ERDMAGNETISCHE MESSUNGEN AUF SEE MIT DEM DOPPELKOMPASS ALS TAUCHGERAT

by

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(EARTH MAGNETIC MEASUREMENTS AT SEA WITH DOUBLE COMPASS AS IMMERSED APPARATUS).

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As is well known two great difficulties are encountered in the measurement of the earth's magnetism at sea. First, the instruments and methods employed for these measurements ashore are not applicable owing to the movements of the vessel, and secondly, the natural field of the earths' magnetism is so badly distorted by the modern iron ships that an accurate calculation of the field is only possible after a very careful and repeated determinations of the deviation, which, in part, is very variable.

F. Bidlingmaier (1) has succeeded, with the aid of the double compass, in very appreciably reducing the disturbing influence of the vessel's movements. In order to avoid the disturbing influence of the ship's hull, ships were constructed without iron, of which the "Carnegie" has probably accomplished the most important work up to now in the measurements at sea (2). Reports have been made by v. Gernet (3), Slaucitajs (4), Odelsiö (5). Keranen (6) and Ljungdahl (7) in connection with the expedition for measurements in the Baltic on a small non-magnetic ship.

Since it was not possible up to now to obtain a non-magnetic ship for the German measurements of the earths magnetic field at sea, experiments were undertaken in the last few years by the Deutsche Seewarte on the measurement of the horizontal component with the aid of a new model of the double compass, considerably reduced in size and specially adapted for the requirements, placed in an iron-free immersion apparatus consisting of a sphere of 0.76 metres diameter. The immersion apparatus was allowed to float at a sufficient distance from the ship and at a depth where it suffered little or no disturbance from the sea-way. The reading of the compass rose was recorded photographically by means of a film-camera operated from the ship in accordance with the improvements on a method introduced by G. Fanselau (8) and the mean angle of the deviation was then calculated from a sufficiently large number of photographs taken at equal intervals of time. H is then obtained by the well-known formula :—

$$\lg H = \lg C + \lg \cos \frac{\psi}{2}$$

in which C is the constant to be added, ψ is the deflection angle of the compass card, which is composed of the deviation angles φ_1 and φ_2 of each individual compass card. Even the very first tests were successful. The immersion sphere was tared with lead weights to cause it to sink slowly and attached to a diving cord which was fitted where necessary with hollow glass balls of alight buoyancy. The sphere was prevented from sinking too deeply by the buoyancy of the hollow balls, so that the immersion apparatus was kept floating at the desired depth and about 100 meters off the quarter or the beam of the ship. Generally the sphere lay sufficiently quiet a few minutes after having been put overboard and immersed. It is important, in the case of a rough sea, that sufficient depth of water be available. In general a depth of immersion of about 20 meters proved adequate. It was more difficult with the rolling to get the device in the water without damage, but the number of accidents from his cause diminished greatly as the crew obtained more practice. In order to prevent large angular oscillations and continuous revolving of the sphere about its vertical axis which would endanger above all the conducting cable, anti-rolling vanes (guide vanes) were rigidly secured to the sphere and proved successful. In cases where sufficient depth of water existed the sphere was lowered vertically alongside the ship to a depth sufficient to remove it from the disturbing field of the vessel itself, and, at the same time both cable and hauling-in lines were kept slack so that the movement of the rolling vessel was not imparted to the instrument. This on the supposition that the envelop is sufficiently impervious to pressure and that the stuffing-box for the cable is tighly set-up. In such conditions it was found possible to measure also the vertical gradient of H oven where strong perturbations existed.

The compass cards of the double compass, constructed by the Askania-Werke in Berlin, were reduced to 11 cm. diameter in order to economize space. Under these conditions it was necessary to insure the proper centring of the compass to within — 0.1 mm., since otherwise the resultant error of 0.05° might be carried over into the half angle of deflection. The moments of the individual cards were, taken by 2 pairs, about 625 and 1260 L xcm.3 respectively. The inequality of the deflections of the two cards $(\varphi_1 - \varphi_2)$ necessitates an additional correction to the above formula of the form :—

$$\log\left(1 + \frac{M_1 - M_2}{M_1 + M_2} \tan^2 \frac{\psi}{2}\right),$$

which thus depends essentially on the difference between the two moments. The factor $\frac{M_1 - M_2}{M_1 + M_2}$ amounted to 0.0048 and 0.00079 respectively in the above mentioned pair of cards, so that with between 60° to 80° the correction for the weaker card was about 2 γ, while that of the stronger was 15 γ. These corrections could therefore be left out of consideration for the time being. The cards were graduated on their circumference in full or half degrees, which permitted readings to 0.1°. In the upper card they are on the lower side, while on the lower compass card they are on the upper side and progress from north towards the east. The separation of the cards was maintained constant at 15 cm. since it was feared that the transposition device would become the source of an indeterminate error under the severe requirements at sea. With a constant separation of the cards the value of log C becomes definite and the uncertainty in the determination of the moment, as described by G. FANSELAU (9) is eliminated. This disposition however renders it essential, with large variations in the latitude, to choose pairs of compass cards with different moments if one wishes to work with the most favorable angles of deflection. The basic calculations for this have been given by G. FANSELAU (9).

The cards are illuminated by a pocket-lamp (3 watts) which is secured between them (fig. 1). The images of the graduations on the circumference of the card is thrown on the lens of the film camera (which is free from magnetic disturbance) by means of a system of prisms and lenses. The film of the camera is operated through three beryllium springs and its motion is started and stopped electrically by distant control aboard ship. In the first experiments the photographs were taken at intervals of 0.25 seconds each; but experience soon proved that a longer interval between exposures would suffice. Fig. 2 shows a photographic record with the present usual interval of 1 sec. which proved adequate even in bad weather. The accuracy of reading of the individual images lies between 0.1 and 0.2°, the mean error of calculation for the measurement of a fixed point is 0.02°; i.e. $\pm$ 2.5 γ, the average inner error of the final result of $\frac{\psi}{2}$ remains less than 0.1°. The sensitivity was maintained between about 50 — 80 γ /0.1°, but could easily be increased by suitable choice of the constants. Since, in conformity with $\frac{dH}{H} = -\tan\frac{\psi}{2}\, d\frac{\psi}{2}$, increases with a decrease in $\frac{\psi}{2}$, or with decreasing moment of the cards, its practical limit is found in the security accuracy of adjustment which decreases considerably as the deflection angle becomes smaller, since in this case the friction about the pivot predominates over the magnetic moment.

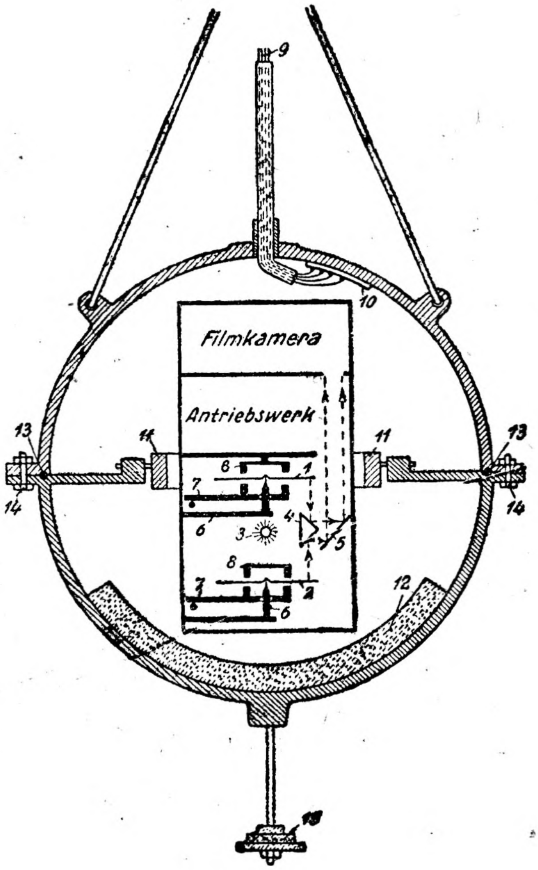


FIG. 1. — *Double compass in the immersion apparatus (schematic).*

1. *upper card*
2. *lower card*
3. *lamp*
4. *prism*
5. *mirror*
6. *card support*
7. *stop lever*
8. *counter stop*
9. *cable*
10. *connecting part*
11. *cardan ring*
12. *lead weight*
13. *watertight rubber*
14. *locking screw*
15. *adjusting weight*

The entire arrangement of the apparatus was based on the fundamental desire to produce primarily a sea-worthy device and to test the method as such. Our further efforts will be directed towards improving the accuracy of observation by means of suitable modifications. In 1939 K. RAMSAYER was able to test the apparatus on a flight on a Zeppelin and to successfully measure the value of H at an altitude.

The check measurements of the first apparatus in the Wingst Observatory of the Deutsche Seewarte showed a consistent semi-circular deviation which in four measurements from April 1938 to February 1939 remained approximately the same and had an amplitude of ± 0,3°. However after severe trials of the instrument at sea, it did not remain quite so regular. Since the photographic record of the azimuthal adjustment of the instrument in the measurements at sea can be readily reproduced with sufficient accuracy, a correction for deviation is easily applied, in so far as it may be considered as constant. The instrument must unfortunately stand the strain of being put over and hauled in with the compass card free (not clamped) as a result of which the pivots and caps are subject to severe strains and it is therefore necessary to check these carefully and frequently to insure that they are in perfect condition.

The semi-circular deviation can be conditioned mechanically as well as magnetically. The first can occur when the pivots, in the normal position of equilibrium of the cardan suspension do not stand exactly peprpendicular, one above the other. This condition should be carefully noted and checked both with the instrument on the turn-table and when being introduced into the sphere. It is clear that such a faulty adjustment will also give rise to pure magnetic perturbations. Graduation errors of the compass cards can be corrected directly on the photographic record of the numerals.

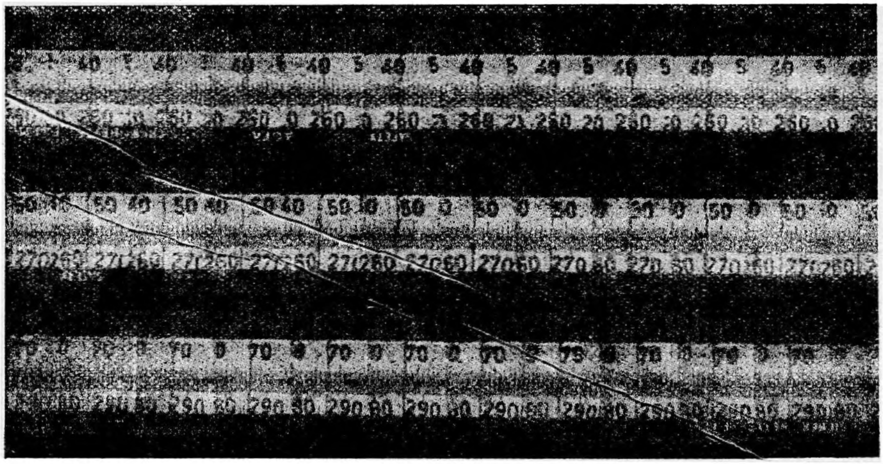


FIG. 2. — *Specimen of film for measuring horizontal intensity with double compass as immersion apparatus.*

Perturbations resulting from permanent or inductive magnetic materials of construction may become rather complicated as a result of the fact that they generally affect only one of the cards so that the disturbing field is non-homogenous. Such errors, in so far as they come from the outside, have been treated by BIDLINGMAIER (2). He shows that the double compass is very sensitive towards such non-homogeneous fields and can even be used to determine their existence, when the compass cards are cut apart and the difference in the two deflection angles is observed.

The lack of homogeneity is made apparent if the upper or the lower compass card is fixed and the deviations investigated separately, as is done by the manufacturing firm for the determination and elimination of the source of perturbations.

For the measurement of H the perturbation vector must pass through line joining the center of the compass cards. On the assumption that the conditions for the application of, the Poisson equation are available, we obtain on rotating the instrument in its hollow sphere through any desired azimuth z, the following formula :—

$$H_Z = \frac{\lambda H_0}{\cos \delta}\left[1 + \mathfrak{B} \cos z - \mathfrak{C} \sin z + \mathfrak{D} \cos 2z - \mathfrak{E} \sin 2z\right].$$

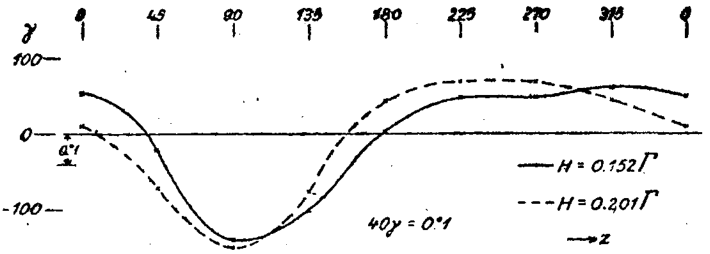
In this H_0 represents the undisturbed earth field, δ the false compass deviation corresponding to the azimuth, at the reference point, λ, $\mathfrak{B}$, $\mathfrak{C}$, $\mathfrak{D}$, $\mathfrak{E}$ are the deviation coefficients which are calculated from the observations on the 8 cardinal points.

In order to test effect of both permanent and induced fields of perturbations the test instruments 1 and 2 were exposed in a quadrantal coil system according to G. FANSELAU (12), and exposed to fields of different values of H and Z. The resultant deviation curves are shown in fig. 3. Instrument 1 shows semi-circular deviation (max. difference of 0.4° or

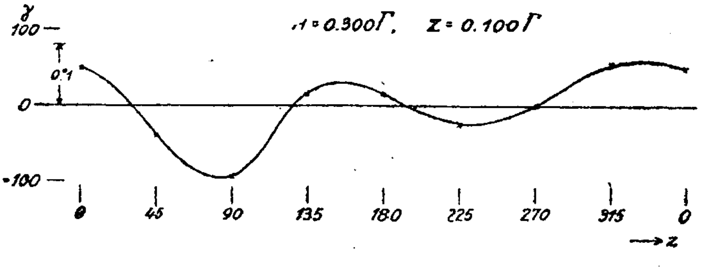
150 γ), although the curves for H = 0.2009 and H = 0.1518 do not differ essentially from each other. The small displacement in the Z direction is accidental, since the course in this case was calculated, not by halving the deflection angle, but from the position of the North point on the upper compass card. (see fig. 3a). The deviation obtained with instrument N° 2 in fields H = 0.175, z = 0.440 shows with inner irregularity of about 30 γ a predominately semi circular part of 70 γ ; the quadrantal part amounts to 20 γ. In field H' = 0.3000 z' = 0.100 (fig. 3b) the mean inner irregularity was only 10 γ, the quadrantal deviation was much more pronounced, remained however at 40 γ. The calculation of the deviation coefficients gave :—

$\mathcal{B}$ = 0,0040 $\mathcal{B}'$ = 0,0005
$\mathcal{C}$ = 0,0009 $\mathcal{C}'$ = 0,0016
$\mathcal{D}$ = 0,0018 $\mathcal{D}'$ = 0,0013
$\mathcal{E}$ = 0,0002 $\mathcal{E}'$ = 0,0002
λ = 1,000 λ = 1,000

FIG. 3. — *Deviation curves.*



3a — predominating semi-circular deviation (Instrument 1).



3b — semi-circular and quadrantal deviation (Instrument 2).

In accordance with the theory, $\mathcal{D}$, $\mathcal{E}$ and γ must be constant, and this is the case within the limits of the irregularity. The determination of the deviation in fields of different H and Z values permits the evaluation of the so-called Poisson constants of the horizontal component. If X, Y and Z are the components of the earth field; X', Y' and Z' those of the measured field, *a* to *f* factors which determine the part of the field induced by X, Y and Z, P and Q the perturbating components resulting from the permanent magnetisation, then, with certain reservations the Poisson system of equations

$$X' = X + a X + b Y + c Z + P$$
$$Y' = Y + d X + e Y + f Z + Q$$

may be assumed to be valid. The factors a to f then bear the following relations to the deviation coefficients :—

$$c = \frac{\lambda\,(\mathcal{B}\,H - \mathcal{B}'\,H')}{Z_1 - Z_2} \qquad f = \frac{\lambda\,(\mathcal{C}\,H - \mathcal{C}'\,H')}{Z_1 - Z_2}$$

$$a = \lambda\,(1 + \mathcal{D}) - 1$$
$$e = \lambda\,(1 - \mathcal{D}) - 1 \qquad b + d = 2\,\lambda\,\mathcal{E}$$
$$P = \lambda\,\mathcal{B}\,H - c\,Z \qquad Q = \lambda\,\mathcal{C}\,H - f\,Z$$

There-from the following values :

$a = 0{,}0015$ $e = 0{,}0016$ $P = 9\,\gamma$
$c = 0{,}0015$ $f = 0{,}0009$ $Q = 77\,\gamma$

The calculated value of Q is undoubtedly too large, since the maximum divergence from the deviation curve lies below this value; it shows that for a reliable determination of the constants the observations on the stand must be more exactly carried out. Still, one must be prepared to encounter such values and more attention must be given to material of construction free from disturbing influences or else to compensate the sources of disturbance. In comparison with the values of the perturbations on iron ships these values are exceptionally small. Bidlingmaier had to deal with values of

P = 0.003 cgs units (outward bound) and 0,0025 (homeward bound)
Q = 0.0013 » » 0.0002 »

or magnitudes which reached as much as 300 γ.

A check of the liaison constants in various H fields showed that variation in the field of ± 2500 γ was still not detrimental :

Δ H in γ	C *N over E*	C *N over W*
0	0,3111	0,3415
2490	0,3115	0,3416
— 2490	0,3115	0,3416

With larger variations of H it is necessary to count on needle induction so that C must then change; check with liaisons then becomes essential. A test to determine to what extent Z influences the deflection angle, showed that for $\Delta Z = 0.1\,\Gamma$ a change of $\frac{\psi}{2}$ of only 0.02°; the influence of Z is therefore inappreciable in this instrument.

One serious drawback to this test-method must be noted; it is not possible to separate the compass cards at will; for this a very complicated supplementary structure is required. Therefore in the liaison measurements the determinations of log C were always made for the two usual working positions of " North above over East under " and " North above over West under ". The accidental cases which then occur in the numerical values can be readily recognized and the corresponding value of log C substituted.

The conditions under which the work must be carried out at sea may easily result in shocks to the apparatus which, in spite of its robust construction, may result in the danger of a jump in the value of log C. In order to obtain experience the work was carried out at first in all kinds of weather.

The following table gives the comparisons of C before and after the sea voyage, for which different compass cards were assembled under various conditions.

	C	Mean Irregularity	In %	In γ for H = 18000
I before the voyage	0.3469	0.0012	0.35	63
after the voyage 1....	0.3450			
» » 2....	0.3448			
Comparison	—	0.0002_5	0.08	14
II before the voyage	0.3419	0.0001_5	0.04	7
after the voyage	0.3416			
III before the voyage	0.3119	0.0004	0.08	14
after the voyage	0.3111			
IV before the voyage	0.4960	0.0004	0.08	14
after the voyage 1....	0.5000			
» » 2....	0.5005			
V before the voyage	0.3076	0.0007	0.23	41
after the voyage	0.3089			

According to this the values of C show changes throughout up to case I, which gave rise to errors under 50 γ and in case I a compensation for the perceptible temporal change in the error would reduce it to 14 γ. The safety of 0.001 Γ was not threatened in any case. In one instance the sphere struck the side of the strongly rolling ship so hard when it was being put over that the point of suspension inside was torn right off and the pivots were damaged. After a quick repair in port and a series of test measurements the instrument was ready for immediate service.

Bidlingmaier reports that in his measurements of *D. Poseidon* (Lit. 1, page 93) a deviation from of the course of 2° produced a change in intensity of 2%; i.e. with $H_0 = 0.150$ of about 300 γ. Our deviation curves show that the immersion apparatus of the Deutsche Seewarte, with a sensitivity of 40 γ per 0.1° and a change of course of 10° produced an error of reading of 38 γ and in another case of 75 γ. As example of measurements with large changes of course the following case is cited :—

The compass cards changed from :

258.7° to 296.0° for the upper card
40.7° to 77.0° for the lower card

i.e. a change of course of 36.5° occured. The half-angle of deflection in the first half on the measurements lay near 70.74° and in the second half near 70.30°; they therefore remained sufficiently constant. (fig. 4).

For comparative check measurements at sea, readings were taken for several consecutive days while the ship lay in the same position at anchor in a locality completely free from all disturbing influences. The change of position resulting from swinging of the ship about the anchor was without effect.

Date	Série	$\Psi/2$	Corr.	$\Psi/2$	H	H average
10.VIII.1938	1	71.5°	— 0.3°	71.22°	0.1834	0.1835 ± 10 γ
	2	76.6°				
	3	71.5°				
11.VIII.1938	1	71.3°	— 0.2°	71.1°	0.1836	
	2	71.3°				

With repetition measurements after intervening cruises there is the additional difficulty of being able to come back to the same position with sufficient accuracy. This is only possible when bearings from three fixed points are available. In the field of perturbations to the southward of Bornholm we obtained the following values for one such points :—

Date	$\Psi/2$	Inner Error	H	Average
22.VIII.1938	71.32°	± 0.03°	0.1732	0.1735 ± 30
17.X.1938	71.24°	0.02°	0.1738	

The earth magnetic variation is not taken into account in this. The values of $\frac{\psi}{2}$ are derived from 6 or 5 series of measurements, which are based on 20 to 30 photographs. The time requirements for each complete measurement were less than 5 minutes.

Further repetitions :—

	Date	$\Psi/2$	H	Average
Station A	17.VIII.1938	71.5°	0.1737	0.1735 ± 15 γ
	18.X.1938	71.3°	0.1734	
Station B	10.VIII.1938	71.2°	0.1743	0.1747 ± 40 γ
	11.VIII.1938	71.1°	0.1751	

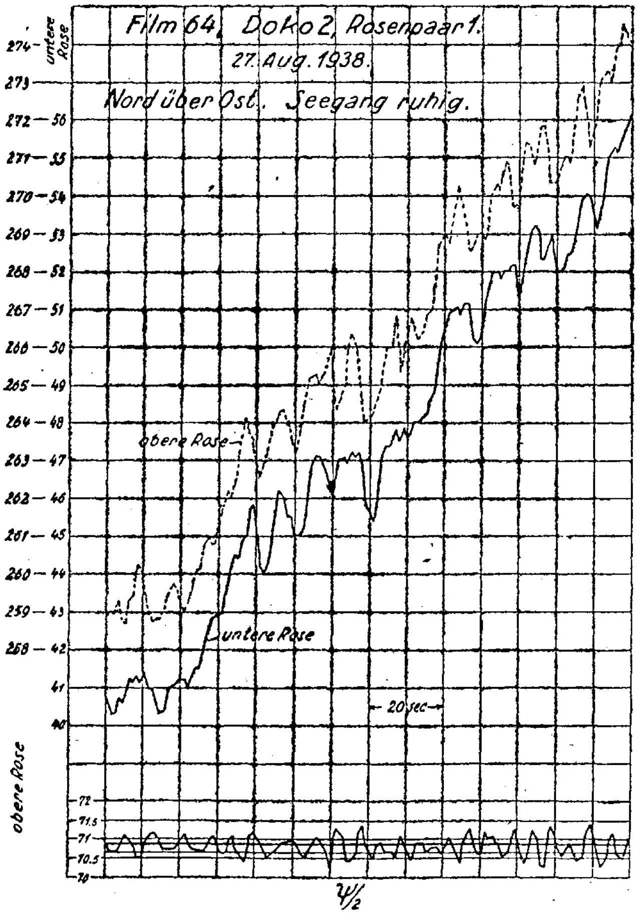


FIG. 4. — *Position of upper and lower cards and half deflection angle*
One esposure per second.

In the above mentioned case of severe damage there was obtained :

before .... 24.VIII.1938 $\Psi/2 = 69.9^\circ \pm 0.2^\circ$ $H = 0.1858$
after .... 27.VIII.1938 $\Psi/2 = 69.7^\circ$ 0.1875 $\Big\}$ 0.18665
difference : 0.0017

The third decimal place can show here only the probable values.

It cannot be denied that with repetition measurements some cases of poor agreement occur. With astronomical navigation one must count on an error in position of 1 nautical mile, and consequently with a difference in ships position which in areas of magnetic disturbance may easily lead to a difference in the field of several 100 γ. It is therefore not surprising when uncertainties as great as ± 170 γ occured. Even in the above cited comparison of 24 and 25 VIII there is a possible position error of 0.5 nautical miles, while in addition this position lay in a field of great perturbations in the eastern Baltic. Measurements with very rough sea naturally call for a repetition, but should not be used as a criterion of the accuracy of the method any more than measurements taken ashore on days of magnetic disturbances. As regards the measurements of the First Order secular stations of the German Magnetic Reichsvermessung every station today is measured not only with two instruments but also by two observers in order to insure the greatest possible reliability in the measurement. With large-scale measurements at sea in accordance with the above described method, it would appear advisable to work in the same manner with two complete instruments, of which the second is put overboard the moment the first is hauled in. The additional time required for this, which comes to about one half hour with well trained ship personnel, could well be profitably utilized for a better check of the individual station.

In the following table we give as example an extract from the observed values for a normal measurement.

In this the inner error of the individual measurement is given. The actual error, shown by repetition measurements was previously determined as between about 10 to 50 γ.

Station 17. 14.VIII beginning 13 h. 34 m., Average T, sea: calm.
1. series. N. over E.

	lower card	*upper card*	ψ
	68.3	288.1	140.2
	66.7	286.7	140.0
	65.4	284.9	140.5
	65.0	283.9	141.1
	65.6	284.6	141.0
	65.8	285.7	140.1
	66.8	286.9	139.9
	67.6	287.5	140.1
	67.7	287.3	140.4
	68.0	287.2	140.8
	68.0	287.2	140.8
	67.9	287.6	140.3
	67.4	287.3	140.1
	67.5	287.4	140.1
	67.9	287.0	140.9
	68.4	287.5	140.9
	67.6	287.3	140.3
	67.6	287.1	140.5
	67.1	286.4	140.7
Average	67.20	286.75	$140.45 \pm 0.08_4$

$\psi/2 = 70.23^\circ \pm 0.04^\circ_4$
Course correction $-\ 0.16^\circ$
$\psi/2 = 70.07^\circ$

$\psi/2$ after serie 1		70.07°
Also after 20 readings	Serie 2	70.00°
	» 3	70.03°
	» 4	69.99°
	» 5	70.03°
	» 6	69.95°
	» 7	70.00°
	» 8	69.94°
	» 9	70.00°
	Average ψ =	70.00° ± 0.001°

The question then arises as to whether the measurements in the immersion sphere can be properly compared with the measurements obtained in the conditions at sea up to now. The following data can be given with regard to the requirements for accuracy in the best known of the previous tests.

With regard to the measurements on board the "Galilee", it was reported in the Carnegie Works, Vol. III, that the error is in the vicinity of the third decimal place and that the fourth decimal place is only retained as a result of calculation. The example which is given there on page 56 in table 4 for the measurement in a position by three different methods shows that even between the individual values there is a maximum difference of over 200 γ. The mean values, on the other hand, determined from the results obtained by the different methods, agree to within about 60 to 70 γ. In the measurements aboard the "Carnegie" four decimal places are given, but a note states (vol. III, p. 257) that the error may be as much a four or five units in the fourth decimal place. F. Bidlingmaier has found that the inaccuracy in the corrections due to the ships iron is greater than the observation itself and the calculator of the observations, P. Nelle, comes to the conclusion that the inaccuracy in general must be assumed at about 100 γ (p. 398). He found that in individual cases there was even a maximum difference of 400 γ, which occured between four different series of observations on the same day! The new observations made with the double compass on board iron-free ships or ships with little disturbance will be considerably better. H. v. Gernet assumes an inner error of 50 γ, for his measurements in 1924 on the "Cäcilie", which he derived from his supplementary values. The report of L. Slaucitajs on the measurements in 1928 aboard the same ship gives for the difference from the basic station 37 γ; from the two positions N over E and N over W he determines the difference $\frac{He - H_w}{2}$ and notes that at sea this factor reaches 50 γ in 75% of the cases, during which however the changes in the field during the voyage must be taken into consideration. He also assumes only the third decimal place to be correct.

Keranen and Odelsiö (3c) find the very favorable value of 23 γ as a measure of the accuracy, but in their tables are places where the stations show a difference of more than 300 between the two measurements.

In the latest pupblications of Ljungdahl (7) on the measurements with the Askania double compass on board the yacht "Compass" it is shown that he had to count on deviations of as much as 1000 γ. For one station measured twice he obtained an inner error of 20 γ, but points out that the true errors at times were twice that amount.

From the above it follows that the object of the previous measurements at sea was the reliable determination of the third decimal place. In the magnetic measurements ashore efforts have been made to push the reliability of the measurements of H to the fifth decimal place, but this has not been achieved because the inner irregularities must be assumed to reach as much as 5 γ. Only by accumulating completely independent measurements at one point will it become possible to guarantee reliable results to the fifth place in spite of the difficulties arising above all from the temperature determinations and the reduction of the variation. When in the measurements at sea, we gain a tenth in the inner irregularities, then we can assume that the method under consideration satisfactorily fulfills the present requirements. This also presumes that a reduction of the error may be obtained. The principal advantage of the method of sinking the double compass in an immersion sphere, lies primarily in the fact that for the measurement of H in the oceans one is not restricted to the use of an iron-free ship, but may make use of any vessel used for oceanographic service for taking complementary H measurements, without the necessity for disproportionately large expenditures for the instrument, auxiliary apparatus and ship.

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