THERMOMETRIC MEASUREMENT OF DEPTH

by

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From the technical point of view, the problem of deep-sea sounding seems nowadays to have been solved to the last detail, thanks to the development of methods of sounding by wire and the perfection attained in methods of echo-sounding. But with respect to the sources of error in soundings as measured by wire and as observed by echo, *i. e.* the question of reducing the measured depth to the true depth, we are still only at the point where we started. To anyone with personal experience of the continually changing external conditions of deep-sea sounding (sea, current, angle of wire, drift, etc.) it is obvious that the question of the sources of error cannot be solved by theoretical considerations, and that a conclusive representation of their values can only be obtained by means of observations. In this connection it is of very great value to take strictly simultaneous soundings by wire and by echo at the same position of the ship, as was done, for example, at 322 stations during the *Meteor* Expedition. But no less important is the checking of the two soundings by a third indirect method of sounding, independent of the first two. It is well known that the practical needs of navigation, *viz.* to be able to obtain depth data with the ship steaming at full speed, have led to the discovery of a whole collection of appliances for the indirect measurement of depths, mainly based on the principle of measuring the pressure; but either they are capable of use up to 200 m. only, or they give approximate values only at great depths.

The fact that, as a result of experience of the thermometric method of depth measurement gained by the German Atlantic Expedition in the hydrographic and exploring vessel *Meteor*, we possess an indirect method of sounding which enables us to sound with sufficient accuracy at any depth up to 6,000 m., is thus of importance. In the course of this expedition the method was employed regularly for serial oceanographic measurements, and worked extremely well. At the author's instigation the method was employed more often, even with soundings by wire, during the latter stages of the expedition (Profiles X to XIV) in tropical waters. After all these trials there was no longer any doubt that the thermometric method of depth measurement is a valuable auxiliary for finding the true depth when sounding by wire, and at the same time for determining the sources of error in the depth by wire (due to the slope of the wire) and in the depth by echo (due to the reduction).

Reverting to the detailed explanations given by the author in Vol. IV of the *Meteor* reports (1932), the following is a summary of the thermometric method of depth measurement and the results obtained thereby during the *Meteor* expedition. To this have been added the principal results of a study of the mean relationship between depth by wire and true depth for different angles of wire, as obtained with regard to both the serial oceanographic measurements and the soundings by wire of the *Meteor* expedition.

I. *THERMOMETRIC METHOD OF DEPTH MEASUREMENT.*

1. *Historical Notes.*

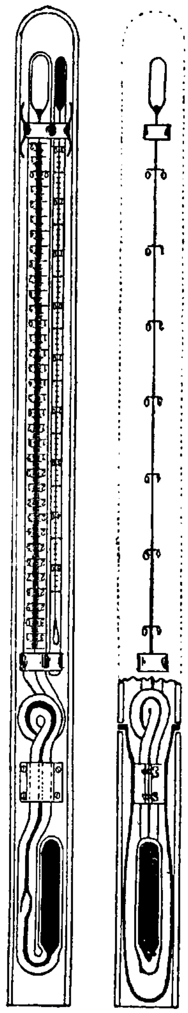
The thermometric method of depth measurement did not originate, like most other methods of sounding, from the needs of marine surveying or practical navigation, but is an outcome of the efforts made in scientific exploration of the sea to check the depth of reversal of reversing thermometers and of instruments for taking samples of sea water, in order to obtain the high order of accuracy required in the measurement of temperature and observation of salinity in the ocean deeps ($\pm$ 0.01°C and $\pm$ 0.02 ‰ respectively). While in exploring the sea we have always attempted, by manœuvring the ship, to keep the angle of departure of the wire as small as possible in serial measurements of temperature and salinity, we have also taken more and more into account the fact that at times, through the drifting of instruments (e. g. in waters with strong currents), appreciable variations in temperature and salinity readings may arise from the fact that too great a depth is attributed to the measurements, namely the depth by wire (= length of wire run out). But owing to the lack of systematic research into the relationship between angle of wire and true depth, we have hitherto had to neglect this source of error completely in the exploration of the sea; and we have as a rule taken the length of wire run out as read from the counter, *i. e.* the *Solltiefe* or depth by wire, as being equal to the measured depth: in other words,

length of wire or *Solltiefe* (assumed depth) = true depth. $D = W$.

Isolated trials for checking the measured depth have been undertaken since 1906. They were based on the idea first propounded by RUPPIN (1906), of using simultaneously a reversing thermometer protected against pressure and alongside it a reversing thermometer not protected against pressure; and of obtaining, from the difference in level of the columns of mercury in the two instruments, a measure of the depth at which the reversing frame or the sampling bottle had reversed. Research on a vast scale, extending over the column of water comprised between 10 and 1,500 m. depth, was undertaken by BRENNECKE (1921), using this method, during the outward passage of the *Deutschland* in 1911/12; without however using the results obtained for correcting the serial measurements. A. SCHUMACHER (1923), on the other hand, developed the fundamental mathematical principles of this method in the form of an exact formula of correction, and of "auxiliary tables for the reversing thermometer with open protecting tube", and dealt also theoretically with the question of the accuracy of the thermometric method of depth measurement.

2. *Open unprotected reversing Thermometers of the German Atlantic Expedition.*

Armed with the experience acquired, A. MERZ, when the German Atlantic Expedition was in preparation, entrusted the firm of RICHTER & WIESE with the construction of some unprotected reversing thermometers usable to a depth of 6,000 m. (3,280 fms.) with several new improvements on the models previously used (scale polished to a plane, visible point of rupture, large loop in the stem, improved graduation). After many experiments the firm in question succeeded in making two new models which satisfied the required conditions (Fig. 1).



MODEL I,

usable to 6,000 m. (3,280 fms.) depth, graduated in fifths of a degree from – 2° to + 60°, volume between 200° and 300°, accuracy of reading ± 0°02.

MODEL II,

usable to 2,000 m. (1,093 fms.) depth, graduated in tenths of a degree from – 1° to + 30°, volume between 100° and 200°, accuracy of reading ± 0°01.

FIGURE 1.

Unprotected reversing thermometers (German Atlantic Expedition Pattern)

As in model I pressures reaching 600 atmospheres act directly upon the mercury reservoir and the stem, the construction of these instruments represents a remarkable technical performance. The thermometers were submitted to a severe test by the *Physikalisch-Technische Reichsanstalt*, to wit : (1) from the point of view of slight errors of graduation ; (2) from that of the coefficient of pressure, *i. e.* of the rise in level of the mercury for each kg/cm² increase of pressure. These trials revealed the important fact that the coefficients of pressure vary but imperceptibly with the increase in pressure, or in other words each instrument has in practice a *pressure constant* valid without alteration over the whole range of the scale up to the limit of rupture. In the instruments of the German Atlantic Expedition this pressure constant lies between 0.0750 and 0.1050, or a mean of 0.0900; *i. e.* on the average, the rise of the mercury is 0°09 per 10 m. (33 ft.) of water-pressure. The pressure constant of each instrument is determined to within about ± 0.0005.

The correction of the readings of the unprotected thermometers follows from the formula deduced by A. SCHUMACHER:

$$C = \frac{(T + v_0) \ (Tw - t)}{6080} \cdot \left(1 + \frac{Tw - t}{6080}\right)$$

where T = the reading of the *main* thermometer of the *unprotected* thermometer,

t = the reading of the *auxiliary* thermometer of the *unprotected* thermometer,

v_0 = the volume of the quantity of mercury broken off up to the graduation 0°0 of the main *unprotected* thermometer.

Tw = the true temperature (calculated from the readings of the *protected* thermometer).

6080 = the coefficient of apparent expansion of mercury in normal Jena glass.

The attached graphic table of corrections, which enables the required corrections C for all the current values of $T + v_0$ and $Tw - t$ to be determined rapidly and with sufficient accuracy, was worked out from this formula (Plate I).

3. *Method of taking observations, and calculation of true depth.*

Two modern reversing thermometers, one protected against pressure, the other open and unprotected, are placed side by side in a double thermometer case mounted in a reversing frame or in a reversing water-sampling apparatus. By screw release or, better, by messengers, simultaneous release of both thermometers at the same level is obtained when the greatest depth has been reached (in soundings by wire, on reaching the bottom; in serial measurements, on reaching the depth of measurement), after a lapse of 5 to 10 minutes for the mercury to settle down. In the main thermometer of the protected thermometer, the mercury shows the true temperature of the depth examined. In the unprotected thermometer on the other hand, the mercury will reach a level which, in harmony with the pressure constant of the instrument, will be exactly proportional to the pressure, *i. e.* to the depth of water. Suppose the depth is 6,000 m. and the true temperature 2°00; the unprotected reversing thermometer (with a pressure constant equal to 0.0900) will indicate in this case a temperature of $2.00 + \frac{0.09 \times 6{,}000}{10}$, or 56°00. On recovery, it is true, the level of the mercury will alter slightly in the main thermometers, and with the readings effected necessarily with a magnifying glass only rough values will be obtained of the true temperatures, or of the temperature of the unprotected instrument. But thanks to the instrumental temperature reading

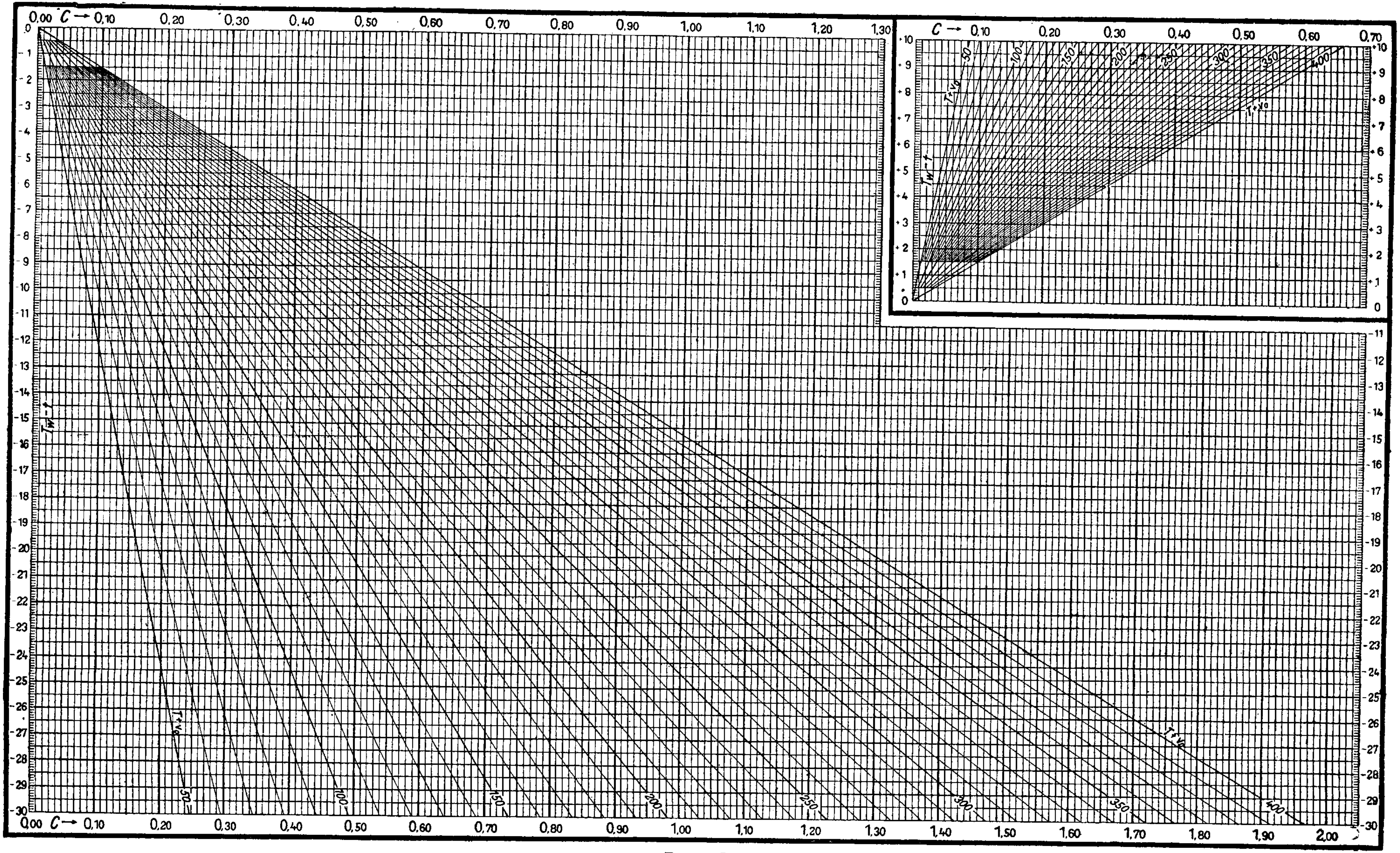


PLATE I

taken from the auxiliary thermometer, we are able, by using a formula of correction (for unprotected thermometers we use the formula given below), to calculate the correction C which must be applied to the readings to obtain the true temperature of the depth, or the true height of the mercury in the unprotected thermometer (at the moment of reversal at the depth).

Let:

Tw be the true temperature of the depth (*i. e.* the corrected reading of the protected reversing thermometer),

Tu the true height of the unprotected reversing thermometer at the depth of reversal.

Then

$$\Delta t = Tu - Tw,$$

Δt being the true rise of the mercury level in the unprotected thermometer at the moment of reversal in the depths. Further, let α be the pressure constant (*i. e.* the rise in level in the unprotected thermometer for an increase in pressure of 1 kg/cm²) and ρm the mean density of the column of water to be measured.

The thermometric depth required or the true depth W (independent of the length of wire run out and of the angle of the wire) is then obtained from the equation:

$$W = \frac{10}{\alpha . \rho m} . \ \Delta t = Q . \Delta t,$$

$$\text{where } Q = \frac{10}{\alpha . \rho m} .$$

The pressure constant α is indicated to the 4th decimal place on the test certificate of each unprotected thermometer; the value of Δt is given us to two decimals by the readings of the two instruments (after applying all corrections). It thus only remains to determine the density ρm of the column of water in question, *i. e.* the mean density, taking account of temperature, salinity and pressure. If, as in oceanographical calculations, it were required to obtain values of ρm to the 5th decimal place, the determination of these values would be a very laborious affair, for it would be necessary for the calculation to have recourse to BJERKNES' hydrographic tables. But a calculation of the errors shows that it is quite sufficient, for columns of water of over 1,000 m., to calculate ρm to the nearest 5 units of the 4th decimal place, and for the next 1,000 m. we only need the 3rd decimal of ρm. Within these limits of error we can take the distribution of the density in the sea as being constant. For the Atlantic Ocean it is thus quite sufficient to extract the values of ρm from the following table of mean distribution of density (Table 1).

TABLE 1.

MEAN DENSITY OF COLUMNS OF WATER IN THE ATLANTIC OCEAN.

Column of Water.	*Mean Density.*	*Column of Water.*	*Mean Density.*
m		m	
0 – 100	1,0262	0 – 2600	1,0336
0 – 200	267	0 – 2700	339
0 – 300	271	0 – 2800	341
0 – 400	275	0 – 2900	344
0 – 500	278	0 – 3000	346
0 – 600	1,0282	0 – 3100	1,0349
0 – 700	285	0 – 3200	351
0 – 800	288	0 – 3300	353
0 – 900	291	0 – 3400	356
0 – 1000	294	0 – 3500	358
0 – 1100	1,0297	0 – 3600	1,0361
0 – 1200	300	0 – 3700	363
0 – 1300	302	0 – 3800	366
0 – 1400	305	0 – 3900	368
0 – 1500	308	0 – 4000	370
0 – 1600	1,0310	0 – 4100	1,0373
0 – 1700	313	0 – 4200	375
0 – 1800	316	0 – 4300	377
0 – 1900	318	0 – 4400	380
0 – 2000	321	0 – 4500	383
0 – 2100	1,0323	0 – 4600	1,0385
0 – 2200	325	0 – 4700	387
0 – 2300	328	0 – 4800	390
0 – 2400	331	0 – 4900	392
0 – 2500	334	0 – 5000	395

TABLE 2.

THERMOMETRIC MEASUREMENT OF DEPTHS IN THE *METEOR*.
SOUNDING STATION N° 249.

Unprotected reversing thermometer N° 1437.		*Protected reversing thermometer* N° 1095.	
Length of wire to reversing frame .... =	5025 m.	Length of wire to reversing frame .... =	5025 m.
Temperature as read .... =	42.28° (27.5°)	Temperature as read .... =	1.18° (27.8°)
Reading + calibration correction .... =	42.34° (27.5°)	Reading + calibration correction .... =	1.18° (27.5°)
Temperature (at moment of reversal) *Tu*... =	41.22°	True temperature of depth *Tw*... =	0.66°

Elevation of level .... $\Delta t = Tu - Tw$ =	40.56°
Pressure constant of instrument n° 1437 .... α .... =	0.0786
Mean density of the column of water (0 – 5025 m.) ρ *m* .... =	1.0396
Depth of reversal determined thermometrically *W* .... =	4970 m.
Distance, depth of reversal to driver tube .... =	65 m.
Depth of the sea determined thermometrically .... =	5035 m.

Depth of wire 5080 m. (for a 10° angle of wire) ; depth by echo 5040 m.
The screw-release reversing frame was fixed to the sounding wire 55 m. above the driver tube, and reversed on raising after a travel of 10 m. through the water.

With the help of this table, and using the appropriate pressure coefficient, we can work out for each unprotected thermometer a new table for all columns of water (or, which is practically the same thing, for all lengths of wire), from which the values of the quotient Q can be extracted directly. Nothing else remains but to multiply this value Q by the rise of level Δt, to obtain the true depth W required.

For the Pacific and Indian Oceans, tables of the mean density of columns of water can also be prepared, the values of which do not differ appreciably from those of our table above. For secondary seas with large salinity anomalies, it is preferable to work out special tables of mean density. The method of summary calculation of thermometric depth indicated below seems to us to be the simplest and most easily understood for practical purposes. But it will be noticed that for the thermometric depth calculations of SUDA (1931) and GEISSLER (1931) we have given slightly different methods of calculation.

Let us illustrate the method of thermometric depth measurement by an example (Table 2).

The question now arises, with what degree of accuracy do we get the true depth by this thermometric method. The accuracy of the result depends on the errors of the three variables α, ρm and Δt. Adding the partial errors, the calculation furnishes the maximum and mean errors of thermometric depth measurement contained in Table 3.

TABLE 3.

LIMITS OF ERROR OF THE THERMOMETRIC DEPTH MEASUREMENTS.

Solltiefe.	Total maximum error.		*Solltiefe.*	Mean error.	
m	m	%	m	m	%
100	± 6	± 6,0	100	± 3	3,0
500	± 9	± 1,8	500	± 4	0,8
1000	± 14	± 1,4	1000	± 6	0,6
2000	± 23	± 1,1	2000	± 9	0,5
3000	± 32	± 1,1	3000	± 12	0,4
5000	± 49	± 1,0	5000	± 19	0,4

In other words : *The mean accuracy of the depths of reversal determined by thermometric depth measurement in the course of the German Atlantic Expedition was from 0.4 to 0.6 % for depths over 1,000 m. while between 100 and 1,000 m. its absolute value remained nearly constant and was ± 5 m. in round numbers.*

II. *RESULTS OF THERMOMETRIC DEPTH MEASUREMENT WHEN SOUNDING BY WIRE.*

The thermometric depth measurements made on the tropical profiles and with the object, among other things, of checking soundings by wire, have not the same degree of accuracy as regularly taken serial measurements; firstly because the measurements were taken in a frame released not by messengers but by screws, and also because, to avoid the formation of kinks, the necessary 5 minutes "adapting time" for the thermometers was not observed.

The use of screw frames could not be avoided in sounding by wire, because, owing to the danger of the driver tube being carried away, we could not wait for the impact of the messengers. With release by screw, reversal on raising only took place, as a rule, after a travel through the water of about 10 m. But even after applying this correction, the result of the thermometric depth measurement in sounding by wire admits a further source of error, arising from the shortening of the "adapting time" (2 to 5 minutes). In unfavourable cases the difference of temperature Δt may on this account be much too small; and in summing the two sources of error, large inconsistancies may sometimes be produced in the values of the thermometric depth, as shown by the figures in brackets in Table 4.

TABLE 4.

SYNOPTIC TABLE OF THE THERMOMETRIC DEPTH MEASUREMENTS AT THE SOUNDING STATIONS.

COLUMN 2. — *Solltiefe*, *i. e.* length of wire from surface to reversing frame at the moment of touching bottom (thus the depth by wire diminished by the length of wire below the reversing frame).

COLUMN 3. — Temperature read off the protected reversing thermometers graduated in tenths of degrees.

COLUMNS 4 & 5. — Maker's number and corrected readings of the open unprotected reversing thermometers.

COLUMN 6. — Rise of level in the reversing thermometer unprotected against pressure, *i. e.* difference Δt between corrected readings of the protected and open reversing thermometers.

COLUMN 7. — Depth of reversal (measured depth) of the reversing frame calculated from the formula $W = \frac{10}{\alpha.\ \rho m}\ .\ \Delta t$. The measurements marked with an * are manifestly false, *i. e.* the tripping of the reversing frame did not occur at the nearest point to the bottom but at a lesser depth.

COLUMN 8. — Distance of reversing frame from driver tube, increased by 10 m. for travel through the water (on account of the delay in release by the screw); in other words, the distance of the measured depth from the bottom of the sea.

COLUMNS 9 to 12. — Depth of sea bottom by the three different methods of sounding. The values in brackets are obviously false measurements.

NOTE. — Measurements marked with an asterisk (*) are manifestly false, values in square brackets [ ] have been incorrectly read. Thermometric depths in brackets ( ) must therefore not be used for determining the true depth of the bottom; the same applies to the depth by wire at Station 256 and the depth by echo at Stations 243, 288a, 290, 292 and 302.

TABLE 4.

1	2	3	4	5	6	7	8	9	10	11	12
	Solltiefe	PROTECTED THERMOMETER.	UNPROTECTED THERMOMETER.					DEPTH OF BOTTOM.			
Sounding station. No.	(Length of wire to reversing frame) *m*	Temperature. C°	Maker's N°	Temperature.	Rise of level. Δ *t*	Thermometric depth measurement. *m*	Bottom distance —depth measurement	Thermometric depth. T*b*	Echo depth. E*b*	Wire depth. Angle of wire	Wire depth. D*b*
242	**5116**	2.21	1437	43.645	41.44	**5082**	50	**5132**	**5169**	0°	**5156**
243	**4287**	2.30	1437	37.01	34.71	**4265**	65	**4330**	(4195)	0°	**4342**
244	**3371**	2.47	1437	28.98	26.51	**3264**	50	**3314**	**3378**	0°	**3411**
244a	**1949**	3.55*	1437	18.21*	14.66*	**1812***	65	(1872)	**1954**	30°	**2004**
245	**3323**	2.555*	1437	28.59*	26.03*	**3206***	65	(3271)	**3382**	0°	**3378**
246	**4934**	0.76	1437	39.50	38.74	**4755**	65	**4820**	**4888**	0°	**4989**
247	**5111**	0.72	1437	42.15	41.43	**5081**	70	**5151**	**5122**	3°	**5171**
249	**5025**	0.66	1437	41.22	40.56	**4970**	65	**5035**	**5040**	10°	**5080**
250	**4913**	0.87*	1437	37.78*	36.91*	**4530***	65	(4595)	**4985**	0°	**4968**
251	**4663**	0.77	1437	[33.32]	[32.55]	[3997]	65	(4062)	**4658**	0°	**4718**
252	**2437**	3.12	1437	22.00	18.88	**2330**	67	**2397**	**2402**	30°	**2494**
254	**3953**	2.34	1437	33.57	31.23	**3840**	65	**3905**	**3992**	0°	**4008**
256	**2921**	2.82	1437	24.74	21.92	**2705**	65	**2770**	**2794**	0°	(2976)
257	**4080**	1.83	1437	34.38	32.55	**4002**	65	**4067**	**4080**	0°	**4135**
258	**4514**	1.08*	1437	35.85*	34.77*	**4275***	60	(4335)	**4564**	10°	**4564**
260	**3456**	2.51	1437	29.95	27.44	**3380**	65	**3445**	**3513**	5°	**3511**
261	**2687**	2.89	1437	24.16	21.28	**2625**	65	**2690**	**2748**	0°	**2742**
262	**3779**	2.495	1437	32.30	29.81	**3668**	65	**3733**	**3772**	5°	**3834**
263	**4532**	2.36	1437	38.10	35.74	**4389**	65	**4454**	**4544**	5°	**4587**
264	**5392**	2.32*	1437	42.74*	40.42*	**4954***	65	(5019)	**5439**	0°	**5447**
265	**5125**	2.35*	1437	42.99*	40.64*	**4984***	65	(5049)	**5242**	15°	**5180**
266	**4702**	2.34	1437	40.18	37.84	**4647**	65	**4712**	**4748**	0°	**4757**
267	**4190**	2.36	1437	35.69	33.33	**4097**	65	**4162**	**4216**	7°	**4245**
268	**2861**	3.14*	1437	20.58*	17.44*	**2155***	65	(2220)	**2914**	2°	**2916**
271	**3471**	2.84*	1437	25.50*	22.66*	**2795***	65	(2860)	**3493**	5°	**3526**
272	**3666**	2.98*	1437	24.52*	21.54*	**2656***	55	(2711)	**3657**	0°	**3711**
273	**3293**	2.82*	1437	25.64*	22.82*	**2812***	55	(2867)	**3268**	20°	**3338**
274	**2541**	3.25*	1437	20.82*	17.57*	**2171***	65	(2236)	**2543**	15°	**2596**
277a	**3188**	2.76*	1437	28.44*	24.68*	**3042***	70	(3112)	**3248**	10°	**3248**
286	**2741**	2.90	1437	24.54	21.64	**2669**	62	**2731**	**2743**	3°	**2793**
287	**3361**	2.65	1437	29.78	27.12	**3340**	64	**3404**	**3364**	3°	**3415**
»	**3271**	2.66	1437	29.07	26.41	**3254**	68	**3322**	**3364**	5°	**3329**
288a	**4303**	2.08	1437	37.05	34.97	**4300**	64	**4364**	(4460)	5°	**4357**
288b	**4338**	2.05	1437	37.40	35.35	**4345**	65	**4410**	**4400**	0°	**4393**
289	**4896**	1.77	1437	41.54	39.77	**4881**	68	**4949**	**4843**	10°	**4954**
290	**4671**	1.90	1437	39.91	38.01	**4668**	63	**4731**	(4562)	5°	**4724**
291	**2964**	2.72	1437	26.72	24.00	**2959**	63	**3022**	**3024**	5°	**3017**
292	**1083**	4.71	1437	13.43	8.72	**1080**	63	**1143**	(1020)	3°	**1136**
294	**4113**	2.28	1437	34.31	32.03	**3938**	63	**4001**	**3984**	20°	**4166**
296	**2398**	3.26	1437	22.16	18.90	**2334**	60	**2394**	**2334**	0°	**2448**
297	**3759**	2.40	1437	32.64	30.24	**3722**	65	**3787**	**3710**	0°	**3814**
»	**3496**	2.50	1437	30.57	28.07	**3457**	325	**3782**	**3752**	0°	**3811**
298	**4126**	2.22	1437	35.13	3[illegible].91	**4046**	60	**4106**	**4046**	0° – 5°	**4176**
299	**4632**	1.46	1437	38.95	37.49	**4605**	64	**4669**	**4677**	0°	**4686**
300	**4717**	1.52	1437	40.13	38.61	**4740**	63	**4803**	**4666**	0°	**4770**
301	**3501**	2.57	1437	30.52	27.95	**3441**	55	**3496**	**3444**	0°	**3546**
302	**3574**	2.50	1437	31.60	29.10	**3583**	64	**3647**	(3463)	0°	**3628**
303	**3931**	2.40	1437	34.09	31.69	**3898**	65	**3963**	**3976**	5°	**3986**
308	**4804**	2.385*	1437	39.98*	37.60*	**4604***	25	(4629)	**4792**	0° - 15°	**4819**
309	**3019**	2.79	1437	27.18	24.39	**3006**	25	**3031**	**3028**	5°	**3034**
310	**4125**	2.43	1437	35.64	33.21	**4083**	25	**4108**	**4140**	5°	**4140**

In Table 4 we give a synoptic table of the thermometric depth measurements made at the 51 stations of profiles XI to XIV. To exclude the danger of collision with the tailing, the reversing frame was, as a general rule, secured to the latter at a distance of 50 to 55 m. (27 to 30 fms.) from the driver tube. This distance (increased by 10 m. on account of the delay in tripping by screw) must consequently be added to the depths of reversal obtained thermometrically, to obtain the thermometric depth of the bottom. A comparison of the bathymetric figures thus obtained with those furnished by the two other methods of sounding (by wire and by echo) shows that in 14 cases the thermometric depth was far too small, clearly because reversal did not take place at the point nearest the bottom but at a lesser depth. In 6 cases the result of the wire or the echo sounding is clearly in error.

There remain then 31 cases in which the depth of the sea was determined simultaneously and in impeccable fashion by all three methods. By suitable calculation of averages we obtain figures which enable us to form an idea of the *sources of error in the three methods of sounding*. The working up of the materials in this respect was done by Professor H. MAURER in Vol. II of the *Meteor* report (1933). While on the subject of this work we would mention the established fact that the depth of the sea as determined thermometrically must be increased by an average of 15 m. to obtain a value agreeing as closely as possible with the true depth of the sea. It even seems plausible that this systematic error may have a practically constant absolute value, *i. e.* that with the increase in depth of the sea it may diminish in percentage, given that the variations discussed above are independent of the length of wire run out. If we bear in mind the fact that in the soundings by wire the foremost question was that of obtaining bottom samples, and that for this reason we could hardly give much attention to the elimination of every source of error in the thermometric depth measurement, the results obtained may be considered to be good. The measurements have proved without fear of contradiction that thermometric depth measurement is an excellent method of checking the results obtained by other methods of sounding, and that by comparing the results with echo soundings it can furnish the means of undertaking systematic research into the true vertical velocity of sound in the sea. For, as we know, tables of reduction for echo soundings are based for the most part on theoretical formulae; direct measurements of the velocity of sound have hitherto been made but rarely, and usually only near the surface.

Such systematic investigations will enable us also to answer more truthfully than has been possible till now, the question of the accuracy of sounding by wire, and in particular of the magnitude of the error introduced by the angle of the wire. Our 31 cases are not sufficient for this purpose, and we are consequently reduced to seeking a rough solution of the question by taking our stand on the wire and echo soundings taken simultaneously at all the *Meteor's* sounding stations. This we shall now do.

III. *RELATION BETWEEN DEPTH BY WIRE AND DEPTH BY ECHO FOR DIFFERENT ANGLES OF WIRE AT THE SOUNDING STATIONS.*

Our investigations lead us to the important question of the sources of error in sounding by wire and by echo. It had generally been assumed until now in the exploration of the sea that the length of wire run out, read from the counter at the moment of touching bottom, agreed to within a few metres with the true depth. KRÜMMEL (1907) worked out, for example, the total mean error of a modern sounding at $\pm$ 5 m. VON DRYGALSKI (1926) is much more sceptical, concluding that the "error in rough seas may reach 100 m. and more". The *Meteor's* simultaneous soundings by wire and echo show even greater differences, although when sounding the ship was always "manœuvred over the wire." The question arises whether these differences are due solely to the sources of error in the acoustic soundings, or whether they are principally caused by the errors of the wire soundings resulting from the deviation of the wire from the vertical. Some light can be shed upon this question by a statistical study of the differences which arose between the wire and echo soundings at 322 sounding stations of the *Meteor*. After eliminating the 7 false observations, I have grouped the remaining 315 depths obtained synchronously by wire and by echo according to the intervals of the angle of wire, and have calculated for these intervals mean values of the quotients depth by echo / depth by wire. The result is given in Table 5.

TABLE 5.

—

DEPENDENCE OF THE RATIO
DEPTH BY ECHO / DEPTH OF WIRE
ON ANGLE OF WIRE.

Angle of wire β	*No. of cases.*	*Mean depth by wire* (*round figures*).	*Ratio* *Depth by echo / depth by wire* v = E*b* / D*b*	*Difference with respect to* v
0°—4°	96	3500	0.993	$\pm$ 0.014
5°—9°	59	3650	0.993	$\pm$ 0.013
10°—14°	54	3600	0.989	$\pm$ 0.018
15°—19°	47	3050	0.982	$\pm$ 0.016
20°—24°	25	2800	0.978	$\pm$ 0.018
25°—29°	12	3400	0.972	$\pm$ 0.020
30°—34°	9	3750	0.966	$\pm$ 0.019
35°—39°	4	3500	(0.968)	$\pm$ 0.013
40°—44°	9	3500	0.957	$\pm$ 0.021

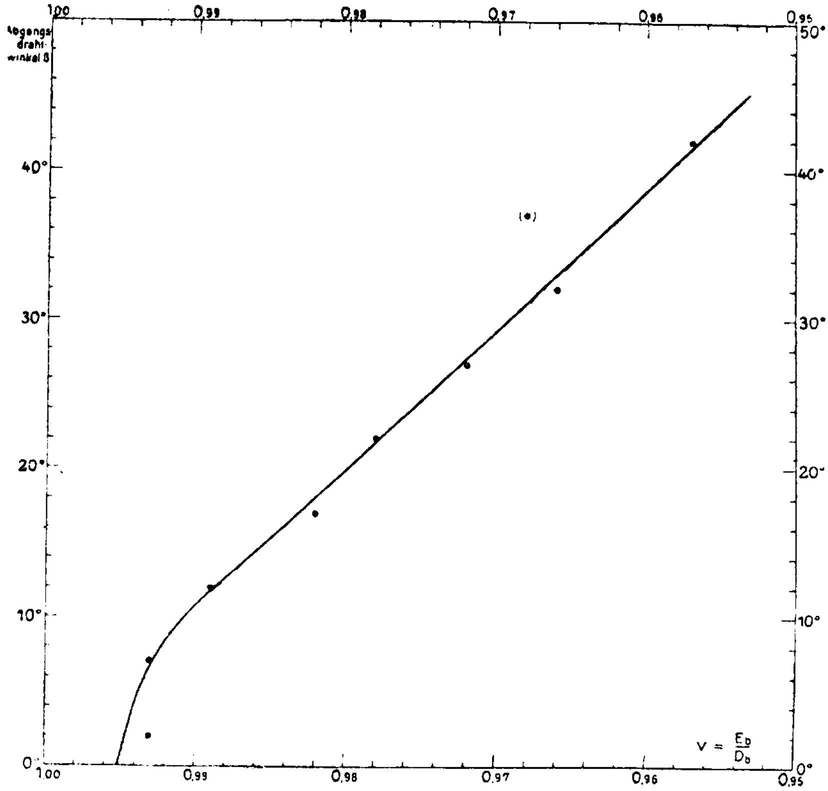


FIG. 2.

Mean relation between quotient v *(echo sounding / wire sounding) and angle of wire* β *at the sounding stations of the German Atlantic Expedition.*

The Table, as well as Fig. 2, shows that *the relation between the quotient* v *and the angle of wire follows a definite law, viz: the depth by wire represents, more or less, a function of the angle of the wire.* But if we calculate the mean departure of the single values from the mean values of the quotients, we find that the difference is fairly large; *i. e.* that there must still be a series of sources of error in the values of the quotient, engendered in part by the poor basis of comparison for the values of the angle of wire (1), and in part also by other errors in the two methods. A remarkable point is that the curve does not pass through zero, which means that even for an angle of wire of 0° the concordance in the results of the two methods is not, on the whole, perfect. This difference must be due to other sources of error in the methods, and a special study will be necessary to determine by what distribution of the errors these residual differences can be eliminated.

The first question which arises is to know *by what factor of reduction the soundings by wire, taken with an angle of wire* β, *must be multiplied to reduce them to a zero angle of wire.* To answer this, by obtaining the factor of reduction *k* required, we must make our curve of relation pass through zero, *i. e.* increase the values of *v* by 0.005. The values of the factor of reduction thus deduced are given in Table 6 for the different angles of wire.

(1) Measured with pendulum quadrant.

TABLE 6.

FACTOR OF REDUCTION k FOR SOUNDINGS BY WIRE TAKEN WITH ANGLE OF WIRE β.

Angle of wire β	k	1,000 (1-k)	*Angle of wire* β	k	1,000 (1-k)	*Angle of wire* β	k	1,000 (1-k)
0°	1.000	0	20°	0.985	15	40°	0.963	37
1°	1.000	0	21°	0.984	16	41°	0.962	38
2°	0.999	1	22°	0.983	17	42°	0.961	39
3°	0.999	1	23°	0.982	18	43°	0.960	40
4°	0.999	1	24°	0.980	20	44°	0.959	41
5°	0.998	2	25°	0.979	21	45°	0.958	42
6°	0.998	2	26°	0.978	22	46°	0.957	43
7°	0.997	3	27°	0.977	23	47°	0.956	44
8°	0.997	3	28°	0.976	24	48°	0.955	45
9°	0.996	4	29°	0.975	25	49°	0.953	47
10°	0.996	4	30°	0.974	26			
11°	0.995	5	31°	0.973	27			
12°	0.994	6	32°	0.972	28			
13°	0.993	7	33°	0.971	29			
14°	0.992	8	34°	0.970	30			
15°	0.990	10	35°	0.968	32			
16°	0.989	11	36°	0.967	33			
17°	0.988	12	37°	0.966	34			
18°	0.987	13	38°	0.965	35			
19°	0.986	14	39°	0.964	36			

With the aid of this factor of correction k we have reduced all the depths observed by wire to an angle of departure of 0°, and by this means have calculated the corrected depths by wire D_k. By eliminating the angle of wire we have indeed removed the principal source of error in sounding by wire, but not all the differences between the mean results of the three methods of sounding. For even with an angle of wire of 0°, the soundings by wire must, taking the average of numerous cases, furnish a value somewhat in excess of the true depth; observing that the wire, owing to the variable drift, is not necessarily vertical, even when it is tautened while breaking out the driver tube. On the other hand, owing to the influence of the slope of the bottom, the mean values of the echo depth must have a tendency to furnish a slightly deficient value. These two sources of error must be added together, with the result that, even taking the mean of numerous cases, there remains a positive difference $D_k - E_b$. Professor H. MAURER found the figure 0.7 % for this difference, and reached the conclusion that, on an average, soundings by wire D_k corrected to 0° furnish a value about 0.4 % in excess and soundings by echo E_b a value deficient by about 0.3 %. In accordance with this distribution of the sources of error, we must then *reduce to the true depth* the results of the three methods of sounding, as follows:

Corrected depth by wire $D_v = 0.996\, D_k$
Corrected depth by echo $E_v = 1.003\, E_b$.
Corrected thermometric depth $T_v = T_b + 15$.

We find the most probable value of the true depth by simply striking the mean, $W = 1/3 \ (D_v + E_v + T_v)$.

In Table 7 the mean ratios of the depth of bottom (*i. e.* depth observed by wire) and the true depth (*i. e.* depth by wire corrected to true depth), in sounding by wire, have been collected in synoptic form.

It transpires from the table that in 66 % of all the cases the angle of wire was less than 15°, and the error in depth was 1 % or less of the length of wire. On the other hand, in 33 % of all the cases the angle of wire was greater than 15°, and at the same time the error in depth rose to 1.5 % and more, *i. e.* for a length of wire of 4,000 m. the sounding gave a depth of 60 m. or more in excess. In spite of manœuvring the ship continuously, the soundings by wire had to be taken in 7 % of cases with an angle of wire of over 30°. In these unfavourable cases the error in depth reached more than 3 %, *i. e.* the sounding by wire taken at about 4,000 m. gave depths in excess by 128 to 172 m. with angles of wire of this order. Plate II gives a graphical representation of the position taken up by the submerged wire (piano wire of 1/8 in. circumference (1 mm. diameter) weighted at its lower end by a sinker of about 66 lbs. (30 kgs.), for different angles of departure.

TABLE 7.

MEAN ERRORS OF DEPTH IN SOUNDINGS BY WIRE OF THE GERMAN ATLANTIC EXPEDITION FOR VARIOUS ANGLES OF DEPARTURE OF THE WIRE.

Depth by wire D_b m	*Difference,* Depth by Wire D_b — true depth D_v *in metres for an angle of wire of*								
	0°-4° (30 %)	5°-9° (19 %)	10°-14° (17 %)	15°-19° (15 %)	20°-24° (8 %)	25°-29° (4 %)	30°-34° (3 %)	35°-39° (1 %)	40°-44° (3 % *of all cases*)
200	1	1	2	3	4	5	6	8	9
300	2	2	3	5	6	8	10	11	13
400	2	3	4	6	8	11	13	15	17
500	3	4	5	8	11	14	16	19	22
600	3	4	6	9	13	16	19	23	26
700	4	5	7	11	15	19	22	27	30
800	4	6	8	12	17	22	26	30	34
900	5	6	9	14	19	24	29	34	39
1000	5	7	10	15	21	27	32	38	43
1200	6	8	12	18	25	32	38	46	52
1400	7	10	14	21	29	38	45	53	60
1600	8	11	16	24	34	43	51	61	69
1800	9	13	18	27	38	49	58	68	77
2000	10	14	20	30	42	54	64	76	86
2250	11	16	23	34	47	61	72	86	97
2500	13	18	25	38	53	68	80	95	108
3000	15	21	30	45	63	81	96	114	129
3500	18	25	35	53	74	95	112	133	151
4000	20	28	40	60	84	108	128	152	172
4500	23	32	45	68	95	122	144	171	194
5000	25	35	50	75	105	135	160	190	215
6000	30	42	60	96	126	162	192	228	258

It is claimed that the error in the result of the soundings is not nearly as considerable as one might expect from the angle of departure of the wire ; in other words the wire, inclined at the surface, follows a much more nearly vertical path as it goes deeper.

While the error in the soundings by wire is appreciably smaller than, for example, in the serial measurements of which we are about to speak, in the present state of observational technique we cannot afford to neglect it. Both from the methodical point of view and for all delicate morphologic research, the reduction of soundings to the true depth seems necessary. The faculty of being always able to carry out thermometric depth measurements simultaneously with sounding by wire, furnishes the means of making this reduction in future with greater precision than has been attainable with the materials available hitherto.

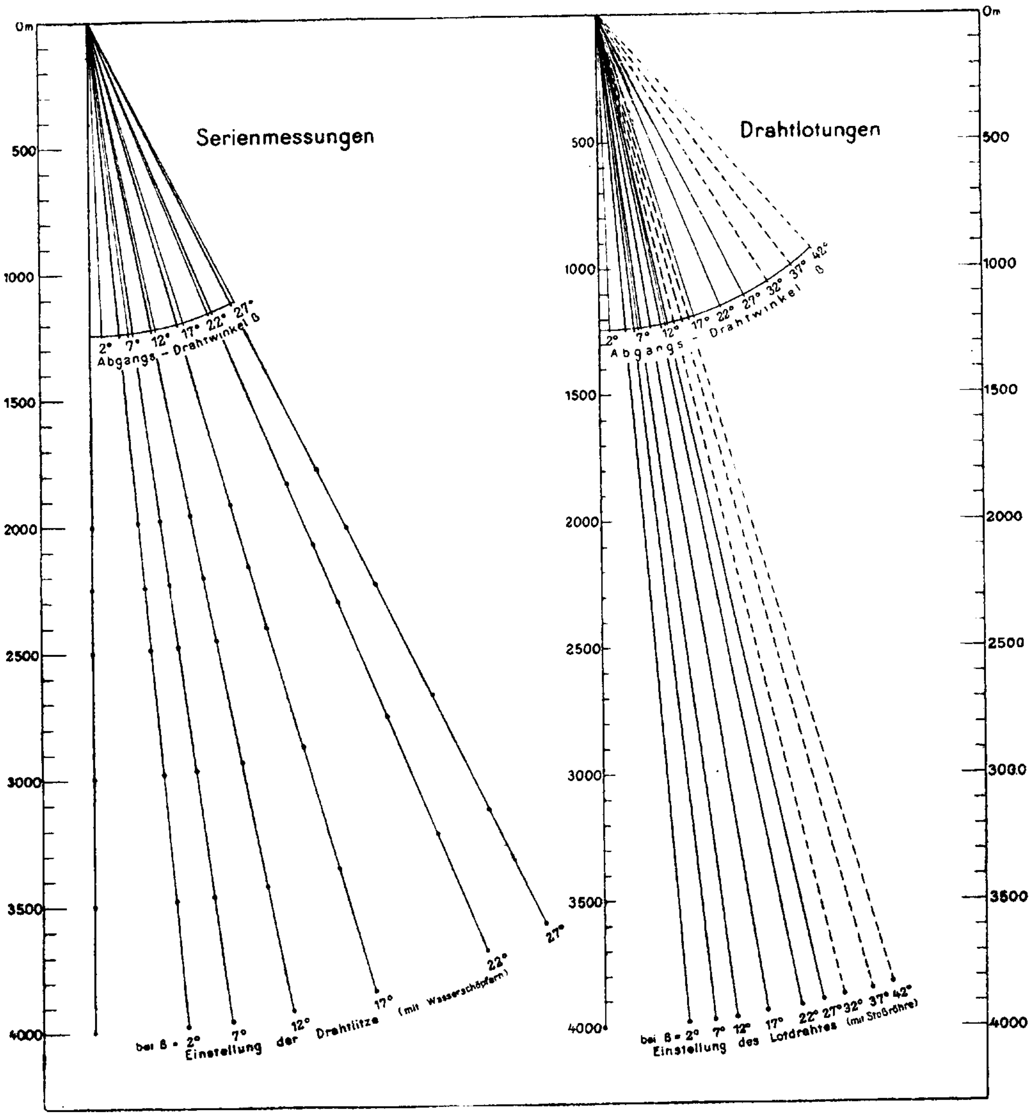


PLATE II.

IV. *RELATION BETWEEN DEPTH BY WIRE AND TRUE DEPTH IN SERIAL MEASUREMENTS FOR DIFFERENT ANGLES OF WIRE.*

It is interesting to compare the dependence of the depth by wire on the angle of wire, as described above, with the results obtained during serial measurements. In the serial observations of temperature and salinity taken in the course of the German Atlantic Expedition, the true depth of reversal of the water-sampling bottles was determined at three points of each series, *i. e.* at 9 points at least of a vertical section extending from 0 to 4,000 m.; for a vertical section of this type was generally carried out in three series: 0 to 1,000 m.; 1,000 to 2,500 m.; 2,500 to 4,000 m. or bottom. During the actual work, 4 to 8 sample bottles were streamed each time, attached to the wire at intervals of 100 to 500 m. Reversal of the bottles and of the protected and unprotected thermometers in the serial observations was effected by messengers, after a lapse of 10 to 20 minutes for adaptation. The sources of error in the thermometric depth measurement, which appear when sounding by wire owing to the shortening of the lapse of time for adaptation and to the delay in reversal inherent in release by screw, were thus non-existent. The results of thermometric depth measurement consequently give much more precise results in the serial observations, and on the average can be kept within the limits shown in Table 3 resulting from the partial errors of measurement of the temperature and the pressure coefficient.

The principle of thermometric depth measurement was thus used systematically in the serial observations at every station of the German Atlantic Expedition. Altogether the thermometric depth was observed in 2,400 cases, in round figures, at the 310 stations. These voluminous materials enable us to deduce a mean relationship between the true depth and the depth of the bottom, or depth by wire, for the different angles of departure of the wire, by the same method as was applied above for soundings by wire but with greater accuracy; they also enable us to find a solution for the following special case of the general problem: What curve in space is traced in the water by a sounding wire weighted at various points under the influence of current or drift of ship? *A priori* we must expect that, for the same angle, the departure of the wire from the vertical will be notably greater in serial measurements than in soundings by wire. For the soundings by wire were taken with a fine piano wire 1/8 in. in circumference (1 mm. diameter), weighted at its lower end only by a driver tube. In the serial measurements, on the other hand, we used a much stronger wire of 1/2 in. circumference (4 mm. diameter), to which from 6 to 10 bulky water bottles were invariably attached, and which offered more resistance to the water than the driver tubes.

Since in the above-mentioned shallow, medium and deep series the wire was weighted in different ways by the water bottles, a separate study was made in the *Meteor* report, Vol. IV, for the three series, as well as for the 3 water bottles in each series fitted with unprotected thermometers; but neglecting the measurements for depths between 0 and 500 m. on account of the limit of error of ± 5 m. in the thermometric depth measurement. If,

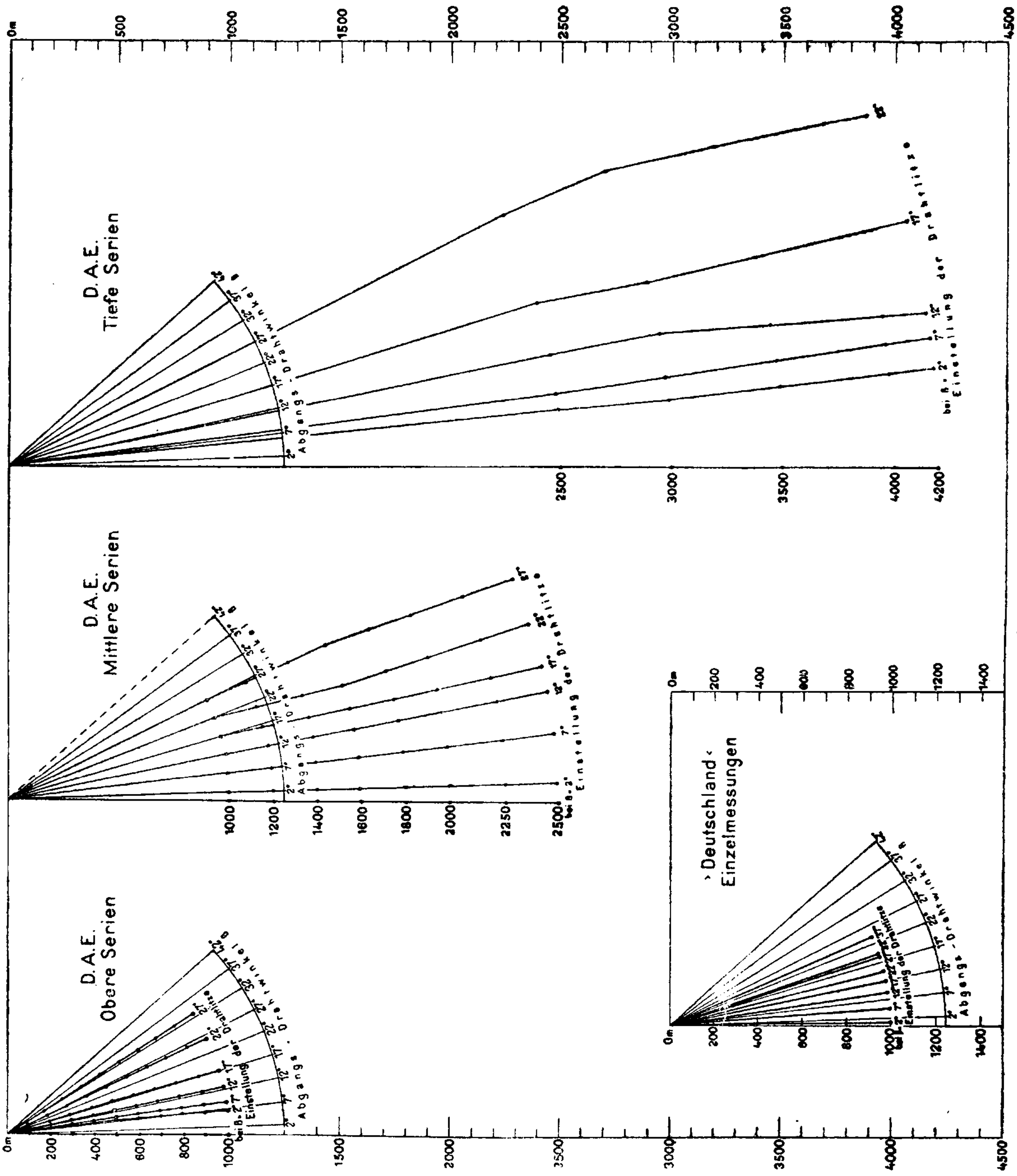


PLATE III

with the data of observation thus limited and grouped (1,002 measurements in 549 series), we calculate mean values of the quotients *k* (true depth / depth by wire), we again find *that the ratio between angle of wire* β *and quotient* k *follows a definite law. It is shown that the error of depth in the serial measurements is abnormally great,* and this on the whole almost invariably at the higher end of the series, while at the lower extremity the wire bends slightly (Plates II and III). *Taking it by and large, we see that* *the wire weighted with 6 to 10 water bottles assumes more or less the direction of the angle of departure of the wire, so that the error of depth is about proportional to the cosine of the angle of wire* β. In absolute quantities, the mean error of depth for the three groups of serial measurements of the German Atlantic Expedition works out as follows :—

TABLE 8.

MEAN ERROR OF DEPTH IN THE SERIAL MEASUREMENTS OF THE GERMAN ATLANTIC EXPEDITION.

SERIES.	*Solltiefe*	*Difference, Solltiefe — true depth in metres for an angle of wire of*					
	m	0° – 4°	5° – 9°	10° – 14°	15° – 19°	20° – 24°	25° – 29°
Highest	200	2 m	2 m	4 m	9 m	20 m	32 m
	300	3	3	7	13	31	49
	400	4	4	9	17	41	65
	500	5	5	11	22	51	81
	600	5	5	13	26	61	97
	700	6	6	15	29	71	113
	800	6	7	17	34	82	130
	900	6	8	19	38	92	146
	1000	6	9	21	41	102	162
Middle	1000	5	10	21	42	71	115
	1200	6	12	25	49	80	137
	1400	7	14	29	55	90	157
	1600	8	17	34	59	98	178
	1800	9	20	38	65	108	189
	2000	9	22	42	70	120	200
	2250	10	25	45	77	133	211
	2500	10	28	50	83	148	220
Lowest	2500	17	23	50	110	265	—
	3000	18	30	60	117	306	—
	3500	21	35	60	130	333	—
	4000	24	44	61	140	352	—
	4500	27	50	63	158	396	—
	5000	30	55	70	175	440	—

It follows from this table that for angles of wire of 10° the mean error of depth already reaches values which cannot be neglected, and that for angles of wire of 20° it grows to enormous values. It is thus, for example, that for a length of wire of 4,000 m. and an angle of wire of 20° to 24°, the depth of the water bottles is found in fact to be reduced by 352 m. If we take the whole group of 1,002 observations, the points of the system of coordinates $K = f(\beta)$ are found to be nearly on the straight line given by the function $K = \cos \beta$ (Fig. 3). Averaging all these series, we obtain as a result the following mean factors of reduction for the depths by wire of

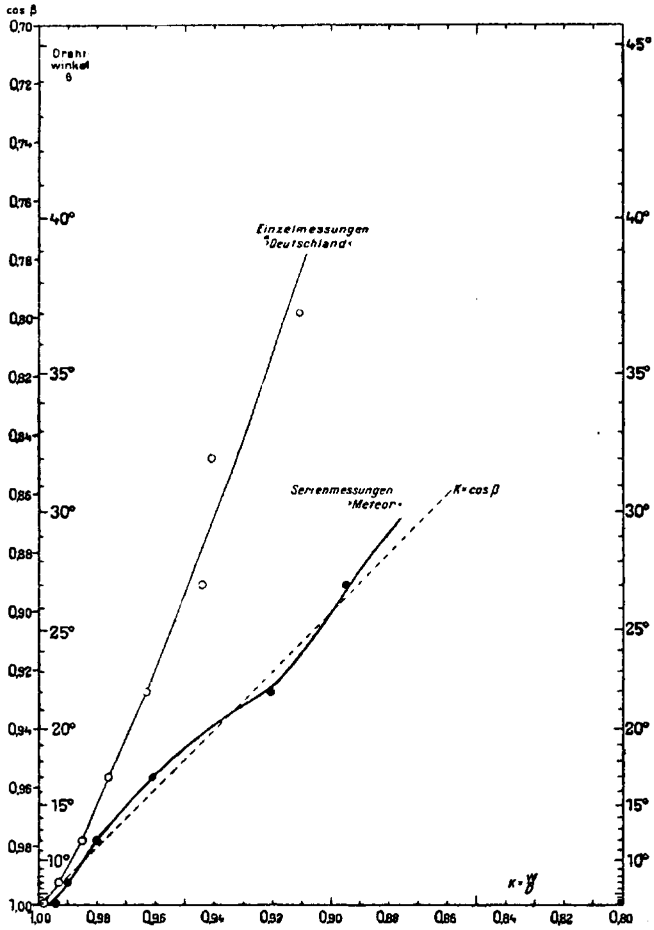


FIG. 3.

Mean ratio between quotient k *and angle of wire* β *in the serial observations of the German Atlantic Expedition and the single observations of the* Deutschland *Expedition.*

the serial measurements, to which we have added the percentage of cases affected by the different intervals of angle of wire.

TABLE 9.

MEAN FACTORS OF REDUCTION FOR DEPTHS OF BOTTOM IN THE SERIAL OBSERVATIONS TAKEN WITH ANGLE OF WIRE β.

Angle of wire β.	0° – 4°	5° – 9°	10° – 14°	15° – 19°	20° – 24°	25° – 29°
Percentage no. of cases.	32 %	29 %	23 %	9 %	5 %	2 %
Factor of reduction	0.994	0.990	0.980	0.961	0.925	0.895

It is thus a question of applying very significant corrections to the series. If in about 60 % of these cases the correction to the depths is smaller than 1.5 %, it is as much the greater in the remaining 40 %; and in 16 % of all the cases (angle of wire greater than 15°) it becomes more than 4 %, in 7 % of all the cases more than 7.5 %, of the depth by wire. The mean of all the series gives an angle of wire of 8°.

In the foregoing considerations it has been a question of mean values. Taken by itself the error of depth may be less, but it may also be appreciably greater as the *Meteor's* observations show. The resulting errors in the value of temperature and salinity are often, in individual cases, notably larger than the accuracy of the temperature and salinity measurement. In unfavourable cases the values of the temperature may on this account be thrown out by as much as tenths of a degree and, for large vertical gradients, even whole degrees; and the values of salinity by tenths of units or even whole units (of 0.001). *We can sum up by saying that the high degree of accuracy in temperature and salinity observations* (± 0.01° *and* ± 0.02 ‰ *respectively*) *required by modern sea exploration, and even claimed by it for years, is in fact attained with certainty only when the error of depth is eliminated from the observations by thermometric depth measurement.*

The use of reversing thermometers and water bottles in serial observations is, apart from the serial measurements of the *Challenger* and *Gazelle* Expeditions, a thing of yesterday. Previous expeditions usually only streamed *one* water bottle at a time, suspended by a wire. In this case the error of depth is naturally much less, as we can verify from our scrutiny of the isolated observations taken by BRENNECKE in 1910-11 on the *Deutschland* Expedition (cf. the thin curve of Fig. 3).

V. *SUMMARY.*

1. Description of the thermometric method of depth measurement with protected and unprotected reversing thermometers, based on the experience acquired in the *Meteor* Expedition.

2. Discussion of the results of the thermometric depth measurements at the *Meteor's* sounding stations.

3. Deduction of a relationship, following a determined law, between the depth by wire and the true depth for different angles of wire. In soundings by wire it is found, taking the relation between the depths by echo and by wire as a basis, that the mean error in depth in two thirds of the cases is less than 1 % of the length of wire run out; it only assumes higher values, which may reach 4 %, for angles of wire above 15°.

4. In serial measurements the submerged wire strays fairly considerably from the line of the angle of departure when average conditions are taken as a basis. The error of depth in serial measurements is roughly proportional to the cosine of the angle of the wire, and for angles of wire above 10° it attains values leading to considerable errors in the measurement of temperature and observation of salinity.

5. To sum up we can say that for serial oceanographical observations of temperature and salinity, thermometric depth measurement is an auxiliary which we can ill spare; for it alone is capable of ensuring the desired precision in the determination of temperature and salinity. Besides, it has proved an excellent method of check in dealing with the sources of error of the methods of sounding by wire and by echo. It would be desirable that systematic investigations should be undertaken in nautical surveys on the sources of error of the methods of sounding by wire and by echo, by taking soundings simultaneously by wire, by echo and by thermometric measurement — in the circumstances the release of the reversing thermometers by messengers, and the precaution of leaving the thermometers a sufficient time to adapt themselves, are indicated.

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