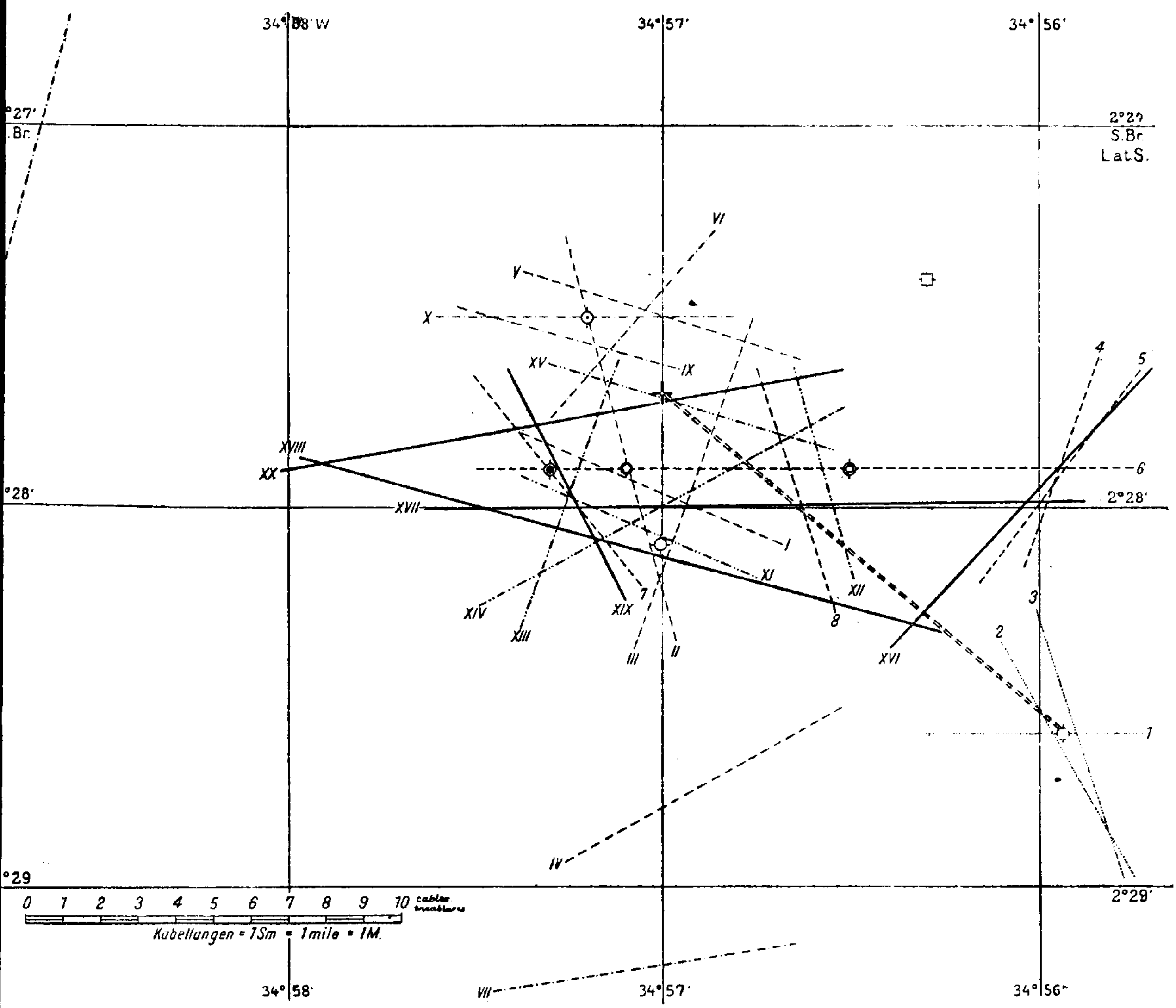

FIG. 7.

Diagram of the astronomical Position-lines observed by the Meteor *at Anchor Station 254 and of the Positions of the ship deduced therefrom. The double-pecked line represents the drag of the ship. For explanation of this figure see text.*

In all 28 position-lines. From these position-lines, the following positions of the ship result :—

1) 31st January, noon, 2°28.6′ S. & 34°56.0′ W ◌
2) 31st January, 21h2m G.M.T. 2°28.1′ S. & 34°57.0′ W. ○
3) 1st February, 8h4m G.M.T. 2°27.5′ S. & 34°57.2′ W. ⊙
4) 1st February, noon, 2°27.9′ S. & 34°56.5′ W. ◎
5) 1st February, 21h1m G.M.T. 2°27.9′ S. & 34°57.1′ W. ○
6) 2nd February, 8h4m G.M.T. 2°27.9′ S. & 34°57.3′ W. ◉

Therefrom it results that, by the end of the anchoring on 31st January, from 12h15m to about 15h50m M.L.T. the ship dragged a total of 1.4 miles to the NWd, *i.e.*, in the direction of the wind, and from then until the completion of the observations she remained steady. The rest of the ship's positions lie within a radius of 0.5 mile and show the movements of the ship at the anchor station. The drag of the ship was recognisable also by the weakness of the surface current from 12h30m to 14h30m on 31st January and by the fact that the wire of the current meter grew *forward* (wire angle = 15°). If it be assumed that the ship, during this period of 3 hours 35 minutes, dragged absolutely regularly (which, however, cannot be confirmed), the rate of dragging would be 0.41 mile to the NWd per hour. The mean astronomical position of Anchor Station 254 was 2°27.9′ S. and 34°57. 3′ W. ✧ . On weighing, on 2nd February, the cable brought up *one* anchor only. The Admiralty anchor was lost as the fish shackle of the patent anchor, which was the connection between the two anchors, broke. It is supposed that this occurred in breaking the Admiralty anchor out of the ground.

ACCURACY OF THE POSITION-LINE METHOD.

Astronomical determination of the ship's position can only be used for determining the total dragging and measuring the amplitude of the swing and the over-ride when it is very accurate. In general, it may be said that, in astronomical navigation, the usual instruments, tables and methods provide an accuracy of ± 1 mile, which amply suffices for practical navigation. KRÜMMEL (1) stresses the fact that the determination of position at sea by surveying vessels and cable ships is closer than is customary in other ships. According to H. MOHN, the inaccuracy arising from astronomical observations can be expressed as a circle with a radius of a minute of arc = 1 mile, with the position obtained as centre. According to the theory of probabilities the consequent error in the position would be, according to MOHN, $\pm 1852 \sqrt{2} = \pm 2620$ m. (2865 yds.). According to the *Manual of Navigation of the German Navy*, Part II, 184, the following may lead to errors in the positions of the position lines : neglect of the curve in the circle of equal altitude, errors in the azimuth, errors in the altitude and the chronometer error. The two first sources of error can generally be ignored, as they need only be

(1) KRÜMMEL. *Handbuch der Ozeanographie*, Part I, page 83.

taken into consideration in the case of *very* great differences between the observed and calculated altitudes. Mistakes in the error of chronometer, seeing that this can be checked daily by W/T (as in the *Meteor*) should likewise be very small. Errors in altitude arise from errors in the observed altitude. In the observed altitude, the errors of the sextant, those in the dip of the horizon and in refraction and the personal error of the observer are included and these, in the aggregate, may reach a high value. In a wind and with a sharply defined horizon, they would barely exceed 1' to 2'. This degree of accuracy is not sufficient, when a ship's movements within a mile are to be determined. In the *Meteor* an attempt was made, therefore, to improve the accuracy of astronomical observations by the position-line method as follows :

The observations were made in sets by several observers, generally 2 to 3, and worked out separately so that personal errors in observation and calculation were eliminated as far as possible. Each observer always used the same instrument (Vernier Sextant) which, before each observation, was corrected for instrumental errors, index error, parallax error and verticality of the horizon glass. The collective corrections contained in the *Nautical Tables* for dip of the horizon, refraction, parallax and semi-diameter (Sun) were not used, but these corrections were applied separately to the observed altitudes. The dip of the horizon was determined either by simultaneous altitudes of the sun above both horizons, taken by two observers, one direct and the other through the zenith, or was measured by a very handy instrument, the PULFRICH Dip-meter (made by ZEISS) with drum-readings. These direct dip measurements gave, at times, results 2 to 3 minutes less than the value taken as the basis for the collective correction, which gives a difference of from 2 to 3 miles in position. The mean value of the refraction was corrected by applying the corrections for atmospheric temperature and pressure at each altitude observation. If, therefore, stars were chosen whose position lines cut at the most favorable angle possible, a very small error polygon was formed, and the accuracy of the determination of position was estimated to be increased to within about $\pm$ 0.3 to 0.4 mile owing to the above mentioned care in observation and application of corrections separately. This is confirmed by the manner in which the ship's positions coincide with the displacements found by analysis (direction of ship's head, wind and current).

THE ANALYTICAL TREATMENT OF OBSERVATIONS AT ANCHOR STATIONS (See Fig. 8).

The analytical treatment of the observations taken at the Anchor Stations, to determine the true displacements of the ship caused by current and wind, was undertaken by Professor A. DEFANT who made the report on the scientific results of the German Atlantic Expedition and who will deal with the working out of the Anchor Stations of the *Meteor*, together with full observational data, in a volume of the Report on the Expedition relative to oceanographic researches. These results show that each separate Anchor Station gives a specific picture of the displacements of the ship. The methodical way in which this was done will be but briefly outlined here, and Anchor Station 254 will again be taken as example (Fig. 8).

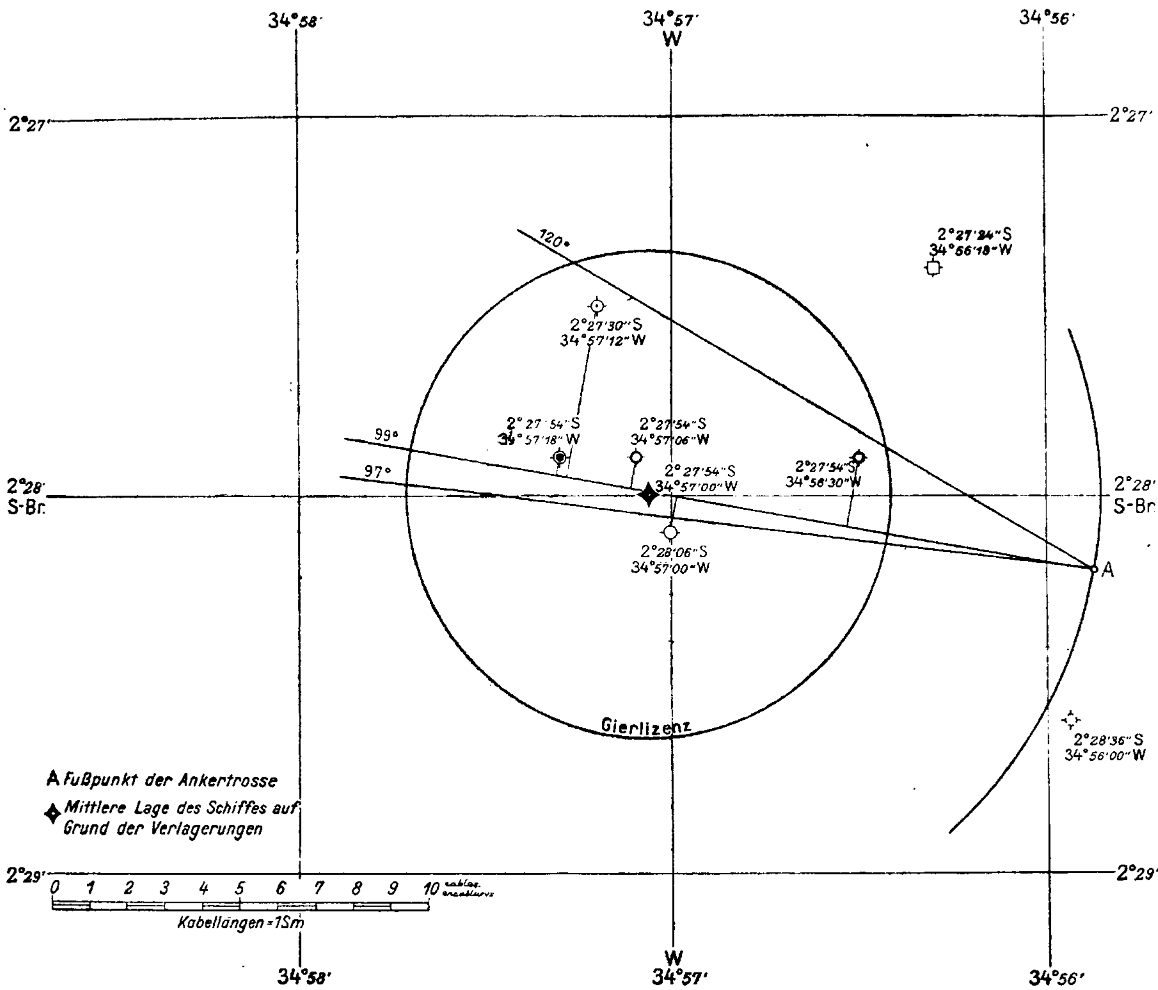

Fig. 8.

Representation of the displacements of the Meteor *at Anchor Station 254 based on the astronomical determinations of position and the other observations made at the Station* (cf. Table I), *according to* A. Defant.

(*The positions of the ship which were observed to within a tenth of a minute are given in seconds in this diagram*).

Gierlizenz	=	Over riding licence.
Fusspunkt der Ankertrosse	=	Foot of the cable.
Mittlere Lage des Schiffes auf Grund der Verlagerungen	=	Mean position of ship based on the displacements.

As was explained above, first the positions of the ship at the moments of observation are plotted graphically, on a large scale, as deduced from the polygons of position lines. The G.M.T.'s of the observations are converted into lunar times in order to appreciate the influence of tidal current on the displacements of the ship. Then the bearings of the ship's head reduced to full hours (zone time) are plotted at the observation points and they are tested to determine whether these phases of the *swing* of the ship can be reconciled with the times and positions of the actual places of the ship. It should be observed that, when doing this, the *yaws* (*i.e.*, the turning of the ship about the point where the cable reaches the knight-head roller, practically the vertical axis of the stem) must be eliminated. The point of convergence of the directions of the ship's head, which represent the different phases of the swing, gives the position of the anchor (foot of the anchor cable) or centre of swing. In addition, from the directions of the ship's head a mean direction in which the ship lay during the whole time at the station is obtained and this is laid off through the centre of swing. If the various positions lying on each side of it are projected on to this general direction of the ship's head, it is possible to obtain an idea, on this line, of the amplitude of the *over-riding* movements of the ship.

Further, by graphic means, one is able to determine, from the depth and the amount of cable out, the position of the limits of over-riding, *i.e.*, with the cable quite slack and quite taut, and therefrom the *over-riding license*, *i.e.*, the greatest possible amplitude of over-riding. It can then be determined, on the general direction of the ship's head from this over-riding license, whether we have to deal with over-riding (which must take place within the limits of the license) or with a case of dragging of the anchor. As checks, use is made of the values of the angle of the cable, the tension, the echo soundings, the surface current and the wind. The actual astronomical positions of the ship should then fit into this analysis of her movements in over-ride and swing, and it is possible to make therefrom a graph of the entire movement which the ship has made on her long cable at each Station. The observations of wind and surface current must also be capable of being inserted logically on this graph, for it is they which caused the movements.

The analysis of the measurements by taffrail log of the surface current, by resolving them into their components, will give the amounts of the tidal current and of the residual current, and these results will be confirmed by the observed positions reduced to lunar time. The diagram of position-lines for Anchor Station 254 (Fig. 7) provides an example of the determination of the direction and amount of drag by astronomical observations. The influence which the amount of drag will have on the results of current measurement in deep water cannot be ascertained from this diagram without other data, as only the *time* elapsed between two observed positions (generally the evening and morning positions) between which the ship has dragged and the *total distance* are known, whereas it is the hourly values of the drag which are required for the reduction of the current measurements. Here, to determine the individual phases of the drag, the assistance of the observations of the surface current, the wind, the relative bearing and angle of the cable, as well as its tension, must be called in.

It must be assumed that, on the whole, the rate of displacement of the ship at each Anchor Station was very slow seeing that, generally, the current and wind were light. In part, the movements will have no influence, *e.g.*, on deep current observations lasting at most 5 minutes, but in the remainder this influence will emerge by calculation as to direction and force. At all events the working out of the observations at the Anchor Stations of the *Meteor*, as above described, indicates that it is possible to determine the displacements of the ship analytically from the observations and to correct the results of current observations, a conception which has been accepted by R. WITTING (1) also. But the practical experience gained in the *Meteor* shows that more accurate results may be expected from current observations by further substantial improvement in the anchor gear and by introducing refinements in the observations of the movements of the ship. Hence it appears advisable to close with one or two practical hints. But, first, a few data as to the deep sea anchoring of the *Willebrord Snellius* will be given below for comparison with the experiences of the *Meteor*.

DEEP SEA ANCHOR GEAR & ANCHOR STATIONS OF THE "WILLEBRORD SNELLIUS" EXPEDITION IN THE WATERS OF THE NETHERLANDS EAST INDIES, 1929-30.

For the following information relative to the deep-sea anchor gear and the Anchor Stations of the *Willebrord Snellius* Expedition I am indebted to the Chief of the Expedition, Mr. P. M. VAN RIEL, Director of the Koninklijk Nederlandsch Meteorologisch Institut, De Bilt, who kindly communicated it to me. The anchor gear was approximately the same as that of the *Meteor* and proved satisfactory. The windlass engine was very powerful and it was necessary to stop it but once when heaving out, on account of overheating. The gear, consisting of a 100 kgs. (2 cwt.) mushroom anchor followed by 30 m. (100 ft.) of cable, a second mushroom anchor, weighing 200 kgs. (4 cwt.) and then 15 fathoms of chain, weighing 165 kgs. (365 lbs.), was thus somewhat heavier than that of the *Meteor*. The cable was the same as the *Meteor*'s, 7500 m. (4100 fms.) long, tapered and kinkless. The cable reel stood likewise on the forecastle but the arrangement of the rest of the various parts of the anchoring gear differed somewhat from that in the *Meteor* as, on board the *Snellius*, not so much space was available. When the Expedition ended the lower half of the cable was still in fairly good condition.

The accompanying table II gives, in greater detail, the conditions in which the ship lay at anchor and took current observations at seven stations. The average period at anchor was 4 days (Columns 1 & 5). The greatest depth in which the ship anchored was 4850 m. (2650 fms.). The average amount of cable allowed was from 1 1/2 to 1 1/3 times the depth (Column 3). The wind, while the ship was at anchor, was light, at Station 253*a* it reached the maximum of 12.6 m. (41 ft.) per second. The surface current varied from nil to 1.8 knots (Col. 7). The greatest tension on the cable, from 4100 to 4200 kgs. (about 4 tons), was recorded at the two deepest Stations, 308*a* (4850 m. =

(1) See also page 10.

TABLE II

SUMMARY OF THE DEEP-SEA ANCHOR STATIONS OF THE **WILLEBRORD SNELLIUS** EXPEDITION

Number	*Date.*	*Mean Geographical Position.*	*Wire or Echo Sounding & Length of Anchor Cable.* } *to the nearest 50 m.*	*Nature of Holding Ground*	*Duration of Observations in Hours.*	*Depths at which Current was Observed.*	*Resultant Surface Current in Knots, Maximum and Minimum. Direction varying between :*	*Resultant Direction of Wind, Force in m.p.s. Maximum and Minimum. Direction varying between :*	*Tension on Cable.*	*Direction of Ship's Head varying between :*	*Greatest Difference in Observed Position. Number of fixes obtained.*
Station	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
39*a*	8/11 Aug. –29	1 – 14 S. 118 – 21 E.	2250 3000	Blue mud.	60	0, 50, 125, 400, 1900.	S.E. b. S. – 0.6' 0.1' – 1.4' From E. to S.	S.S.W. – 4,4 3.0 – 7.0 From S.S.E. to W. b. S.	1300 to 1650	From W. to N.N.W.	2.7' 6
135*a*	17/21 Nov. –29	10 – 7 S. 121 – 18 E.	1150 1850	Sand.	89	0, 20, 50, 75, 100, 200, 1000.	N. b. E. – 0.4' 0.1' to 1.6' From S.W. to E. by N.W.	S.W. b. W. – 5,2 2.9 to 8.0 S.S.W. to W.	700 to 1750	W b. S. to S.E. b. S.	1.5' 6
253*a*	23/27 April –30	1 – 48 S. 126 – 59 E.	1800 2500	Volcanic Mud.	82	0, 50, 100, 200, 350, 500, 700, 1000 (1), 1200, 1400 (2), 1500.	E.N.E. – 0.3' 0' to 1.5' All directions.	W.N.W. – 1.6 calm to 12.6 All directions.	1000 to 2050	All directions.	1.4' 10
308*a*	29th June– 1st July –30	3 – 21 N. 120 – 36 E.	4850 6500	Ooze.	53	0, 10, 25 (2) 50, 75 (2), 100 (2), 150, 250, 400.	N. – 1.2' 1.0' to 1.8' From N.W. to N.E.	S.W. b. S. – 7.2 5.0 to 3.9 S.S.W. to S.W.b.W.	3650 to 4100	S.S.E. to S.W.	2.6' (3) 2
317*a*	21/24 Aug. –30	7 – 55 S. 122 – 13 E.	2400 3300	Ooze (4).	51	0, 25, 75, 125, 175, 300, 600.	N.N.E. – 0.2' calm to 0.7' S.S.W. – W.N.W. N.E. – E.S.E.	S.E. b. E. – 2.2 calm to 6.0 N.W. – N.E. S.S.E.	1750 to 2150	W. – S. – S.E.b.S.	1.6' 6
354*a*	6/8 Oct. –30	1 – 29 S. 129 – 11 E.	1350 1950	Globigerina ooze.	35	0, 25, 50, 100, 150, 250. 400, 600, 800 (5), 1000 (5).	S.S.W. – 0.5' 0.1' to 1.3' S.E. – S. – N.W.	E. – 0.9 calm to 2.7 S.E. – E. – N.E.	850 to 1350	S.E. b. S. N.E. – N.W. b. W.	0.9' (6) 4
364*a*	23/24 Oct. –30	6 – 27 S. 131 – 31 E.	4450 5600	Blue mud.	24	0, 100, 400, 3000.	W.N.W. – 0.9' 0.4' to 1.4' W. - N.W.	E.S.E. – 5.4 4.0 to 7.3 E. – S.E.	3500 to 4200	E. – S.E. b. E.	1.0' 3

At Anchor Station 312*a* in the Java Sea the deep-sea anchor gear was not used.

1) One Observation.
2) Two Observations.
3) Rain & overcast sky. Astronomical Observations for position not accurate.
4) Station 197.
5) Two Observations.
6) By four bearings.

2650 fms.) and 364*a* (4450 m. = 2435 fms.). The greatest differences in observed position at the Anchor Stations were 2.7′ and 2.6′, but at the latter (Station 308*a*) the astronomical determination was not exact on account of rain and an overcast sky. Generally speaking, the largest differences of position lay between but 0.9′ and 1.6′ and thus were within the usual limit of accuracy of astronomical observation. The Chief of the Expedition states, with reference to Station 308*a*, that it is not without the bounds of probability that in the beginning, during repetition of the serial observations, the ship dragged somewhat but, as mentioned above, the astronomical determinations of position at this Station were not satisfactory.

Taking everything into consideration it appears that the anchor gear of the *Willebrord Snellius* was entirely satisfactory and that, even in strong wind (force 7) and in a surface current reaching 1.8 knots, the ship did not drag. The heavier ground gear (1 anchor of 2 cwt. and one of 4 cwt.) and the more suitable form of the anchor (mushroom) were without doubt a considerable improvement on the method of anchoring employed by the *Meteor* (1 Admiralty and 1 patent anchor of only 2 cwt. each).

PRACTICAL PROPOSALS WITH REFERENCE TO THE ANCHOR GEAR AND OBSERVATIONS AT STATIONS.

It would be better to use heavier anchors than those employed by the *Meteor*. The fact that the *Meteor*'s anchors were somewhat too light is proved by the damage done to them (*cf.* Col. 25, Anchor Stations 176 & 254). Otherwise one or more *mushroom anchors* should be used, as was done by the *Willebrord Snellius*. This type of anchor was purposely not provided in the *Meteor*, for experience had shown that, in good holding ground, it requires a great effort to break it out, *i.e.*, the cable and the windlass, the latter, in the *Meteor*, being provided for normal anchoring only, would be heavily overloaded. However, the experience of the *Willebrord Snellius*, with her specially strong windlass, was that the cable always stood up to the strain of breaking out the mushroom anchor and that this anchor always stood the test. For the same weight it gives a better hold then the Admiralty anchor. The experiments of the *Blake* justify the insertion of a *spring* (accumulator) in the anchoring gear. This is confirmed by the carrying away of the *Meteor*'s cable when she was pitching while heaving in. It would be well to study whether the spring dynamometer could not be replaced by some sort of powerful spring capable of damping the violent jerks when the ship is pitching. The parting of the cable in the *Meteor* shows, further, that the diameter of the knight-head roller was too small, thus introducing a too sharp bend in the cable at the very point where the strain is greatest. The diameter of the roller should rather be in the vicinity of 1 m. (3 ft.) and the knight-head roller should be more of the type of the wide stern rollers used by minesweepers.

As the *over-riding* and *swinging* movements can be determined fairly accurately by means of the compass and of astronomical observations for position, it would be, perhaps, advisable to *ride at a longer stay* than was customary in the *Meteor*, say about 1 ½ times to twice the depth of water. The short stay at which the *Meteor* rode was intended to limit the over-ride and swing as far as possible. When bad weather is working up it is best to await better weather at anchor (in the case of the *Meteor* this was not possible on account of shortness of coal supply) as the cable is quite capable of holding the ship even in fairly considerable wind and sea (6), but will not stand the strain, which cannot be checked, due to weighing while the ship is pitching heavily. The breaking of the *Meteor*'s cable is due to the simultaneous action of these two forces.

As to the observations at the Anchor Station, the following improvements commend themselves :— It would perhaps be well to use an electric "course recorder " to register accurately the variations in the *direction of the ship's head* and, similarly, to record the *tension* on the cable, to use a self-registering dynamometer. For the *angles* and the *relative bearings of the cable*, which were estimated, in the *Meteor*, by means of the "sounding wire inclination meter" commonly used in wire sounding, it might be possible to develop more reliable recording instruments. It is extremely difficult to estimate these two values from the forecastle. More accurate and more frequent observations of the *surface current* than were taken by the *Meteor*, are necessary. They should be taken at least half hourly. When doing this the bearing and distance of the drifting log-ship should not be merely estimated but should be determined as accurately as possible by alidade compass-bearing and measurement of distance (such as by observation from aloft of the angle below the horizon), the direction of the ship's head should be read at the same time. Even at night it is possible to make these surface current observations by throwing the beam of a searchlight on the log-ship. While current observations last it is recommended that (as NANSEN (1) has suggested) a second current meter, preferably an electric current recorder, be lowered to a greater depth. This will make the total displacement of the ship appear with reference to the weak deep sea current. Finally, and as was done by the *Meteor*, *oceanographic serial observations*, at the depths at which the current is observed, should be taken about every three hours in order to determine the short and long period variations in temperature and salinity which serve to explain the variations in the results of the current observations.

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(1) See page 9.