Editorial Note.

We welcome the appearance, in November last, of the first number of the *Journal of Marine Research*, published by the Sears Foundation for Marine Research, Bingham Oceanographic Laboratory, Yale University, New Haven, Conn. This journal is to be devoted to "any aspect of scientific marine investigations or any subject with a direct or indirect bearing upon the problems of the sea". It is to appear three times a year, and the annual subscription price is $ 3.

Water Movements in the Straits of Dover.*)

By

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THE streams were measured during some months in 1934 and several weeks in 1935 and 1936 with the so-called "heavy Ott" current-meter (Fig. 1), a well-known precision instrument. When strong currents had to be measured at great depths (up to 70 metres), it was found to be necessary for the instrument to weigh 100 kilograms. For weaker currents 50 kilograms sufficed. Every half-hour the currents were measured from top to bottom at intervals of 2 metres, but when the depth was large, these were increased to 5 metres.

It is a well-known fact that in turbulent water current-meters often give results which are either too high or too low. In the laboratory of Iowa, U.S.A., the engineers Yarnell and Nagler¹) found that some types of instrument showed errors up to 200 % when measurements took place in very turbulent streams. Much attention was therefore given to the checking of our "Ott" current-meter during all weather conditions. A handy way of doing this is by using as submerged floats, small bits of sea-weed floating by the ship's side. These were timed for a distance of 25 metres by stop-watch. Repetition of this simple test shows not only that the checking is fairly accurate, but also that the "Ott" can be relied upon during all weather conditions. In order to avoid the influence of the ship's side, the instrument was hung at 2½ metres distance (see Fig. 1).

The direction of the streams was observed simultaneously by means of a Jacobsen meter (Fig. 2). We prefer pyramids to any other body, because pyramids (or cones) remain absolutely stable in a stream. The apex of the pyramid must point in the direction from which the current comes.

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*) For more extensive information see: "Onderzoekingen in de Hoofden", with English and French summaries and 147 figures, by Joh. van Veen, Algemeene Landsdrukkerij, den Haag, 1936.

¹) Yarnell and Nagler: "Effect of turbulence on the registration of current-meters." Am. Soc. of Civ. Eng., paper 1778, 1931.

The ship "Oceaan" which was used for these measurements is about 400 tons, and of the following dimensions:— depth 3·50 m., breadth 7·60 m., length 38·30 m. She does not move to-and-fro in the streams when at anchor, and rides very steadily in bad weather so that measurements can go on even during heavy gales. The custom is to continue measurements until the anchor starts to drag or until the specially heavy anchor-chain breaks.

The work of 1934 and 1935 enabled about 300 vertical diagrams of currents in the Straits of Dover to be prepared. They refer to 31 different spots with depths varying from 30 to 70 metres. In 1936, 392 similar diagrams were drawn for one point only, near Dover.

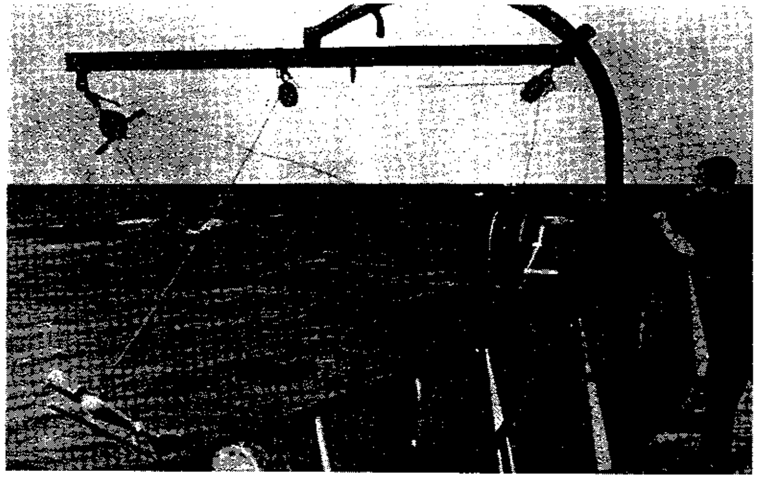

Fig. 1. The "heavy Ott" current-meter. It gives signals on board ship by means of electricity.

Stream-Diagrams for Verticals.

According to both old (1875 and later) and recent measurements of the Rijkswaterstaat, the diagrams for the currents from top to bottom show the following characteristics. The strongest currents occur at the surface, and velocity falls off with depth in such a manner that the diagrams resemble parabolas with vertical axes, whose vertices touch the bottom in the zero of the figure.

It should be added that most investigators reached other conclusions[2]; some found rectilinear or logarithmic forms, others elliptical or even parabolic ones with horizontal axes, etc. The German writers on this subject, Forchheimer[2] (1931) and van Rinsum[3] (1935), maintain that parabolic forms with vertical axes do not satisfactorily represent the stream-diagrams for a vertical. The German schools teach that the highest velocity occurs at some distance below the surface.

Apparently there is still much difference of opinion, though the problem is not very complicated. Nature itself may in some measure be the cause of these different opinions, because streams need not always yield the same diagram, and a contributory cause may lie in incorrect measurements or in unchecked instruments. Moreover, recent data are rare, so that van Rinsum (1935), for example, uses those of Jasmund (1893).

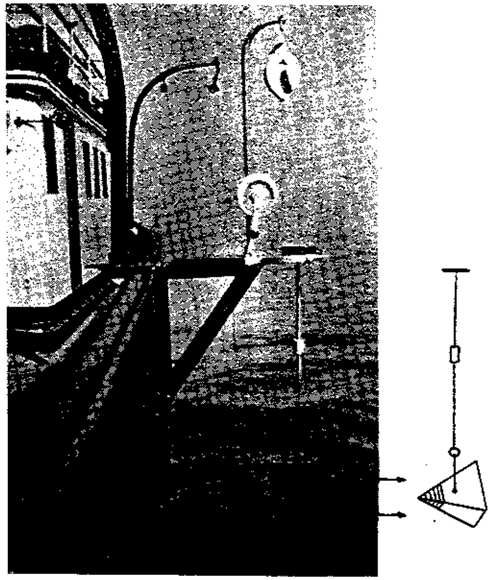

Fig. 2. The measuring of the current-direction by means of Jacobsen's device. A pyramid does not shake in any current.

The modern precision instruments for measuring water currents such as those of Ott or Rauschelbach are reliable, and it seems logical to expect that when those or any other good modern instruments are used, different opinions would unite in principles though some minor differences would remain. For instance, views might differ as to whether the fastest currents occur at the surface or at a small distance below it, because some instruments over-register and others under-register near the surface on account of wave-turbulence. Near steep shores and in laboratory channels the quickest currents do seem to lie below the surface, but the practical significance of this is not great.

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[2] Ph. Forchheimer. Hydraulik, pp. 172—180, Leipzig, 1930.

[3] Anton van Rinsum. Die Abflüsse in offenen natürl. Wasserläufen. Berlin 1935.

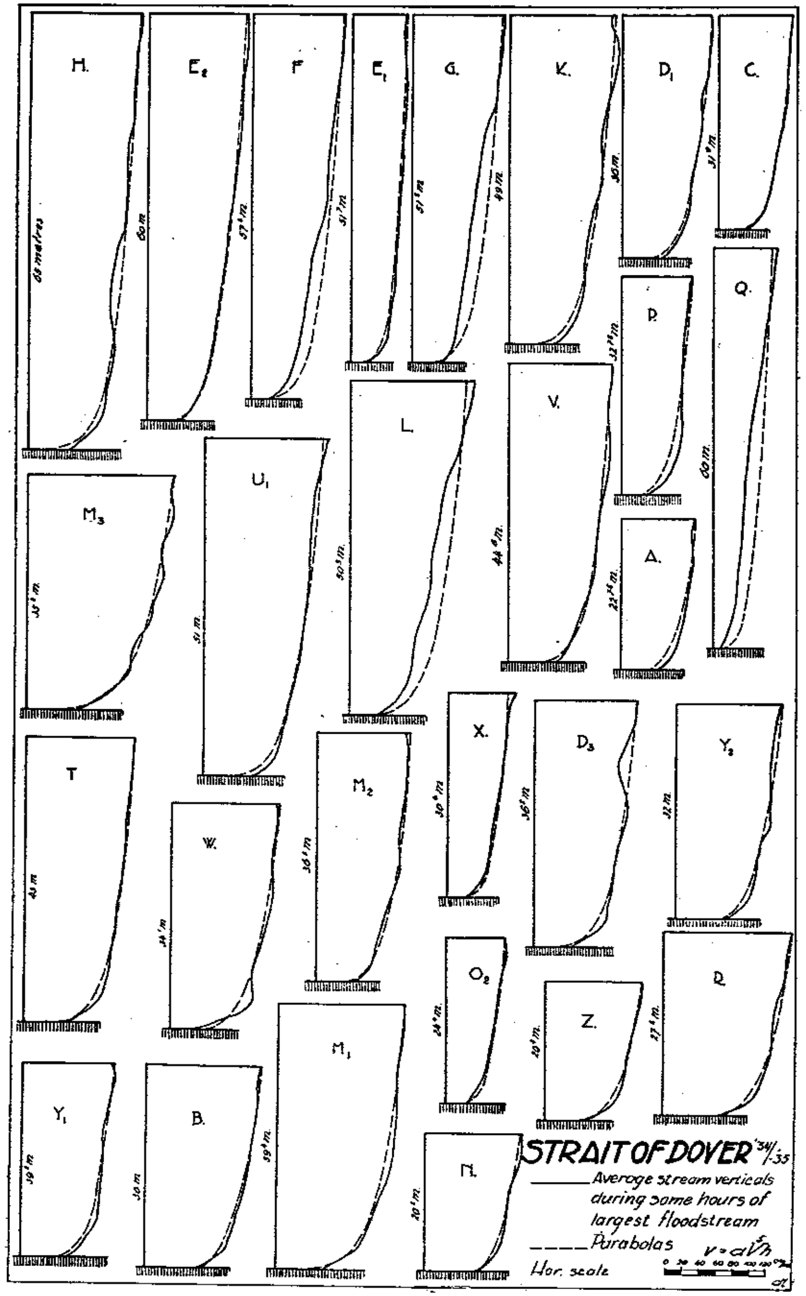


Fig. 3 and 3a. Diagrams for velocities from top to bottom in different places (refer to Fig. 16) of the Straits of Dover during flood and ebb.

different places
d ebb.

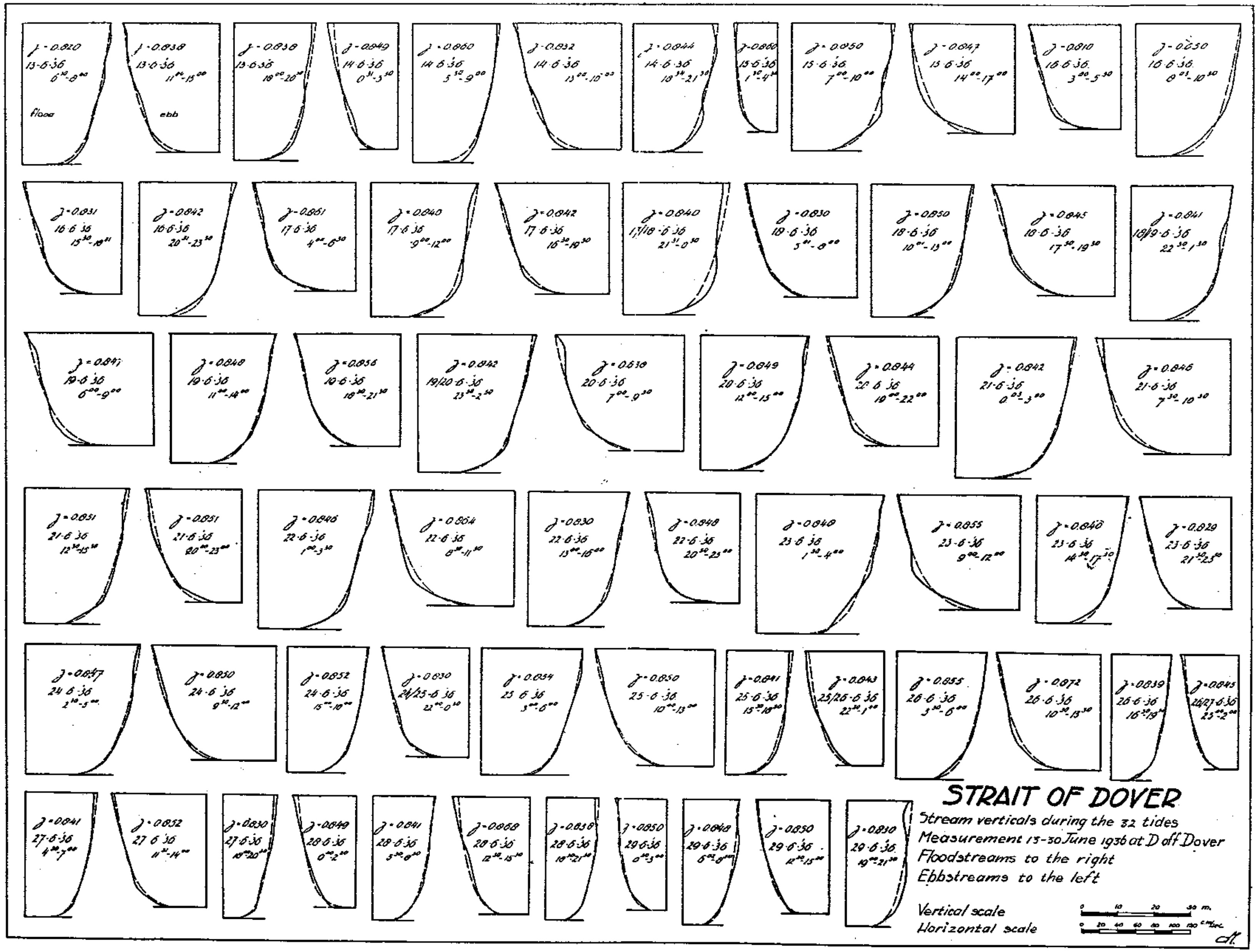
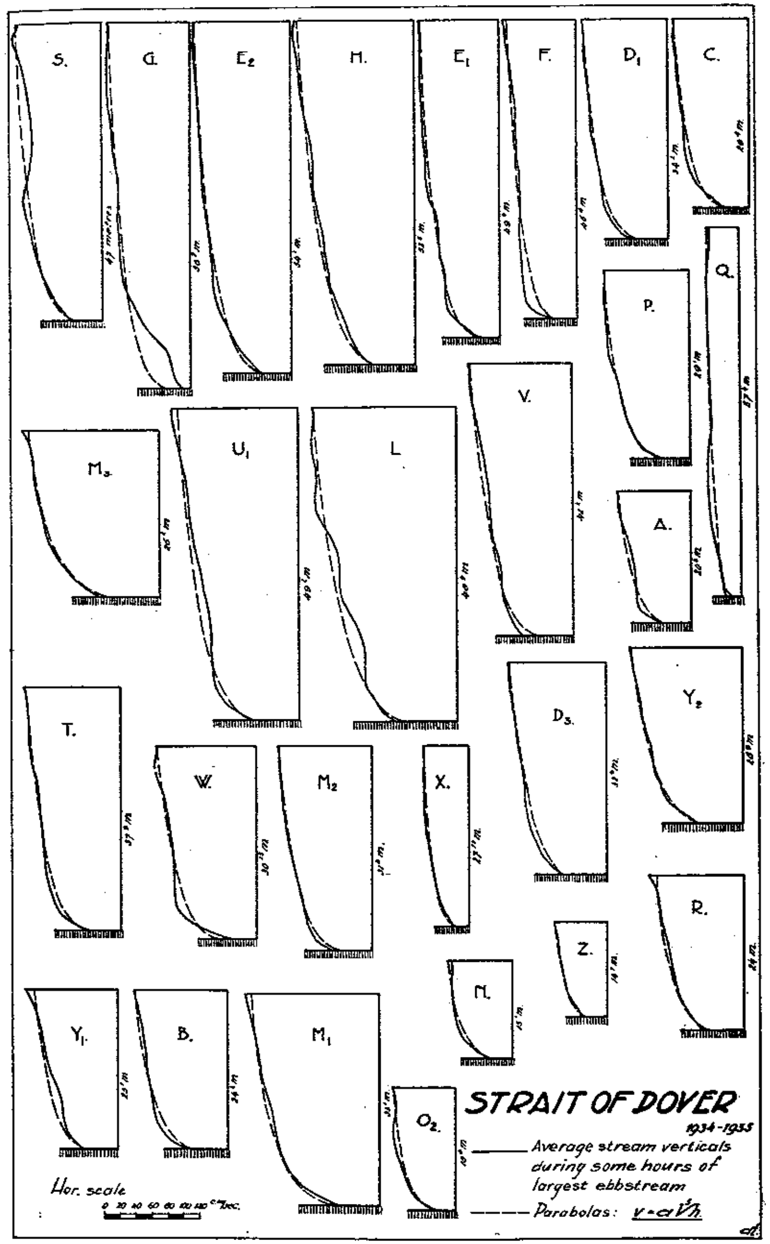


Fig. 4. Diagrams for velocities from top to bottom at point D, 5 miles off Dover.


S.
G.
E_2
H.
E_1
F.
D_1
C.
Q.
P.
V.
M_3
U_1
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A.
T.
W.
M_2
X.
D_3
Y_2
R.
Z.
N.
Y_1
B.
M_1
O_2
47 metres
Hor. scale
0 20 40 60 80 100 120 cm/sec.
STRAIT OF DOVER
1934-1935
Average stream verticals during some hours of largest ebbstream
Parabolas: $v = a\sqrt[5]{h}$

The thing that is not to be overlooked in practice is the simplicity of the formulae to be used. Formulae such as those of Hessle, Harden, Lavalle, Christen and others, in which many different factors are impressively included, may give good approximate results, but they cannot well be used for practical purposes.

Although the German writers on this subject discourage the use of parabolas with vertical axes, the present writer has tried whether the simplest parabola imaginable, namely

$$V = a\sqrt[q]{h} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

would fit the very extensive measurement data collected by the Rijkswaterstaat during the years 1931—1935 closely enough to be of practical value.

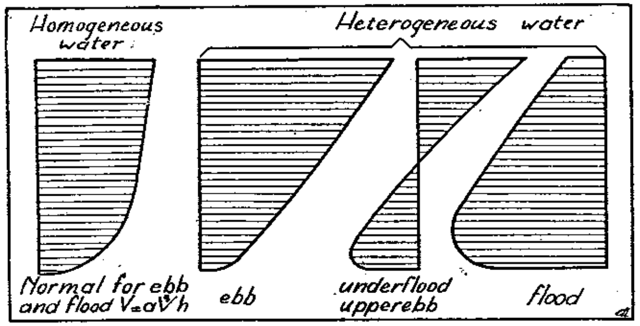

Fig. 5. Diagrams for velocities in heterogeneous water; salt below, fresh above.

In this formula V is the velocity at a height of *h* metres, and *a* the velocity at 1 metre above the bottom, while *q* is a figure which proved to be between 5 and 10.

Figures 3 and 4 give a number of specimens of stream-diagrams for verticals in the Straits of Dover, and show also the approximating parabolas.

The correspondence seems not only to be good enough for practical purposes, but the fact that sometimes the parabola is on one side of the measurement-graph and sometimes on the other side of it suggests that Formula 1, though simple, is more or less theoretically right too. The currents increase with distance from the bottom according to some regular law — at least when the density of the water is the same from top to bottom. When it is not, different types of diagram result, of which Fig. 5 gives some idea.

Generally we find that the differences in specific weight do not influence the form of the diagrams, when these differences remain under one per mille. The three distorted diagrams pictured at the right side of Figure 5 occur when differences in specific weight of about 5 to 20 per mille are apparent.

We never could find any distortion of the diagrams as resulting from wind. Therefore we cannot accept the theory taught in German shools that the friction between air and water causes lower velocity at the surface than at some deeper layer.

It should be remarked that the curves pictured in Figures 3 and 4 are the averages of about 6 individual ones, taken in one point of the stream during 3 successive hours of the main ebb and main flood. The individual diagrams of the currents from top to bottom show more irregular forms, because of pulsations (turbulence), which increase or decrease the mean velocity by about 10 %. The rather regular diagrams shown in Figures 3 and 4 could also have been obtained by taking measurements for at least 3 or 4 minutes at several points in the vertical, but in tidal streams this takes too much time, especially when the depth is considerable.

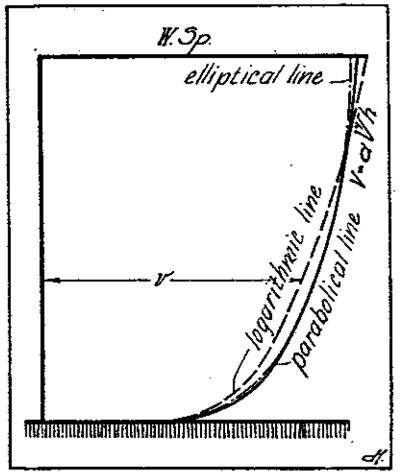

Fig. 6. Comparison of Jasmund's, van Rinsum's and van Veen's formulae.

In Figure 6, the formula of Jasmund,

$$V = A + B \,.\, \log(h + c) \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

and that of van Rinsum,

$$V = K_s \sqrt{Hi} + \mu \sqrt{(2Hh - h^2)\, i} \quad \ldots\ldots\ldots\ldots \quad (3)$$

are given graphically. Our Formula 1 is also shown, and it is seen that the three curves diverge little and that the simplest formula may be considered as possessing about the same exactness as those that are more complicated. Moreover, according to our experience, Jasmund's logarithmic line slopes too much near the surface, whereas van Rinsum's is too vertical there.

By means of the formula $V = a\sqrt[q]{h}$, we can determine the bottom, surface, and mean currents quite easily as soon as q and one single point of the vertical diagram are known. In this way the currents of the whole vertical can be learned from the data obtained with self-registering current-meters, working at one point only.

The advantage of the parabolic formula is its extremely simple integration. The mean velocity V_m is the $\frac{q}{q+1}$th part of the surface velocity V_s, and the area of the parabola is the $\frac{q}{q+1}$th part of the enveloping square. This is learned immediately by the integration:—

$$F = \int_0^H v\,dh = a\int_0^H h^{\frac{1}{q}}\,dh = \frac{q}{q+1}\,Hv_{\max}$$

The proportion

$$\gamma = \frac{q}{q+1} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

is here called the "bloc-coefficient" of the parabola, and is expressed in the following formulae:—

$$\gamma = \frac{v_m}{v_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

$$V_m = \gamma\, a . H^{\frac{1}{q}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

$$V_s = a . H^{\frac{1}{q}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

when H is the total depth.

When comparing the γ's for the vertical diagrams in a river, or in a sea, one comes to the conclusion that γ does not change much in a particular area, provided the flow is regular and the water homogeneous up to one per mille.

In 1875—1879 Rijkswaterstaat engineers constructed 532 diagrams relating to the Rhine-Maas branches, and from them $\gamma = 0{\cdot}875$ can be deduced, which gives for these rivers:—

$$V = a\sqrt[7]{h}$$

This coefficient $\gamma = 0{\cdot}875$ is the same as found by Ehrenberger (1924) in the Donau canal, by comparing V_m and V_s.

For sea-inlets in the North Sea along the Dutch coast, and for the Straits of Dover too, we obtain a parabola in the equation for which $q = 5{\cdot}3$. In these places with more or less homogeneous water, the "Oceaan" obtained data sufficient for about 1,000 vertical-diagrams. The γ's of those relating to the Straits of Dover (Dutch: "Hoofden") are given in the following table. Reference to Figure 16 will show to what positions the letters in the second column refer.

Date	Observing Point	Flood Stream Mean Depth in Metres	Flood Stream "Bloc-Coefficient" γ	Flood Stream Deviations from General Mean	Ebb Stream Mean Depth in Metres	Ebb Stream "Bloc-Coefficient" γ	Ebb Stream Deviations from General Mean
14—6 1934	K	49	0·83	0			
15—6 1934	N	20·4	0·85	+0·02	15·1	0·87	+0·04
18—6 1934	O_1	—	—	—	11·1	0·89	+0·06
21—6 1934	G	51·5	0·73*	—0·10	56·7	0·79*	—0·04
25—6 1934	D_1	36	0·84	+0·01	34·2	0·84	+0·01
26—6 1934	E_2	60	0·84	+0·01	54·1	0·84	+0·01
27—6 1934	B	30	0·85	+0·02	24·2	0·85	+0·02
28—6 1934	H	65	0·82	—0·01	53·5	0·82	—0·01
3—7 1934	O_2	24·4	0·80	—0·03	18·8	0·84	+0·01
20—7 1934	M_2	36·5	0·84	+0·01	31·8	0·85	+0·02
23—7 1934	E_1	51·7	0·86	+0·03	49·4	0·84	+0·01
24—7 1934	F	57·3	0·76*	—0·07	46·4	0·83	0
25—7 1934	Z	20·5	0·84	+0·01	14·7	0·82	—0·01
26—7 1934	—	—	—	—	—	—	—
28—7 1934	D_2	—	—	—	32·4	0·83	0
31—7 1934	M_1	39·4	0·85	+0·02	33·1	0·82	—0·01
1—8 1934	I	71·5	0·86	+0·03	59·4	0·81	—0·02
7—8 1934	C	31·9	0·84	+0·01	29·4	0·82	—0·01
9—8 1934	D_3	36·5	0·83	0	32·9	0·86	+0·03
10—8 1934	Y_2	32·0	0·86	+0·03	26·9	0·83	0
4—6 1935	V	44·6	0·86	+0·03	42·2	0·82	—0·01
19—7 1935	M_3	35·2	0·83	0	26·2	0·84	+0·01
22—7 1935	L	50·5	0·73*	—0·10	48·9	0·81*	—0·02
21—8 1935	P	$32{\cdot}7^{5}$	0·85	+0·02	29·1	0·84	+0·01
22—8 1935	A	$22{\cdot}7^{5}$	0·85	+0·02	20·4	0·83	0
23—8 1935	X	30·6	0·79	—0·04	$27{\cdot}7^{5}$	0·83	0
24—8 1935	Q	60·0	0·70*	—0·13	57·4	0·89*	+0·06
26—8 1935	Y_1	29·2	0·85	+0·02	25·1	0·80	—0·03
28—8 1935	R	27·5	0·84	+0·01	24·0	0·82	—0·01
29—8 1935	U_1	51·0	0·83	0	49·2	0·81	—0·02
30—8 1935	W	34·1	0·85	+0·02	$30{\cdot}2^{5}$	0·85	+0·02
2—9 1935	S	—	—	—	47·0	0·82	—0·01
3—9 1935	T	43·0	0·84	+0·01	37·9	0·83	0

Mean Values of γ: Flood 0·824 Ebb 0·834

The mean "bloc-coefficient" obtained from these data is 0·830, and investigation of the deviations from that mean yields a "root-mean-square" value (σ) of 0·043. The appropriate formula is

$$V = a\sqrt[4{\cdot}9]{h}$$

The standard deviation 0·043 is rather high when compared with other cases. For this good reasons exist, because the abnormal γ's always occurred at places where the bottom was very rocky and irregular (measuring points G, F, L, and Q: see Fig. 3). When these points[4]) are omitted, a much smaller σ value is obtained, namely, 0·006.

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[4]) Asterisked in the table.

Then γ becomes 0·838 and the parabola for the Straits of Dover becomes about the same as found for the sea-currents in all other places in the neighbourhood of the Dutch coast, namely,

$$V \quad a\sqrt[5\cdot2]{h}$$

In 1936, a series of 392 diagrams was prepared for point D, 5 miles off Dover. The bottom there was rather flat and about 35 metres below the mean surface level. The diagrams, which were averaged by taking groups of 5 or 6 for every ebb and for every flood, are shown in Fig. 4. The results are

$$\gamma = 0\cdot845, \qquad \sigma = 0\cdot0106, \qquad V = a\sqrt[5\cdot4]{h}$$

The relevant data are set out in the following table, in which σ_f and σ_e denote deviations from the mean for flood and ebb respectively, and wind strength is expressed in metres per second as observed onboard the surveying ship.

Day of June 1936	Flood γ	Ebb γ	σ_f	$\sigma_f^2 \times 10^{-6}$	σ_e	$\sigma_e^2 \times 10^{-6}$	Wind Direction and Strength
13	0·820	0·838	—0·025	625	—0·007	49	E. — 4
13	0·838	0·849	—0·007	49	+0·004	16	SW. — 11 to 13
14	0·860	0·832	+0·015	225	—0·013	169	SW. — 7 to 8
14	0·844	0·860	—0·001	1	+0·015	225	NW. — 6
15	0·850	0·847	+0·005	25	—0·002	4	SW. — 14
15		0·810			—0·035	1225	SW. — 14
16	0·850	0·831	+0·005	25	—0·014	196	SW. — 7
16	0·842	0·861	—0·003	9	+0·016	256	SW. — 8
17	0·840	0·830	—0·005	25	—0·015	225	SW. — 4
17/18	0·840	0·842	—0·005	25	—0·003	9	SE. — 6
18	0·850	0·845	+0·005	25	0	0	NW. — 4
18/19	0·841	0·847	—0·004	16	+0·002	4	SE. — 6
19	0·848	0·856	+0·003	9	+0·011	121	NE. — 4
19/20	0·842	0·838	—0·003	9	—0·007	49	E. — 5
20	0·849	0·844	+0·004	16	—0·001	1	NE. — 4
21	0·842	0·846	—0·003	9	+0·001	1	SE. — 3
21	0·851	0·851	+0·006	36	+0·006	36	SW. — 11
22	0·846	0·864	+0·001	1	+0·019	361	SW. — 5
22	0·830	0·848	—0·015	225	+0·003	9	SW. — 3
23	0·848	0·855	+0·003	9	+0·010	100	E. — 2
23	0·840	0·829	—0·005	25	—0·016	256	E. — 2
24	0·847	0·850	+0·002	4	+0·005	25	N. — 3
24	0·852	0·830	+0·007	49	—0·015	225	NE. — 4
25	0·854	0·850	+0·009	81	+0·005	25	NE. — 6
25	0·841	0·843	—0·004	16	—0·002	4	NE. — 5
26	0·855	0·872	+0·010	100	+0·027	729	N. — 3
26	0·839	0·845	—0·006	36	0	0	NE. — 2
27	0·841	0·852	—0·004	16	+0·007	49	Calm
27	0·830	0·849	—0·015	225	+0·004	16	Calm
28	0·841	0·868	—0·004	16	+0·023	529	SE. — 2
28	0·838	0·850	—0·007	49	+0·005	25	NE. — 4
29	0·848	0·850	+0·003	9	+0·005	25	N. — 4
29	0·830		—0·015	225			SW. — 2
Means and Sums	$\underbrace{0.843 \quad 0\cdot846}_{0\cdot845}$			2215		4964	

$$\sigma = \sqrt{\frac{0\cdot002215 + 0\cdot004964}{64}} = 0\cdot0106.$$

We generally take $q = 5\cdot3$ for homogeneous Dutch tidal waters. It follows that the mean velocity V_m according to Formula 6 occurs at a height of

$$0\cdot4 \ H$$

above the bottom, where H is the total depth.

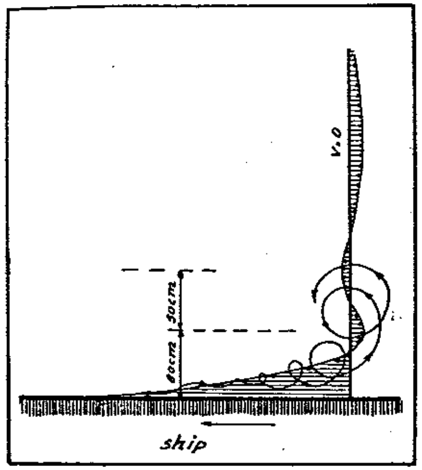

Fig. 7. Velocity distribution near to the side of a moving ship.

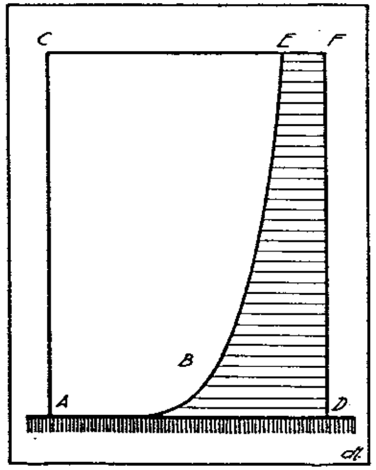

Fig. 8. Diagram showing how friction would limit the transmission of velocity upwards from a sea-floor supposed to be in motion.

It should be clear that high rocks or huge sand-waves on the bottom may disturb the regular distribution of the currents to some extent, while heterogeneous water may disturb it greatly.

Many writers suppose that there exists a so-called bottom-velocity V_b, and they draw the velocity diagram in such a way that it touches the bottom at a distance V_b from the zero of the figure. They therefore find a formula composed of two terms $V_b + V_h$, in which V_b is constant and V_h varies with the height above the bottom.

This is not in accordance with natural phenomena. Even if the bottom were quite flat and smooth the lowest layer of all would not move. The layer immediately above the lowest layer would have a small velocity, exceeded by that of the layer above it, and so on. There can be no sudden changes and the point of contact of the diagram with the bottom has to coincide with the zero of the figure. An analogous state of affairs can be noticed when looking over the side of a moving ship (Fig. 7). The internal friction of the water layers, and much more so the turbulence, cause the 2nd, 3rd, 4th, ... layers to be dragged in the direction of the moving ship. The greater the distance from the ship, the smaller is the force which causes the water to be dragged along with it.

In analogy with a moving ship we can imagine the sea-bed (or river-bed) moving with a constant velocity AD (Fig. 8) and the water at rest. The bottom would drag the water with it, the lowest layers more so than the higher ones.

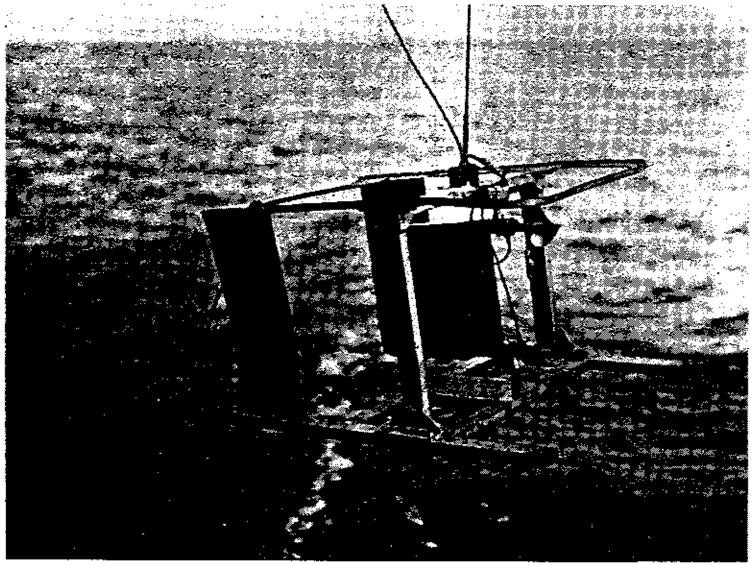

Fig. 9. Ott current-meter for measuring bottom-currents continuously.

The width of the shaded area at any depth would denote what proportion of the velocity was transmitted upwards to that depth. If we knew the imaginary velocity AD, we could calculate the shaded area, and so obtain a figure for the internal and external friction in the stream.

Periodic Changes in the Streams through the Straits of Dover.

From the 13th to the 31st June 1936, the "Oceaan" lay at a point 5 miles off Dover and measured the streams there from top to bottom during 16 successive days and nights. The position is referred to as point D, and its precise location was 51°4'30"N. Lat., 1°25'30"E. Long. Stream-verticals were obtained at every half-hour, and the streams at

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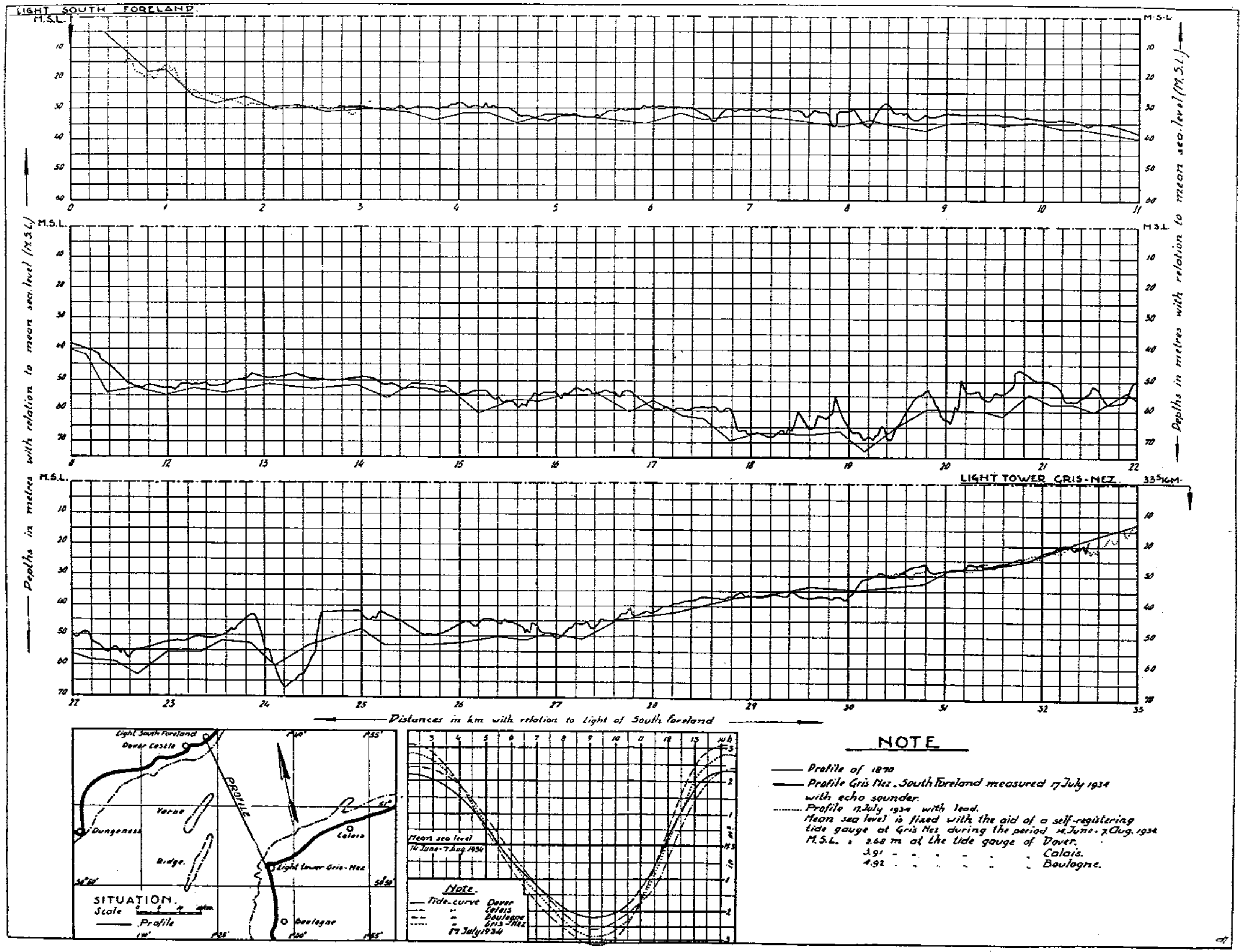

Fig. 10. Graph showing results of measurements for 16 days at point D off Dover.

10 m. depth and at 0·15 m. and 0·50 m. above the bottom were registered continuously. At the lowest levels the instrument shown in Fig. 9 was used.

The vertical tide was registered by the tide-gauge at Dover, and the mean amplitude during the period of observation was found to be 15·13 feet, which is about normal (15·2 feet).

The mean velocity at 10 m. below the surface was 31·2 kilometres per tide, or 69·6 cm. per second. It was 16·3 kilometres per mean total ebb and 14·9 kilometres per mean total flood. The mean ebb-current was 1·35 kilometres per tide larger than the mean flood-current.

The mean velocity from top to bottom (V_m) was lower, of course. It was 28 kilometres per tide or 62·7 cm. per second, composed of 14·7 kilometres per ebb tide and 13·3 kilometres per flood tide. A graph of the horizontal tide at 10 m. depth at D and of the vertical tide at Dover is given in Fig. 10. Spring tides occurred around 21st June 1936. There is a marked difference between day and night streams, but not during the period 17—19 June (just before New Moon). The exact data are given below.

At the beginning of the period strong south-westerly winds prevailed, and a marked flood-excess was measured during 14—15 June (see the lowest graph of Fig. 10). Later the winds were variable, and, in general, an ebb-excess occurred. The regular *daily periodical alternation of flood-excess and ebb-excess* is typical for the Straits of Dover. It is hardly perceptible in the Dutch tidal waters.

The atmospheric pressure did not change much during the fortnight, as is also shown in Fig. 10.

The analysis of the stream-curve (horizontal tide) for the period 14—28 June 1936 at D and of the tidal curve at Dover (vertical tide) for the same period gave the following results:—

Horizontal Tide at Dover (10 m. below surface)				Vertical Tide at Dover	
Tide	Period	Kappa	Amplitude	Kappa	Amplitude
M_2	12·4 h.	10°	109 cm./sec.	337°	237 cm.
S_2	12·0 h.	63°	26 cm./sec.	33°	55 cm.
M_4	6·2 h.	292°	9·6 cm./sec.	235°	30 cm.
O	25·8 h.	32°	12·7 cm./sec.	184°	9·1 cm.
K_2	11·97 h.	63°	6·8 cm./sec.	33°	14 cm.
K_1	23·93 h.	178°	10·1 cm./sec.	13°	6·4 cm.
P	24·07 h.	178°	5 cm./sec.	13°	3·2 cm.

It should be noted that as regards the daily period, the vertical tides are "out of step" with the horizontal tides (see Figure 10). The amplitude of 109 cm./sec. means the highest ebb and flood velocity of the horizontal M_2 tide, etc.

The stream-rose at normal tide for D is given in Fig. 11. The fastest mean ebb-stream at D at the depth of 10 m. was found to be 110 cm. per second, and the fastest mean flood-stream at the same depth, 107 cm. per second (mean figures of all measured tides).

Observations at Point D (51°04′30″ N., 1°25′30″ E.), 5 miles off Dover, during the period 13th to 29th June 1936. Stream speeds at 10 metres depth are given in cm./sec. on the left, and directions (degrees from North through East) on the right. Data are presented for full lunar hours after Dover H.W.

Hour after Dover H.W. / Time	0 H.W. Dover		1		2		3		4		5		6		7		8		9		10		11	
13. 6. 1936 5ʰ15′.	—	—	108	55°	90	52°	59	63°	15	93°	37	207°	88	215°	108	225°	129	225°	116	225°	66	215°	3	270°
	49	43°	89	50°	86	50°	69	60°	35	68°	3	148°	30	222°	75	220°	84	220°	57	223°	7	290°	57	45°
	97	53°	111	49°	84	53°	55	65°	16	70°	30	205°	80	224°	110	225°	123	220°	110	225°	57	239°	14	322°
	76	50°	92	53°	94	60°	77	56°	47	62°	9	80°	21	250°	46	175°	56	242°	41	225°	18	68°	81	51°
	108	50°	113	50°	101	51°	62	67°	21	70°	19	145°	83	243°	116	225°	127	221°	108	240°	55	245°	25	36°
	83	47°	112	54°	108	54°	84	65°	34	64°	6	113°	54	215°	87	221°	99	227°	83	230°	17	240°	57	41°
	108	50°	117	50°	102	52°	67	77°	27	55°	16	205°	83	240°	101	225°	120	229°	100	230°	45	240°	28	37°
	85	50°	111	50°	104	51°	70	50°	34	60°	14	181°	71	230°	100	228°	113	230°	94	230°	33	235°	51	45°
	106	50°	121	52°	106	52°	72	55°	30	61°	15	230°	80	215°	111	229°	120	225°	109	227°	51	235°	35	50°
	96	46°	114	50°	108	58°	81	57°	30	48°	26	204°	83	220°	111	231°	125	226°	119	232°	62	232°	32	110°
	97	45°	120	50°	121	55°	68	57°	28	187°	25	223°	82	231°	114	225°	128	225°	119	227°	59	230°	33	60°
	101	50°	126	55°	112	51°	70	50°	21	80°	34	225°	88	221°	120	230°	140	230°	139	230°	76	230°	10	73°
	92	54°	125	50°	118	50°	81	60°	32	84°	9	171°	72	225°	109	230°	125	230°	116	230°	48	242°	49	45°
	115	52°	139	51°	119	55°	79	55°	30	65°	28	210°	90	230°	122	232°	147	230°	142	225°	85	235°	8	350°
	94	50°	124	52°	120	53°	83	60°	37	75°	11	180°	75	216°	108	228°	125	228°	115	230°	39	235°	65	48°
	124	45°	145	50°	122	50°	75	57°	25	68°	33	217°	88	230°	125	228°	149	226°	148	230°	82	230°	0	—
	86	48°	124	54°	118	53°	80	54°	36	60°	9	125°	54	210°	110	216°	116	228°	99	230°	31	238°	74	42°
	120	45°	131	50°	115	51°	71	52°	30	60°	25	210°	87	227°	122	228°	141	230°	139	230°	82	235°	—	—
	79	50°	119	42°	110	53°	81	50°	40	65°	10	168°	60	245°	95	225°	106	225°	77	232°	16	257°	71	43°
	134	53°	142	59°	116	60°	68	50°	20	80°	35	208°	96	216°	129	228°	135	230°	138	230°	83	238°	—	—
	60	36°	109	45°	105	50°	77	55°	30	60°	12	300°	57	218°	84	225°	99	225°	81	225°	23	264°	60	41°
	120	50°	128	50°	106	50°	60	47°	12	84°	28	219°	80	211°	112	230°	138	225°	132	230°	86	225°	—	—
	54	60°	94	57°	90	50°	68	60°	27	56°	8	175°	48	195°	81	219°	93	225°	74	227°	18	236°	57	48°
	104	46°	120	50°	96	55°	55	51°	8	65°	25	207°	78	221°	109	220°	129	225°	133	225°	86	225°	28	228°
	26	45°	78	46°	81	50°	54	50°	21	15°	12	195°	52	215°	82	225°	87	220°	67	220°	—	—	49	72°
	94	46°	100	50°	88	59°	47	50°	4	69°	32	220°	75	218°	99	220°	114	225°	110	225°	69	225°	15	239°
	38	44°	68	65°	69	55°	51	55°	22	62°	—	—	37	200°	64	225°	69	225°	48	227°	14	226°	32	45°
	75	54°	82	53°	66	50°	32	50°	0	—	35	218°	75	225°	94	220°	99	225°	90	225°	47	228°	—	—
	32	46°	61	50°	65	55°	39	55°	21	62°	10	183°	43	216°	62	224°	67	224°	47	231°	—	—	29	65°
	66	45°	72	52°	59	55°	29	60°	0	—	32	215°	64	215°	79	218°	82	223°	66	225°	44	221°	0	—
	29	65°	59	48°	60	45°	42	56°	18	70°	9	170°	43	212°	53	225°	52	215°	43	232°	—	—	45	65°
29. 6. 1936 19ʰ28′.	68	50°	62	58°	48	53°	32	53°	7	134°	41	194°	71	224°	81	216°	77	225°	62	230°	32	230°	8	30°
Means	83	49°	106	52°	97	53°	63	57°	23	68°	18	207°	67	222°	97	224°	110	226°	97	229°	48	232°	33	49°

Reduction Graphs.

There exists a general empirical relation between the horizontal tide and the vertical tide. At spring tides the amplitude at Dover is much higher than at neap tides and correspondingly the streams at springs are much stronger than those at neaps.

When we put this relation down graphically, we obtain, as in Fig. 12, a "cloud" of points through which we can draw a straight line. The angle α of this line with the horizontal axis can be calculated according to the theory of correlation by using the formulae

$$\sigma_1 = \sqrt{\frac{\Sigma x_1^2}{n}}, \qquad \sigma_2 = \sqrt{\frac{\Sigma x_2^2}{n}}$$

$$r = \frac{\Sigma x_1 x_2}{n \cdot \sigma_1 \sigma_2}, \qquad \alpha = -r \frac{\sigma_1}{\sigma_2}$$

We then obtain the following reduction table, which is the same for both ebb and flood:—

Amplitude in feet at Dover	Amplitude in % of Average	Reduction-Factor for the Streams	Amplitude in feet at Dover	Amplitude in % of Average	Reduction-Factor for the Streams
7·6	50	35	Mean 15·2	100	100
8·4	55	42	16·0	105	106
9·1	60	48	16·7	110	113
9·9	65	54	17·5	115	120
10·6	70	61	18·2	120	126
11·4	75	68	19·0	125	132
12·2	80	74	19·8	130	139
12·9	85	80	20·5	135	146
13·7	90	87	21·3	140	152
14·4	95	94	22·0	145	158
Mean 15·2	100	100	22·8	150	165

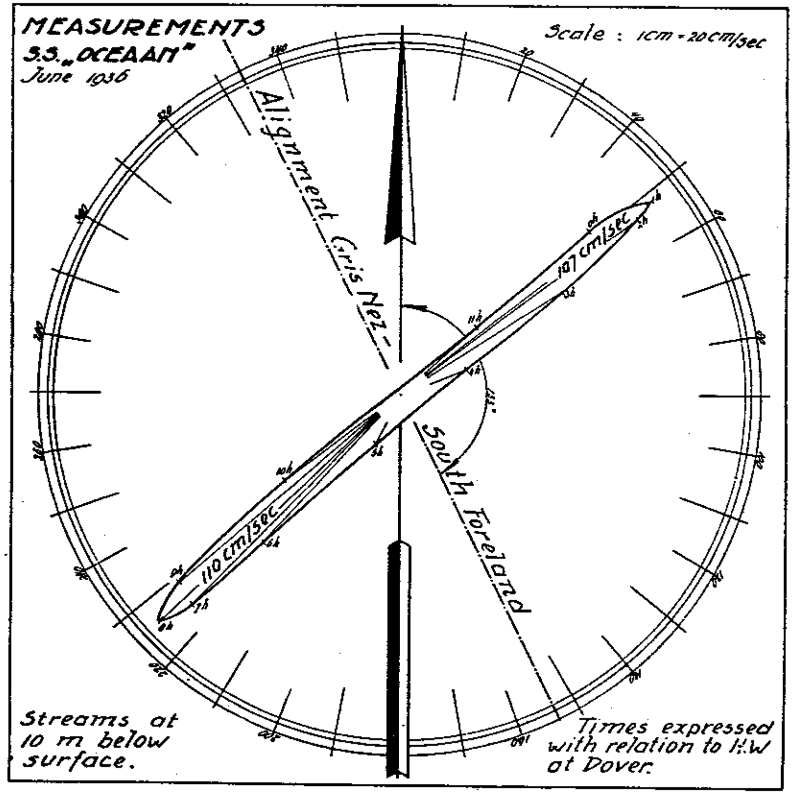

Fig. 11. Stream-rose for point D embracing the results of observations throughout 32 successive tides.

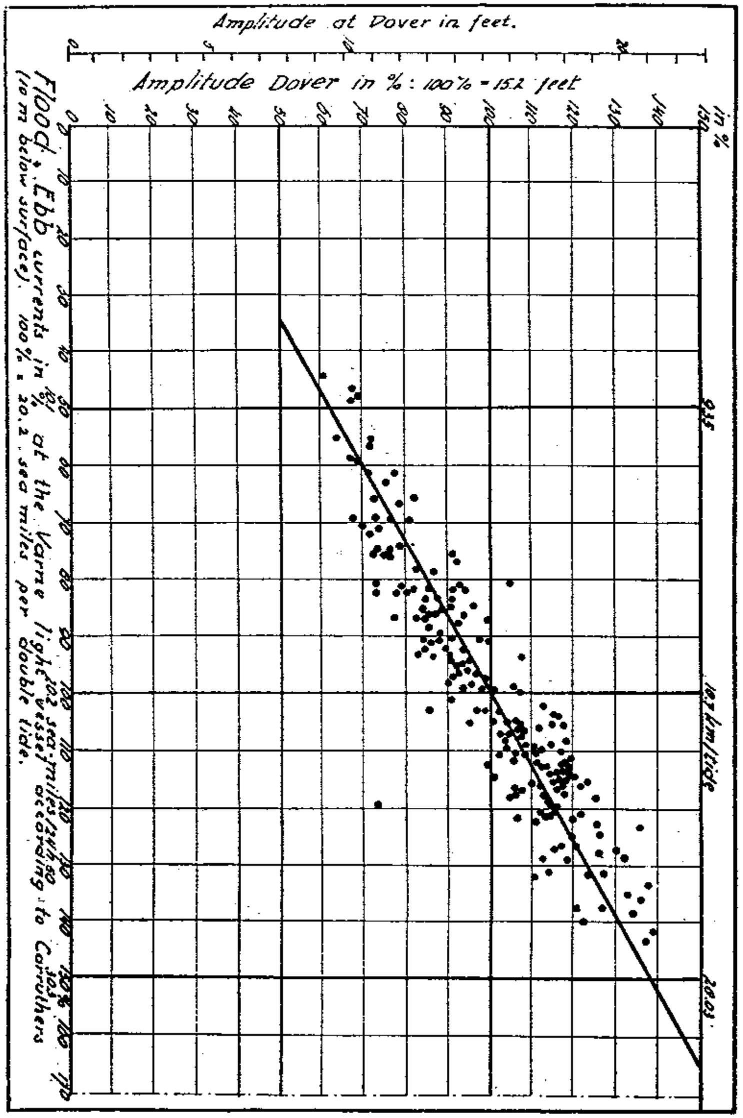

Fig. 12. Reduction graph portraying the relation between vertical and horizontal tide in the Straits of Dover.

We calculated this table from our measurement data of 1934—35, and for those of 1936 separately, and found exactly the same result for both. We also used Dr. Carruthers's measurements at the Varne[5]) and Sandettié lightvessels. All these calculations gave the same result, so that the table given above can be used with confidence for the streams in the area of the Straits of Dover.

It is interesting to add that this relation between the vertical tide and horizontal tide changes regularly towards the north in such a way that for Terschellingerbank the graph slopes quite differently, so that quite another reduction table results.

The use of the reduction table is that when any horizontal tide is measured, the streams during normal or spring or neap tides can be obtained immediately with a fair approximation.

Total Flow.

On 17th July 1935 we took echo-soundings in the alignment of the South Foreland and Gris Nez lights. At Gris Nez, light signals were given by which the "Oceaan" could be kept at distances less than 30 metres from the alignment. This was made possible by the use of a powerful mirror at Gris Nez belonging to the French Navy. This was rigidly fixed to shine in the direction of the lighthouse on the South Foreland, and, of course, the breadth of the "Oceaan" was known. When the ship was too much south short signals were sent out, and when she was too far north long signals were emitted, whilst an uninterrupted beam was shown when she was in position on the line. The soundings were made about 7 times per second, or thrice for every metre of depth. The entire operations lasted about 3 hours, and the results on a very small scale are given in Fig. 13.

The sea-levels were measured at Gris Nez and Dover. At the former place tide-manometers were used during several fortnights, while at Dover the well-known registering apparatus was employed. Assuming that the mean sea-levels for Boulogne, Calais, Gris Nez, and Dover were at the same height, we calculated for the period 14th June—5th August 1934 the zeros of the tide gauges.

At Dover zero was 2·68 m. below M.S.L.
„ Calais „ 3·91 m. „ „
„ Boulogne „ 4·92 m. „ „

Mean sea-level is not, of course, half-way between high- and low-water levels, but is the level above which the area of the tidal curve is as big as it is below.

The total area of the profile Gris Nez—South Foreland was found to be 1,366,400 square metres at mean sea-level.

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[5]) J. N. Carruthers. "The flow of water through the Straits of Dover as gauged by continuous current-meter observations at the Varne lightvessel." Fish. Inv. Series, Vol. XI, 1 and XIV, 4, London 1928 and 1935.

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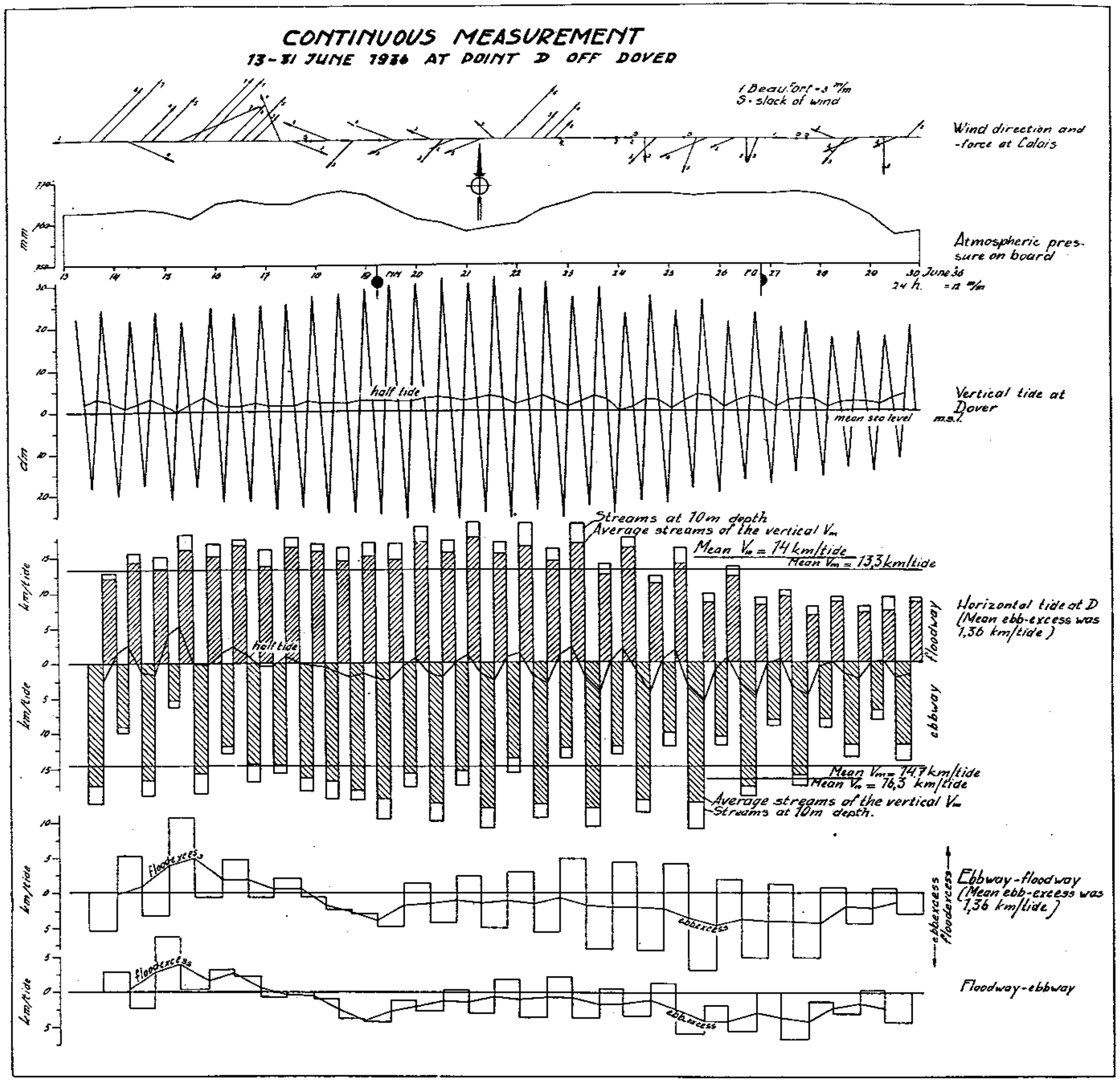

Fig. 13. Bathymetric section along the line Gris Nez—South Foreland from echo-soundings.

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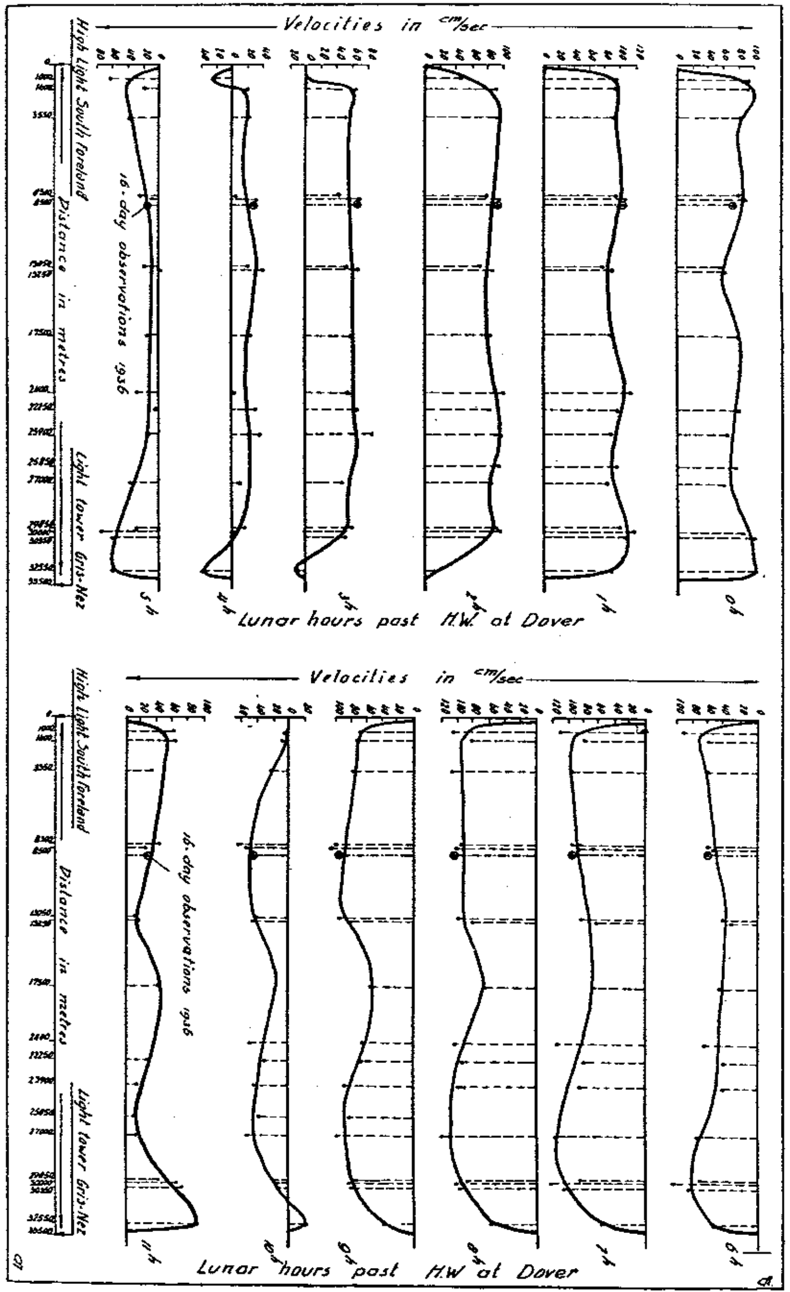


Fig. 14. Velocities (normal components) along the South Foreland—Gris Nez line from hour to hour.

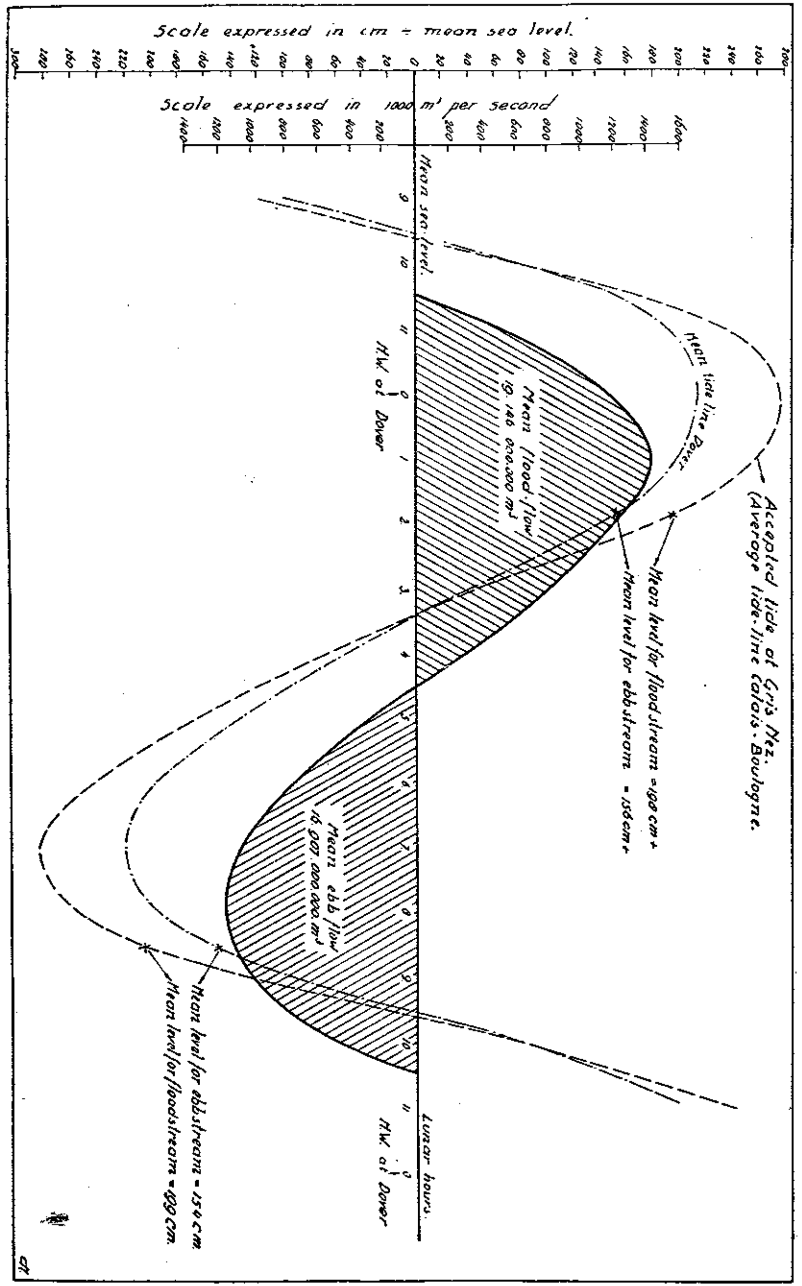


Fig. 15. Graphs showing mean vertical tide at Dover and mean total horizontal tide in the profile Gris Nez—South Foreland.

This profile (see Fig. 13) was divided into several parts by means of vertical lines. Further, the streams which were measured in 18 different places in this alignment during 18 different tides were reduced to normal conditions by means of the reduction table. The directions of the streams not being quite at right-angles to the line of soundings, appropriate velocity components were taken into account. They are indicated in Fig. 14, the broken lines drawn in at the dots denoting the velocities in the profile from hour to hour as averaged for the whole column of water. By multiplying the different profile areas by the appropriate mean velocities, and so taking into account that the water-level changes continually, the total flow for every half-hour can be calculated and put down graphically (Fig. 15).

It is found that there is a water transport of 19,146,000,000 cubic metres per normal flood tide, and of 16,907,000,000 cubic metres per normal ebb tide. This gives a north-east-going drift of 2,239,000,000 cubic metres per tidal period which amount might be considered as more or less "normal".

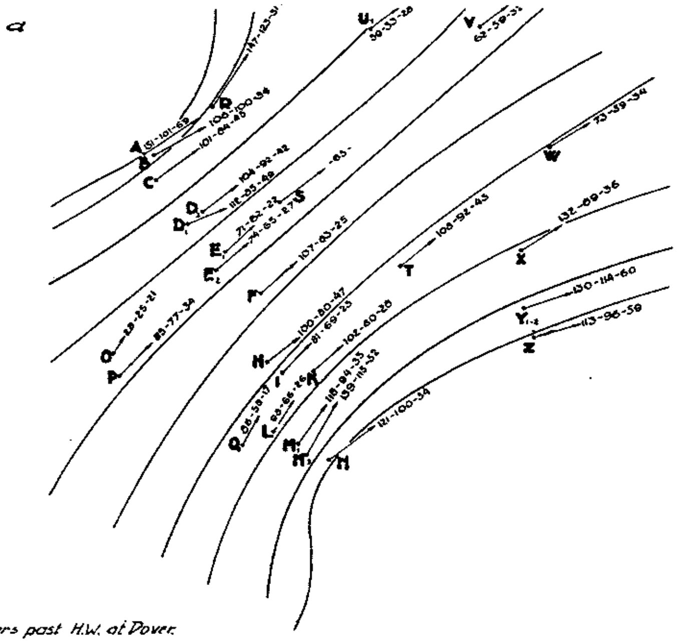
In Fig. 14 we have also indicated the mean velocities at point D from hour to hour as found during 32 successive tides in 1936. It is seen that the velocity lines obtained from the reduced single-tide measurements of 1934/35 coincide fairly well with them.

Twelve charts are presented which show the speed and direction of the streams in the Straits at Dover High Water and at intervals of 1^{h}02 (lunar hours) from that important reference time. The speeds entered are in cm./sec. and can readily be converted into knots on multiplying by 0·02. It should be noted that the phases of the streams near the shore are in advance of those in the middle of the Strait.

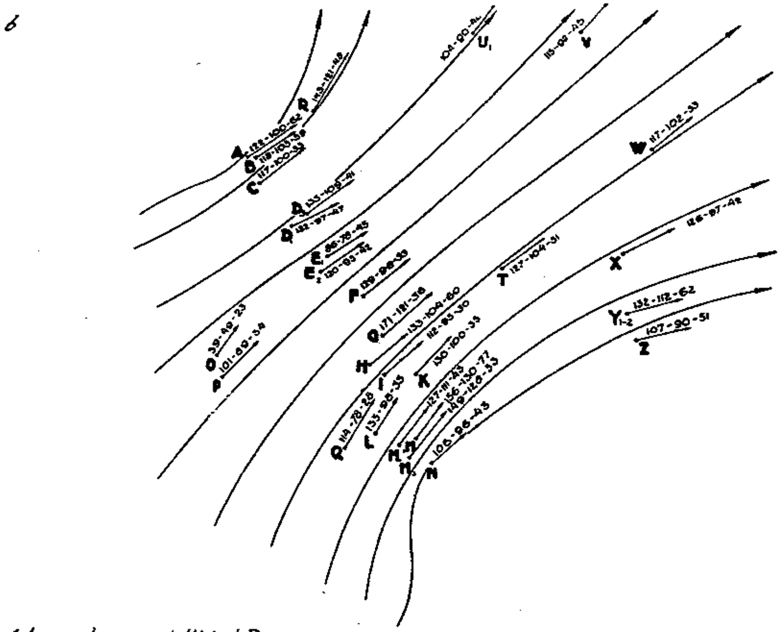
The total Drift through the Straits of Dover.

From the Fisheries Laboratory at Lowestoft, Carruthers has published data relating to the flow of water past the Varne lightvessel at the depth of 6 fathoms (very nearly 10 metres) over a term of years. His data for a 5-year period, when converted into our units, imply a drift towards the North Sea of 3,670,000,000 cubic metres per tidal period. His published figures for total water transport depend, however, on the assumption that the flow at all points in the profile is the same as at 10 m. depth at the Varne.

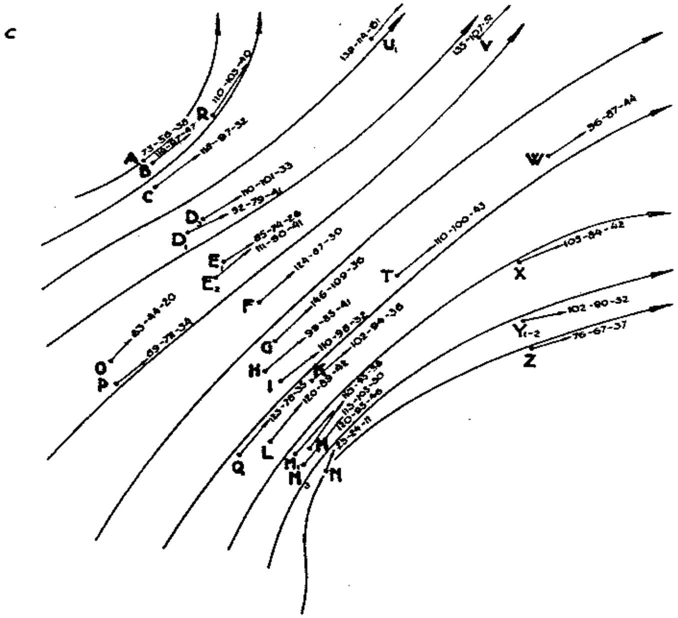
Compared with our corresponding value of 2,239,000,000, Carruthers's figure is about 65 % higher, and in this connexion it should be mentioned that Carruthers took the average cross-section area of the Straits to be 1·204 square kilometres. Our line of soundings gave the profile area as 1·41 square kilometres on the average during the flood, and 1·29 square kilometres on the average during the ebb. If Carruthers's rate of flow were applied to the mean of these two figures, his total transport value would, of course, exceed ours still more.



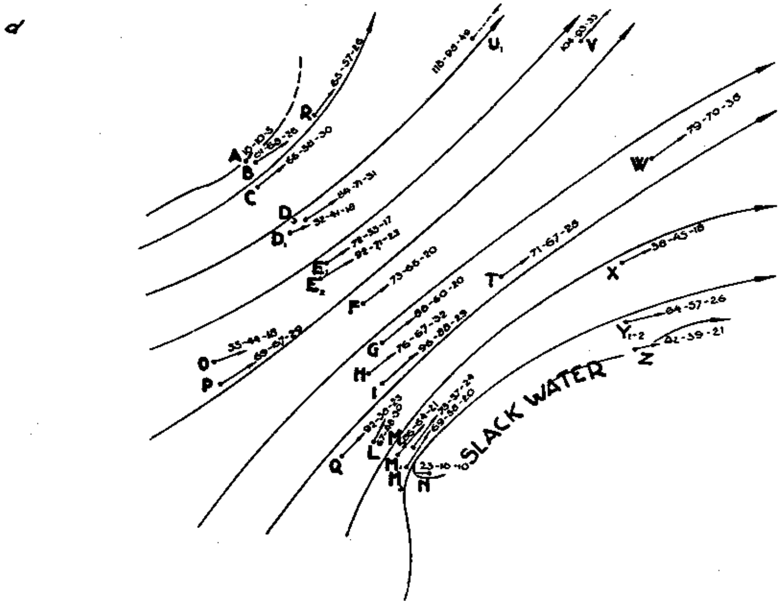
0 Lunar hours past H.W. at Dover.



1 Lunar hour past H.W. at Dover.

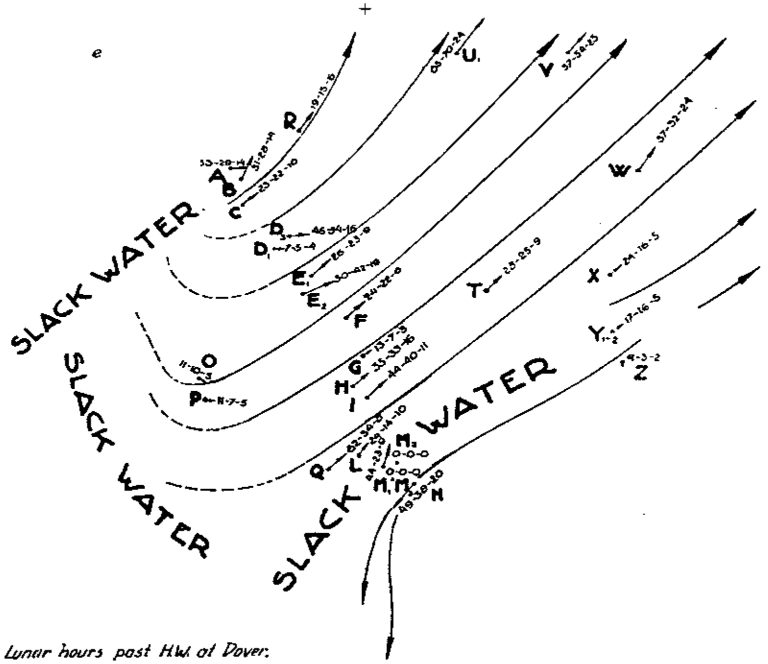


2 Lunar hours past H.W. at Dover.



3 Lunar hours past H.W. at Dover.

e



4 Lunar hours past H.W. at Dover.

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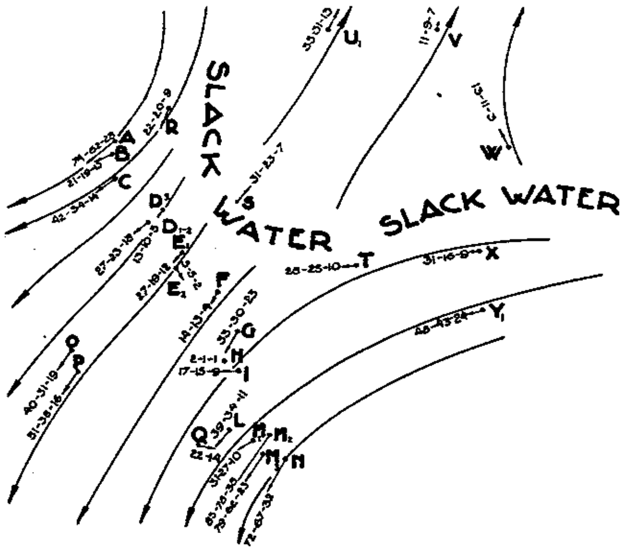

5 Lunar hours past H.W. at Dover.

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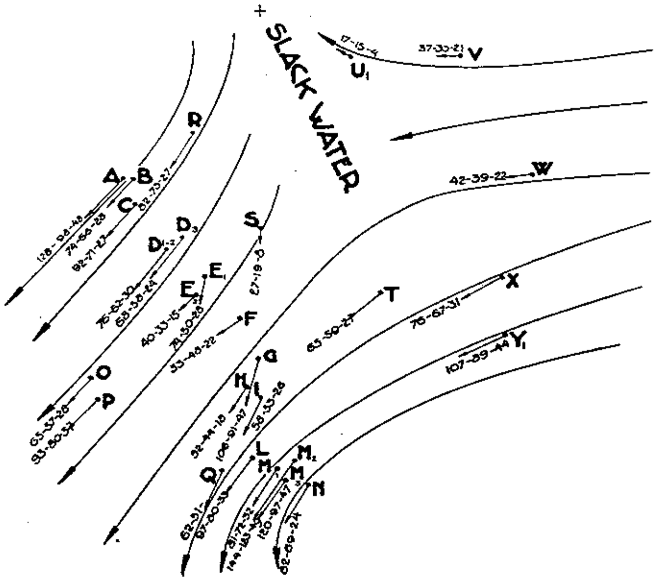
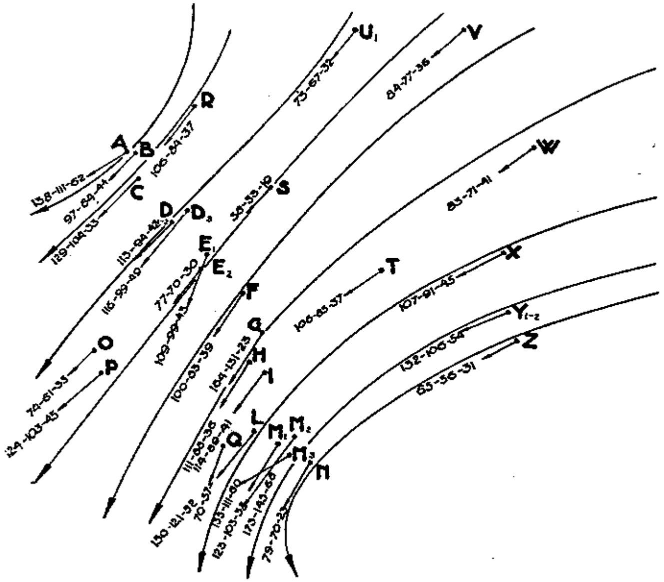


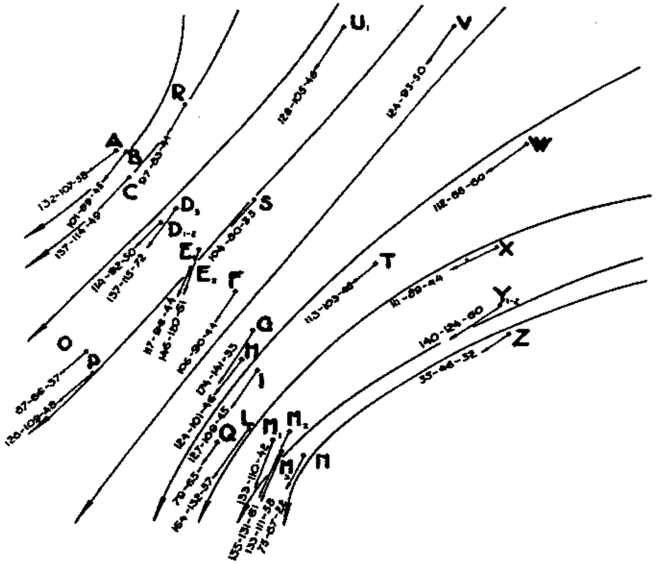
6 Lunar hours past H.W. at Dover.

h



7 Lunar hours past H.W. at Dover.

i



8 Lunar hours past H.W. at Dover

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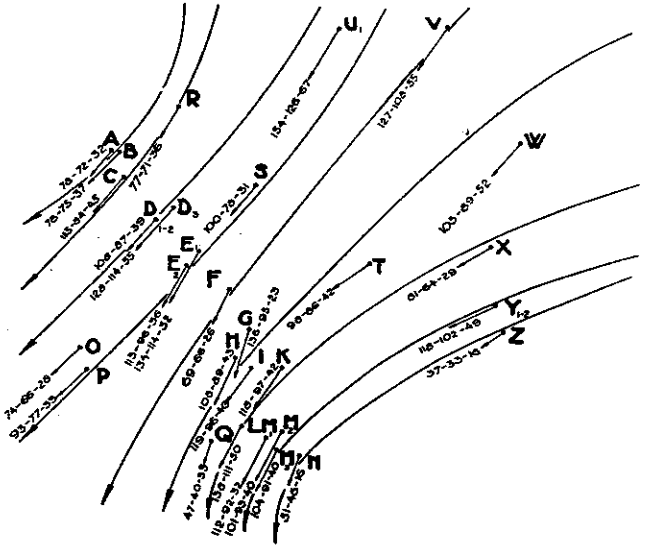

9 Lunar hours past H.W. at Dover.

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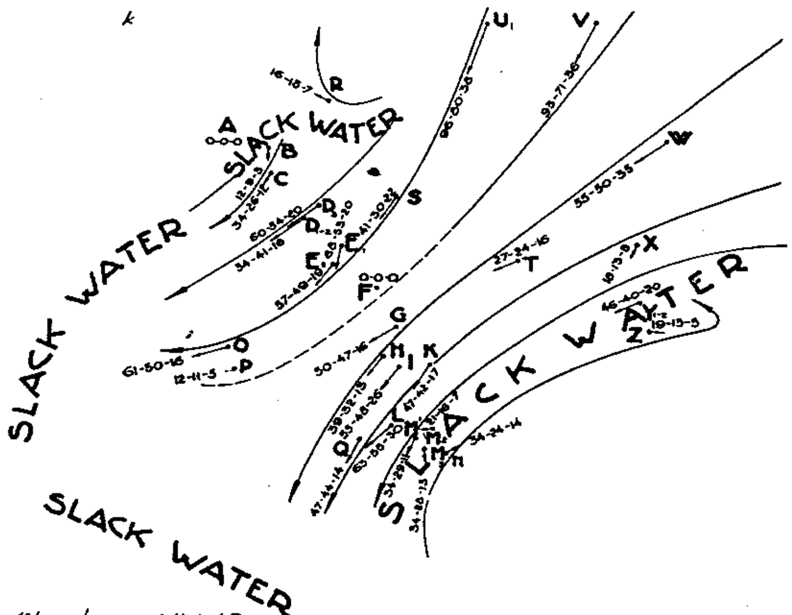
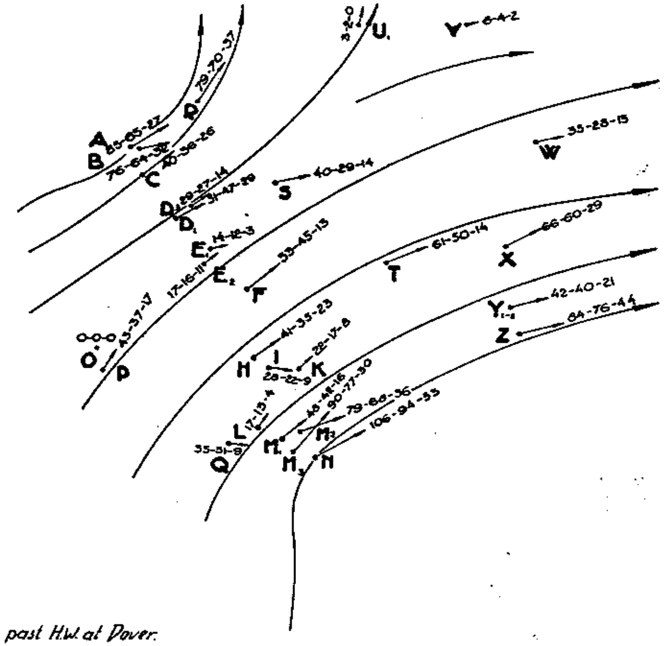


10 Lunar hours past H.W. at Dover.

l



11 Lunar hours past H.W. at Dover.

It is noteworthy that we found the mean ebb-streams for the whole width to be faster than the mean flood-streams for the whole width whenever we measured under normal conditions. Only when the wind was blowing strongly from the south-west was a faster mean flood velocity found. The resulting drift (when expressed in terms of volume), which we found to be in the flood direction, was not due to velocity differences, but to profile-area differences. The average area of the profile South Foreland—Gris Nez is, during the flood-stream 8½ % larger than during the ebb-stream (see Fig. 15) and this must be one of the main reasons why a north-east-going drift exists in the Straits of Dover. According to our measurements the mean tidal streams are more or less in equilibrium when velocities only are concerned, except when storms (wind-effect or atmospheric pressure) cause disturbances.

Moreover, during the 16 days of continuous measurement in June 1936 at point D, the residual current was 1·35 kilometres per tide in the ebb-direction. This means that the mean V_m for flood was again lower than the mean V_m for ebb, V_m being the mean velocity of the whole water column. The total flood flow at D (in cubic metres) was, however, larger than the total ebb flow there, because the depths changed with the tides. Reckoning per kilometre width at point D, there was a transport of 428,000,000 cubic metres of water per flood tide and of 410,000,000 cubic metres per ebb tide.

Carruthers found the following relation for the drift in the four seasons:—

Spring: summer: autumn: winter = 77·8: 83·3: 100: 88·9. Therefore in autumn a larger amount of Atlantic water comes to the North Sea through the Straits of Dover than in the other seasons of the year. In consideration of these figures, 12½ % should be added to our measurement of the drift in order to obtain the annual average.

Without doubt the drift changes much according to different atmospheric pressures, or tidal circumstances, and I would not say that on repetition we should not find a greater volume of Atlantic water passing through the Straits of Dover owing to stronger flood-currents. At times the mean flood velocities may be stronger than the mean ebb velocities.

Consideration of Information from Drift-Bottle Experiments.

In the foregoing article we have set down the results of careful observations made with reliable instruments from a well-equipped ship. We have found the mean ebb-streams to be faster than the mean flood-streams to an extent that would imply a total water transport towards the English Channel, were it not for the consideration of changing depth with state of tide. Obviously, on occasions when drift-bottles pass through the Straits towards and into the North Sea, the flood-streams must be the stronger, at least at one part of the profile. It would be possible to show on reference to the results of drift-bottle experiments carried out by Carruthers, of the Lowestoft Fisheries Laboratory, that in almost every week of two recent years, properly ballasted surface-floating bottles journeyed through the Straits from the Channel. They did so even whilst the observations reported upon above were in progress. We cannot possibly doubt that these drift-bottles indicated the drift rightly. An explanation is obtained on looking at Fig. 17. It is there seen that in the central part of the

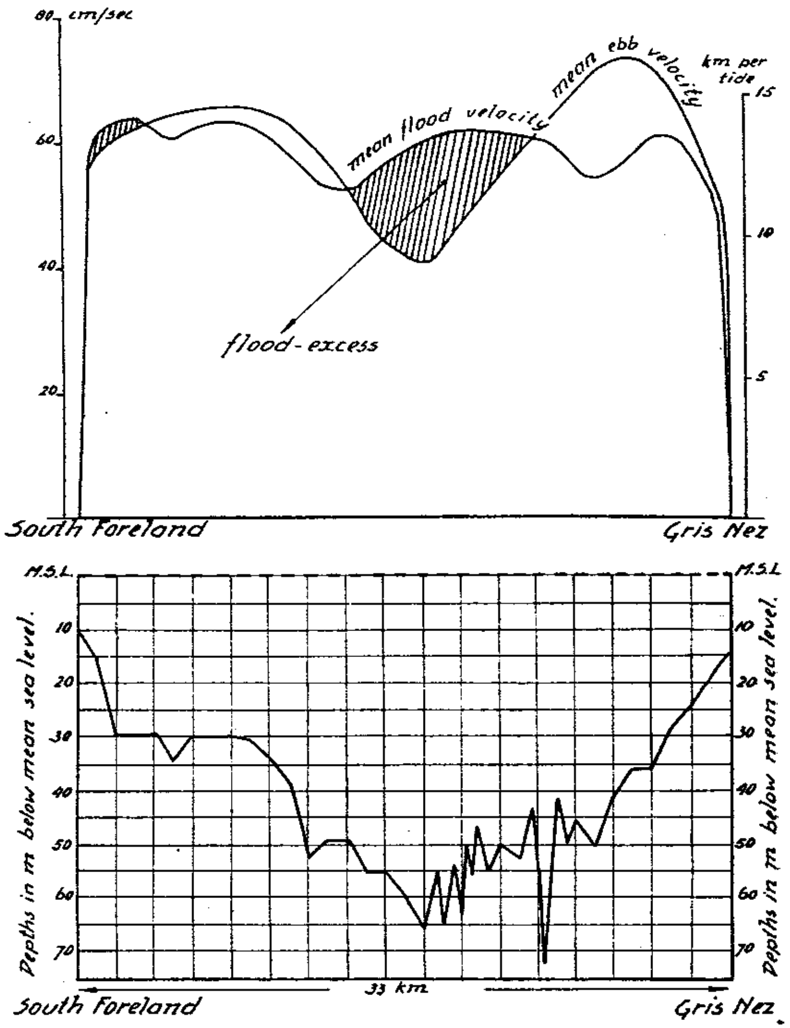


Fig. 17. Graph showing up-Channel and down-Channel drifts in the profile Gris Nez—South Foreland.

Straits of Dover the mean speed of the streams during the whole flood can exceed that during the whole ebb by as much as 20 cm./sec.; elsewhere there is an ebb excess. The figure refers to an aveage tide.

It is significant that the flood excess is in the central deep-water channel where we might expect the momentum of the flowing tide to be strongest. We are consequently inclined to assume that the drift-bottles of the Lowestoft Laboratory passed through the Straits more or less along the middle.

It would be interesting to organize another 16-day period of measurements at some point in the deep-water channel in order to confirm this explanation.

It should be added here that we know the Varne Bank to be composed of loose sand, and that very little change indeed has taken place there since 1848. This is in keeping with the results of our observations upon water movements as shown in Fig. 17.

In conclusion, I wish to express my thanks to Dr. J. N. Carruthers for checking the English of this paper.

Measurement of Submarine Daylight.

By

W. R. G. Atkins, G. L. Clarke, H. Pettersson, H. H. Poole, C. L. Utterback and A. Ångström.

Introductory.

OWING to the interest inherent in submarine light-measurements both to physical oceanography and to biology, the International Council for the Exploration of the Sea at its annual meeting in Copenhagen in 1935 decided to hold a special conference for the discussion of submarine light at its next meeting with a view to including such measurements in its future programme.

In order to have this subject thoroughly discussed, the Council extended invitations to Drs. W. R. G. Atkins and F. S. Russell, of Plymouth, G. Clarke, of Woods Hole, U. S. A., H. H. Poole, of Dublin, C. L. Utterback, of Seattle, and A. Ångström, of Stockholm, to attend the meeting and read papers. With the exception of Dr. Atkins, who was unable to attend, all the above-mentioned experts accepted the invitation, and at the meeting on 13th May 1936 the following papers were read:—

F. S. Russell: "Submarine Illumination in Relation to Animal Life";

H. H. Poole: "The Photo-electric Measurement of Submarine Illumination in Off-shore Waters";

G. Clarke: "Light Penetration in the Western North Atlantic and its Application to Biological Problems";

C. L. Utterback: "Spectral Bands of Submarine Solar Radiation in the North Pacific and Adjacent Inshore Waters";

A. Ångström: "On the Unit for Radiation in Oceanic Research".

In addition, Dr. Hans Pettersson, of Göteborg, read a paper on "The Transparency of Sea Water".

In the discussion after the papers had been read a number of hydrographers and biologists emphasized the importance of submarine light-measurements and the following recommendations were carried unanimously:—