A PRACTICAL MANUAL OF THE COMPASS

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[Laning, Harris]

A SHORT TREATISE ON THE ERRORS OF THE MAGNETIC COMPASS, WITH THE METHODS EMPLOYED IN THE U. S. NAVY FOR COMPENSATING THE DEVIATIONS

AND

A DESCRIPTION OF SERVICE INSTRUMENTS, INCLUDING THE GYRO-COMPASS

PREPARED WITH THE APPROVAL OF THE BUREAU OF NAVIGATION, NAVY DEPARTMENT

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PREFACE

This book, prepared at the Naval Observatory and Naval Academy, is designed to become the service compass manual and to replace Diehl's *Practical Problems and the Compensation of the Compass,* which will not be republished.

It was originally compiled by Lieutenant Commander Harris Laning, Head of the Department of Navigation at the Naval Academy, as a text-book for midshipmen.

Later, however, a revision of Diehl having been undertaken by the Naval Observatory, it was decided to use this book and to add two chapters to it, one on the gyro-compass and the other a description of the instruments supplied to the service in connection with compass work. These two chapters, as well as Chapter VI, and a revision of Chapter X, were prepared at the Naval Observatory by Lieutenant Commander C. T. Owens, in charge of the Compass Office. Acknowledgments are due to Commanders D. W. Blamer and George C. Day, and to Lieutenant Commander C. R. Miller, for notes on compass material and compass work which were used in connection with chapters prepared at the Naval Observatory.

It was further enlarged (1916) by the addition of the chapters on "Compass Corrections by the Azimuth Method," by Commander J. B. Patton, U. S. Navy, and on the "Principles of the Gyroscopic Compass," by Captain L. M. Nulton, U. S. Navy.

This book is a compilation from various sources, which brings together the best practical material on the subject and puts in one volume what would otherwise have to be taken from several books and many pamphlets. The complex mathematical theory of the deviation of the compass and the derivation of formulæ have been entirely omitted, but a sufficient explanation of causes and effects is given to enable the student to understand any ordinary problem that may arise.

For a more complete course on the subject of the Deviation of the Compass, the following books are recommended:

British Admiralty Manual of Deviations.

Navigation and Compass Deviations, Muir.

Deviation of the Compass in Iron Ships, Creak.

VICTOR BLUE,
Chief of Bureau of Navigation.

NAVY DEPARTMENT, WASHINGTON, D. C., April 1, 1916.

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CHAPTER I.

THE COMPASS ERROR.

By COMMANDER G. W. LOGAN, U. S. N.

(Taken from the *American Practical Navigator* (Bowditch).)

CAUSES OF THE ERROR.

1. When two magnets are near enough together to exert a mutual influence, their properties are such as to cause those poles which possess similar magnetism to repel, and those which possess magnetism of opposite sorts to attract one another.

The earth is an immense natural magnet, having in each hemisphere a pole lying in the neighborhood of the geographical pole, though not exactly coincident therewith; consequently, when a magnet, such as that of a compass, is allowed to revolve freely in a horizontal plane, it will so place itself as to be parallel to the lines of magnetic force in that plane created by the earth's magnetic poles, the end which we name north pointing to the north, and the south end in the opposite direction. The north end of the needle—north-seeking, as it is sometimes designated for clearness—will be that end which has opposite polarity to the earth's north magnetic pole, this latter possessing the same sort of magnetism as the so-called south pole of the compass.

2. By reason of the fact that the magnetic pole differs in position from the geographical pole, the compass needle will not indicate true directions, but each compass point will differ from the corresponding true point by an amount dependent upon the angle between the geographical and the magnetic pole at the position of the observer. The amount of this difference, expressed in angular measure, is the *variation of the compass* (sometimes also the *declination,* though this term is seldom employed by navigators).

The variation not only changes as one travels from point to point on the earth, being different in different localities, but, as it has been found that the earth's magnetic poles are in constant motion, it undergoes certain changes from year to year. In taking account of the error it produces, the navigator must therefore be sure that the variation used is correct not only for the *place,* but also for the *time* under consideration. The variation is subject to a small diurnal fluctuation, but this is not a material consideration with the mariner.

3. Besides the error thus produced in the indications of the compass, a further one, due to *local attraction,* may arise from extraneous influences due to natural magnetic attraction in the vicinity of the vessel. Instances of this are quite common when a ship is in port, as she may be in close proximity to vessels, docks, machinery, or other masses of iron or steel. It is also encountered at sea in localities where the mineral substances in the earth itself possess magnetic qualities—as, for example, at certain places in Lake Superior and at others off the coast of Australia. When due to the last-named cause, it may be a source of great danger to the mariner, but, fortunately, the number of localities subject to local attraction is limited. The amount of this error can seldom, if ever, be determined; if known, it might properly be included with the variation and treated as a part thereof.

4. In addition to the variation, the compass ordinarily has a still further error in its indications, which arises from the effect exerted upon it by masses of magnetic metal within the ship itself. This is known as the *deviation of the compass.* For reasons that will be explained later, it differs in amount for each heading of the ship, and, further, the character

of the deviations undergoes modification as a vessel proceeds from one geographical locality to another.

APPLYING THE COMPASS ERROR.

5. From what has been explained, it may be seen that there are three methods by which bearings or courses may be expressed: (a) *true,* when they refer to the angular distance from the earth's geographical meridian; (b) *magnetic,* when they refer to the angular distance from the earth's magnetic meridian, and must be corrected for variation to be converted into true; and (c) *by compass,* when they refer to the angular distance from the north indicated by the compass on a given heading of the ship, and must be corrected for the deviation on that heading for conversion to magnetic, and for both deviation and variation for conversion to true bearings or courses. The process of applying the errors under all circumstances is one of which the navigator must make himself a thorough master; the various problems of conversion are constantly arising; no course can be set nor bearing plotted without involving the application of this problem, and a mistake in its solution may produce serious consequences. The student is therefore urged to give it his most careful attention.

6. When the effect of a compass error, whether arising from variation or from deviation, is to draw the north end of the compass needle to the right, or eastward, the error is named *east,* or is marked +; when its effect is to draw the north end of the needle to the left or westward, it is named *west,* or marked −.

Figs. 1 and 2 represent, respectively, examples of easterly and westerly errors. In both cases consider that the circles represent the observer's horizon, *N* and *S* being the correct north and south points in each case. If *N′* and *S′* represent the corresponding points indicated by a compass whose needle is deflected by a compass error, then, in the first case, the north end of the needle being drawn to the right or east, the error will be easterly or positive, and in the second case, the north end of the needle being drawn to the left or west, the compass error will be westerly or negative.

Considering Fig. 1, if we assume the easterly error to amount to 10°, it will be seen that if a direction of 350° is indicated by the compass, the correct direction should be north, or 10° farther to the right. If the compass indicates north, the correct bearing is 10°; that is, still 10° to the right. If we follow around the whole card, the same relation will be found in every case, the corrected bearing being always 10° to the right of the compass bearing. Conversely, if we regard Fig. 2, assuming the same amount of westerly error, a compass bearing of

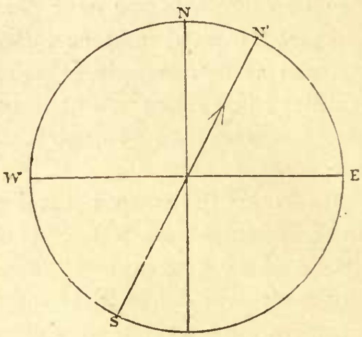

FIG. 1.

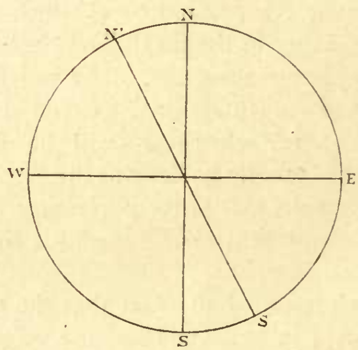

FIG. 2.

10° is the equivalent of a correct bearing of north, which is 10° to the left; and this rule is general throughout the circle, the corrected direction being always to the left of that shown by the compass.

7. Having once satisfied himself that the general rule holds, the navigator may save the necessity of reasoning out in each case the direction in which the error must be applied, and need only charge his mind with some single

formula which will cover all cases. Such a one is the following:

When the CORRECT *direction is to the* RIGHT, *the error is* EAST.

The words *correct—right—east,* in such a case, would be the key to all of his solutions. If he had a compass course to change to a corrected one with easterly deviation, he would know that to obtain the result the error must be applied to the right; if it were desired to change a correct course to the one indicated by compass, the error being westerly, the converse presents itself—the correct must be to the left—the uncorrected will therefore be to the right; if a correct bearing is to be compared with a compass bearing to find the compass error, when the correct is to the right the error is east, or the reverse.

8. It must be remembered that the word *east* is equivalent to *right* in dealing with the compass error, and *west* to *left,* even though they involve an apparent departure from the usual rules. If a vessel steers 45° by compass with 10° easterly error, her corrected course is 55°; and if she steers 135°, the corrected course is 145°. A caution may be necessary to avoid confusion; the navigator should always regard himself as facing the point under consideration when he applies an error; 10° westerly error on South (180°) will bring a corrected direction to 170°; but if we applied 10° to the left of South while looking at the compass card in the usual way—north end up—190° would be the point arrived at, and a mistake of 20° would be the result.

9. In the foregoing explanation reference has been made to "correct" directions and "compass errors" without specifying "magnetic" and "true" or "variation" and "deviation." This has been done in order to make the statements apply to all cases and to enable the student to grasp the subject in its general bearing without confusion of details.

Actually, as has already been pointed out, directions given may be true, magnetic, or by compass. By applying variation to a magnetic bearing we correct it and make it true, by applying deviation to a compass bearing we correct it to magnetic, and by applying to it the combined deviation and variation we correct it to true. Whichever of these operations is undertaken, and whichever of the errors is considered, the process of correction remains the same; the correct direction is always to the right, when the error is east, by the amount of that error.

Careful study of the following examples will aid in making the subject clear:

Examples.

A bearing taken by a compass free from deviation is 76°; variation, 5° W.; required the true bearing. Ans. 71°.

A bearing taken by a similar compass is NW. by W. ½ W.; variation, ¼ pt. W.; required the true bearing. Ans. NW. by W. ¾ W.

A vessel steers 153° by compass; deviation on that heading, 3° W.; variation in the locality, 12° E.; required the true course. Ans. 162°.

A vessel steers S. by W. ½ W.; deviation, ¼ pt. W.; variation, 1 pt. E.; required the true course. Ans. SSW. ¼ W.

It is desired to steer the magnetic course 322°; deviation, 4° E.; required the course by compass. Ans. 318°.

The true course between two points is found to be W. ¾ N.; variation 1¼ pt. E.; no deviation; required the compass course. W. ⅝ S.

True course to be made, 55°; deviation, 7° E.; variation, 14° W.; required the course by compass. Ans. 62°.

A vessel passing a range whose direction is known to be 200°, magnetic, observes the bearing by compass to be 178°; required the deviation. Ans. 22° E.

The sun's observed bearing by compass is 91°; it is found by calculation to be 84° (true); variation, 8° W.; required the deviation. Ans. 1° E.

FINDING THE COMPASS ERROR.

10. The variation of the compass for any given locality is found from the charts. A nautical chart always contains information from which the navigator is enabled to ascertain the variation for any place within the region embraced and for any year. Beside the information thus to be acquired from local

charts, special charts are published showing the variation at all points on the earth's surface.

11. The deviation of the compass, varying as it does for every ship, for every heading, and for every geographical locality, must be determined by the navigator, for which purpose various methods are available.

Whatever method is used, the ship must be swung in azimuth and an observation made on each of the headings upon which the deviation is required to be known. If a new iron or steel ship is being swung for the first time, observations should be made on each of the thirty-two points or for each 15°. At later swings, especially after correctors have been applied, or in the case of wooden ships, sixteen points will suffice—or, indeed, only eight, or with a compass reading to 360° on each 30°. In case it is not practicable to make observations on the exact 15° points, they should be made as near thereto as practicable and plotted on the Napier diagram (to be explained hereafter), whence the deviations on exact 15° points may be found.

12. In swinging ship for deviations the vessel should be on an even keel and all movable masses of iron in the vicinity of the compass secured as for sea. The vessel, upon being placed on any heading, should be steadied there for three to four minutes before the observation is made in order that the compass card may come to rest and the magnetic conditions assume a settled state. To assure the greatest accuracy the ship should first be swung to starboard, then to port, and the mean of the two deviations on each course taken. Ships may be swung under their own steam, or with the assistance of a tug, or at anchor, where the action of the tide tends to turn them in azimuth (though in this case it is difficult to get them steadied for the requisite time on each heading), by means of springs and hawsers.

13. The deviation of all compasses on the ship may be obtained from the same swing, it being required to make observations with the standard only. To accomplish this it is necessary to record the ship's head by all compasses at the time of steadying on each even point of the standard; applying the deviation, as ascertained, to the heading by standard, gives the magnetic heads, with which the direction of the ship's head by each other compass may be compared, and the deviation thus obtained. Then a complete table of deviations may be constructed as explained in Art. 22.

14. There are four methods for ascertaining the deviations from swinging; namely, by *reciprocal bearings,* by *bearings of the sun,* by *ranges,* and by a *distant object.*

15. Reciprocal Bearings.—One observer is stationed on shore with a spare compass placed in a position free from disturbing magnetic influences; a second observer is at the standard compass on board ship. At the instant when ready for observation a signal is made, and each notes the bearing of the other. The bearing by the shore compass, reversed, is the magnetic bearing of the shore station from the ship, and the difference between this and the bearing by the ship's standard compass represents the deviation of the latter.

In determining the deviations of compasses placed on the fore-and-aft amidship line, when the distribution of magnetic metal to starboard and port is symmetrical, the shore compass may be replaced by a dumb compass, or pelorus, or by a theodolite in which, for convenience, the zero of the horizontal graduated circle may be termed north; the reading of the shore instrument will, of course, not represent magnetic directions, but by assuming that they do we obtain a series of fictitious deviations, the mean value of which is the error common to all. Upon deducting this error from each of the fictitious deviations, we obtain the correct values.

If ship and shore observers are provided with watches which have been compared with one another, the times may be noted at each observation, and thus afford a means of locating errors due to misunderstanding of signals.

16. Bearings of the Sun.—In this method it is required that on each heading a bearing of the sun be observed by compass and the time noted at the same moment by a chronometer or watch. By a method that is explained in Chapter XIV, *American Practical Navigator*

the true bearing of the sun may be ascertained from the known data, and this, compared with the compass bearing, gives the total compass error; deducting from the compass error the variation, there remains the deviation. The variation used may be that given by the chart, or, in the case of a compass affected only by symmetrically placed iron or steel, may be considered equal to the mean of all the total errors. Other celestial bodies may be observed for this purpose in the same manner as the sun.

This method is important as being the only one available for determining the compass error at sea.

17. Ranges.—In many localities there are to be found natural or artificial range marks which are clearly distinguishable, and which when in line lie on a known magnetic bearing. By steaming about on different headings and noting the compass bearing of the ranges each time of crossing the line that they mark, a series of deviations may be obtained, the deviation of each heading being equal to the difference between the compass and the magnetic bearing.

18. Distant Object.—A conspicuous object is selected which must be at a considerable distance from the ship and upon which there should be some clearly defined point for taking bearings. The direction of this object by compass is observed on successive headings. Its true or magnetic bearing is then found and compared with the compass bearings, whence the deviation is obtained.

The true or the magnetic bearing may be taken from the chart. The magnetic bearing may also be found by setting up a compass ashore, free from foreign magnetic disturbance, in range with the object and the ship, and observing the bearing of the object; or the magnetic bearing may be assumed to be the mean of the compass bearings.

In choosing an object for use in this method care must be taken that it is at such a distance that its bearing from the ship does not practically differ as the vessel swings in azimuth. If the ship is swung at anchor, the distance should be not less than 6 miles. If swung under way, the object must be so far that the parallax (the tangent of which may be considered equal to half the diameter of swinging divided by the distance) shall not exceed about 30′.

19. In all of the methods described it will be found convenient to arrange the results in tabular form. In one column record the ship's head by standard compass, and abreast it in successive columns the observations from which the deviation is determined on that heading, and finally write the deviation itself. When the result of the swing has been worked up another table is constructed showing simply the headings and the corresponding deviations. This is known as the *Deviation Table* of the compass. If compensation is to be attempted, this table is the basis of the operation; if not, the deviation tables of the standard and steering compass should be posted in such place as to be accessible to all persons concerned with the navigation of the ship.

20. Let it be assumed that a deviation table has been found and that the values are as shown in Form No. 12 (a) on following page.

We have from the table the amount of deviation on each compass heading; therefore, knowing the ship's head by compass, it is easy to pick out the corresponding deviation and thus to obtain the magnetic heading. But if we are given the magnetic direction in which it is desired to steer, and have to find the corresponding compass course, the problem is not so simple, for we are not given deviations on magnetic heads, and where errors are large it may not be assumed that they are the same as on the corresponding compass headings. For example, with the deviation table given above, suppose it is required to determine the compass heading corresponding to 285° magnetic.

The deviation corresponding to 285°, per compass is +12° 00′. If we apply this to 285° magnetic, we have 273° as the compass course. But consulting the table, it may be seen that the deviation corresponding to 273° is +16° 00′, and therefore if we steer that course the magnetic direction will be 289° and not 285° as desired.

A way of arriving at the correct result is to make a series of trials until a course is arrived

[Ships

DEVIATION TABLE.

(For ship's use.)

Form No. 12 (a).

............................* *Compass* ....

U. S. S...

Date.., 191

Latitude............... *Variation used*.....................

Longitude..

Ship's head by compass	Deviation		Ship's head by compass	Deviation	
	°	′		°	′
0°	0	0	180°	0	00
15°	+ 2	00	195°	+ 9	00
30°	+ 0	30	210°	+ 16	30
45°	− 3	00	225°	+ 21	00
60°	− 8	00	240°	+ 22	45
75°	− 14	00	255°	+ 21	15
90°	− 19	30	270°	+ 17	30
105°	− 23	00	285°	+ 12	00
120°	− 25	00	300°	+ 7	00
135°	− 24	30	315°	+ 2	00
150°	− 21	00	330°	− 1	30
165°	− 13	00	345°	− 2	00

Approved: .... *U. S. Navy, Commanding.*

Details of compensation.

....

....

....

Respectfully,

....

U. S. Navy, Navigator.

* Insert designation—as, "Standard," "Steering," etc.
4—169

at which fulfils the conditions. Thus, in the example given:

First Trial.

Mag. course required	285°
Try deviation on 285° p. c.	+ 12°
Trial compass course	273°
Dev. on 273° p. c.	+ 16
Mag. course made good	289°

Since this assumption carries the course 4° too far to the right, assume next a deviation on a course 4° farther to the left than the trial compass course found above.

Second Trial.

Trial compass course	269°
Dev. on 269°	+ 17° 45′
Mag. course made good	286° 45′

This assumption still carries the course too far to the right by 1° 45′.

Third Trial.

Trial compass course	267°
Dev. on 267°	+ 18° 15′
Mag. course made good	285° 15′

This is as close to the required course as the ship may be steered.

21. A much more expeditious method for the solution of the above problem is afforded by the *Napier diagram;* and as that diagram also facilitates a number of other operations connected with compass work, it should be clearly understood by the navigator. This device admits of a graphic representation of the table of deviations of the compass by means of a curve, besides furnishing a ready means of converting compass into magnetic courses and the reverse. One of its chief merits is that if the deviation has been determined on a certain number of headings, it enables one to obtain the most probable value of the deviation on any other course that the ship may head. The last-named feature renders it useful in making a table of deviations of compasses other than the standard, when their errors are found as described in Art. 13.

22. The Napier diagram (Fig. 3) represents the margin of a compass card cut at the north point and straightened into a vertical line; for convenience, it is usually divided into two sections, representing respectively the eastern and western semicircles. The vertical line is of a convenient length and divided into three hundred and sixty equal parts corresponding to each degree, beginning at the top with north and continuing around to the right, with each fifth degree appropriately marked.

The vertical line is intersected at each fifteenth degree by two lines inclined to it at an angle of 60°, that line which is inclined upward to the right being drawn plain and the other dotted.

N. Nav. 2.

CURVE OF DEVIATIONS

(Constructed upon the Napier Diagram.)

Of the ________________ *Compass No.* ____________ *on board the*

U. S. S. ________________

Lat. ____________

Date of observations ____________, 191 *Long.* ____________

Compass courses on dotted lines. Magnetic courses on solid lines.

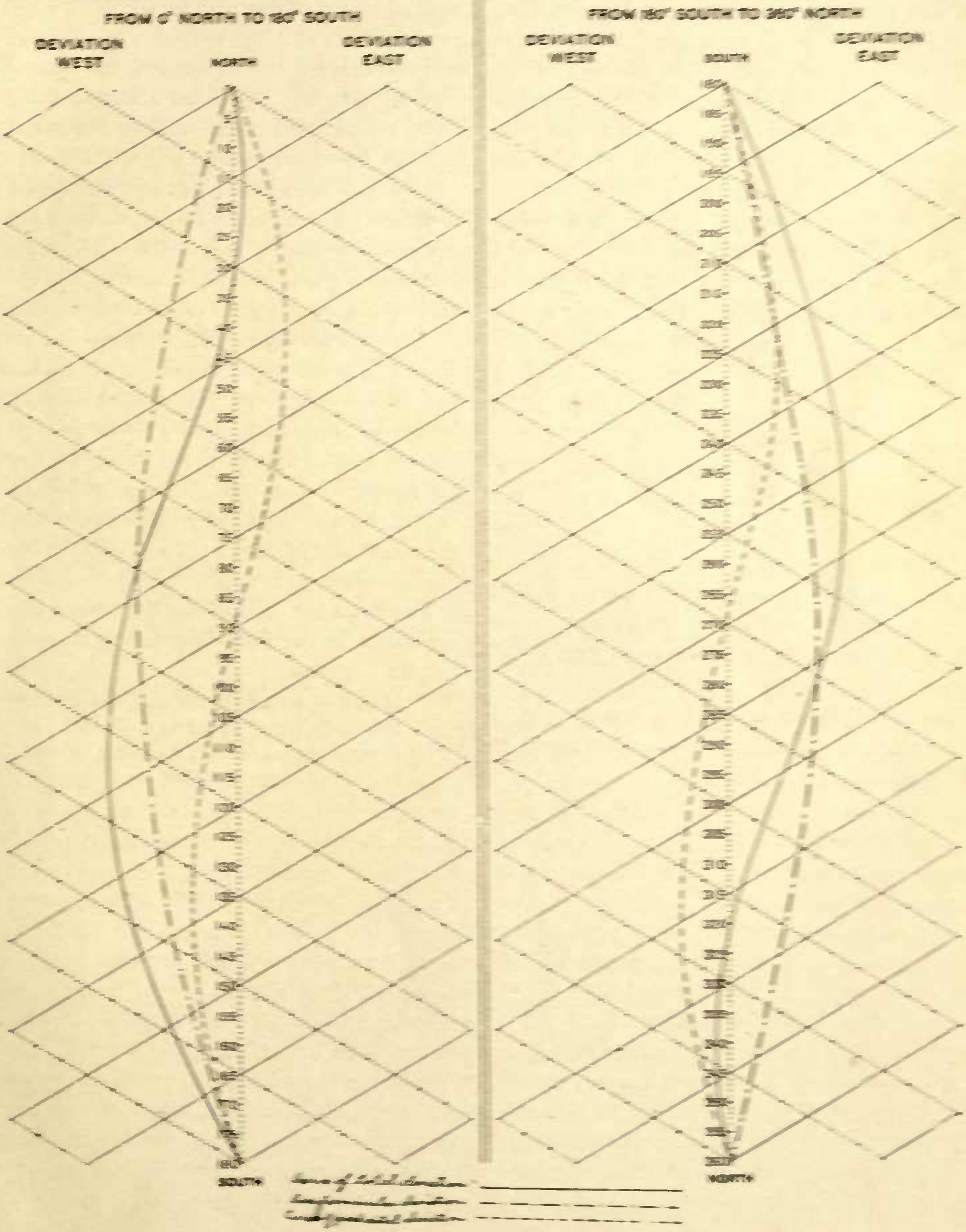

FIG. 3.

To plot a curve on a Napier's diagram, if the deviation has been observed with the ship's head on the 15° courses (as is usually the case with the standard compass), measure off on the vertical scale the number of degrees corresponding to the deviation and lay it down—to the right if easterly, and to the left if westerly —on the *dotted* line passing through the point representing the ship's head; or, if the observation was not made on an even 15° point, then lay the deviation down on a line drawn parallel to the dotted ones through that division of the vertical line which represents the compass heading; if the deviation has been observed with the ship on given magnetic courses (as when deviations by steering compass are obtained by noting a ship's head during a swing on even 15° points of the standard), proceed in the same way, excepting that the deviation must be laid down on a *plain* line or a line parallel thereto. Mark each point thus obtained with a dot or small circle, and draw a free curve passing, as nearly as possible, through all the points.

To obtain a complete curve, a sufficient number of observations should be taken while the ship swings through an entire circle. Generally, observations on every alternate 15° mark are enough to establish a good curve, but in cases where the maximum deviation reaches 40° it is preferable to observe on every 15° mark.

The curve shown in the full line on Fig. 3 corresponds to the table of deviations given in Art. 20.

From a given compass course to find the corresponding magnetic course. Through the point of the vertical line representing the given compass course, draw a line parallel to the *dotted* lines until the curve is intersected, and from the point of intersection draw another line parallel to the plain lines; the point on the scale where this last line cuts the vertical line is the magnetic course sought. The correctness of this solution will be apparent when we consider that the 60° triangles are equilateral, and therefore the distance measured along the vertical side will equal the distance measured along the inclined sides—that is, the deviation; and the direction will be correct, for the construction is such that magnetic directions will be to the right of compass directions when the deviation is easterly and to the left if westerly.

From a given magnetic course to find the corresponding compass course. The process is the same, excepting that the first line drawn should follow, or be parallel to, the *plain* lines, and the second, or return line, should be parallel to the dotted; and a proof similar to that previously employed will show the correctness of the result. As an example, the problem given in Art. 20 may be solved by the diagram, and the result will be found to accord with the solution previously given.

The rules for the use of a " Napier's Curve " are given in the following easily remembered jingle:

If you wish to steer the course allotted,
Depart by plain, return by dotted;
From compass course, magnetic to gain,
Depart by dotted, return by plain.

CHAPTER II.

THE PRINCIPLES OF THE DEVIATION OF THE COMPASS.

By COMMANDER L. M. NULTON, U. S. N.

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23. Introductory.—These notes are not a complete treatise on the deviation of the compass, but are an attempt to explain, by simple laws of magnets, how deviation is produced by the iron of a ship, and, by the same laws, how the deviation may be corrected. It is an explanation of *principles involved,* based upon the physical laws of the attraction and repulsion of magnets.

24. Natural Magnets or Lodestones.—The name magnet, or lodestone, was given by the ancients to certain hard, black stones which possessed the property of attracting to them small pieces of iron or steel.

25. Artificial Magnets.—If a piece of iron, or better still a piece of hard steel, be rubbed with a lodestone, it will be found to have also acquired the properties characteristic of the magnet; it will attract light bits of iron, and, if hung up by a thread, it will point north and south.

26. First Laws of Magnets.—If two magnets be suspended as above and brought near each other, it will be found that the north-seeking end of either magnet will repel the north-seeking end of the other magnet; similarly, if the south-seeking end of one magnet be brought near the south-seeking end of the other magnet, they will repel each other; if, however, the north-seeking end of one magnet be brought near the south-seeking end of the other magnet, these ends will attract each other. The ends of the magnets are called its poles. This brings to notice the fact that the character of the magnetism of one pole of a magnet is different from that of the other pole, and the important law of magnets, that *like poles repel* each other, and *unlike poles attract* each other.

27. Polarity Represented by Colors.—It is convenient to represent the character of the end of a magnet, *i. e.,* its polarity, by colors. In these notes, the character of the magnetism of the *north-seeking end of a suspended magnet* is represented by red, and the other end by blue.

28. Permanent and Temporary Magnets—Hard and Soft Iron.—With reference to its power to retain magnetism, iron is of two kinds, hard and soft. Hard iron when once magnetized remains so permanently. Such a magnet is said to be a permanent magnet. Soft iron is iron which possesses the characteristic of losing its magnetism upon the magnetizing source being removed or discontinued. Soft iron has another magnetic characteristic to which reference will be made later.

29. Induced Magnetism.—If one pole of a magnet be brought near a mass of iron which is not already magnetic, it will induce, in this mass, magnetism, the character of which is of the opposite kind from the pole which is presented to the mass. For example, if the red end of a magnet be presented to a non-magnetic mass of iron, it will induce magnetism in it, and the mass will itself become a magnet, with blue magnetism opposite the red pole presented to it, and red magnetism on the opposite side of the mass. This presents another important law of magnetism, which is as follows: *Induced magnetism is of the opposite polarity to the kind inducing it.* See Figs. 4 and 4a.

30. Earth a Magnet.—The earth is a large magnet the poles of which nearly coincide with the geographical poles. There is also similarly a magnetic equator, the belt of change from one magnetism to the other, or a belt of no magnetism. This belt exists in *all* magnets and is at right angles to the poles. The poles of the

earth attract, or repel, suspended magnets. The magnetism of the earth has also the power to induce magnetism. The direction of the line of action of the earth's magnetism is in the plane of the great circle passing through the magnet poles, *i. e.*, in the *magnetic meridian*.

31. Color of North Pole of Earth.—In accordance with the law of attraction existing between unlike poles, if we color the north-seeking end of the magnetic needle red, the north pole of the earth possesses blue magnetism.

32. Compass Needle a Magnet.—The compass needle is a small *permanent* magnet, or a collection of needles acting as one small permanent magnet.

33. Dip, and Horizontal and Vertical Components of the Earth's Force.—At the north magnetic pole of the earth, the north-seeking end of the needle will point directly downward and the needle will be vertical. At the magnetic equator the needle will rest horizontally. At points of the earth's surface between the magnetic pole and equator, the needle points at some angle to the horizontal. The angle between the horizontal and the direction in which the needle points is called the *dip*.

This is shown in Fig. 5, where the magnetism of the earth is represented by the large magnet, the position of the small needle being shown at different positions corresponding to different points on the earth's surface.

For a position such as *b* in Fig. 5, we have an analysis of the force of the earth as shown in Fig. 6.

The earth's total force, and its horizontal, or its vertical, component, are *each* capable of inducing magnetism.

34. Deviation Defined.—Under the influence of the earth's magnetism acting alone, the needle of the compass is drawn to point directly to the magnetic poles of the earth, and lies in the plane of the magnetic meridian. Under the influence of other forces opposing the action of the force of the earth alone, such as the action of the iron of a ship, or an artificial magnet of either hard or soft iron, the compass needle is caused to deviate from the vertical plane of the magnetic meridian and to lie in some other plane inclined to the magnetic meridian. The angle between this plane and the plane of the magnetic meridian is called the *deviation of the compass*. If the north point of the compass is drawn to the right of the magnetic meridian (facing the north magnetic pole of the earth) the deviation is called *easterly* and is considered *positive;* if the north pole of the needle is drawn to the left of a magnetic north, the deviation is named *westerly* and is considered as being *negative*. From the above definitions it will be seen that (having a compass heading and knowing the deviation for that heading) easterly deviation must be applied to the right hand, and westerly deviation to the left hand, of the compass heading in order to obtain the reading of the correct magnetic heading. See Fig. 7.

35. Different Parts of Deviation.—For all practical purposes, the total deviation of the compass is composed of three parts: the *semicircular, quadrantal,* and *constant* deviations.

36. Semicircular Deviation.—The semicircular deviation is so called because it is easterly in one semicircle, as the ship's head swings in azimuth, and westerly in the other semicircle. The points of change from easterly to westerly deviation, or points of no deviation, are opposite each other, and in iron- and steel-built ships generally occur on those headings upon which the ship rested in building.

Semicircular deviation is fairly regular, reaching a maximum on points about 90° from the direction of the head of the ship in building. A ship built head North, for example, with reference to its semicircular deviation, would have approximately 0° deviation on North, increasing to a maximum on East or West and decreasing to 0° on South. If the head is North in building, the deviation will, as a general rule, be westerly for all courses between North, East, and South, and easterly for all courses between North, West, and South.

Remembering the following, one is in a position to investigate the forces producing deviation:

(1) Permanent magnets always act with the same force.

(2) Soft iron, or temporary, magnets vary in the force exerted.

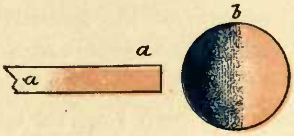

FIG. 4.

FIG. 4a.

a, a' = inducing pole.

b, b' = result of induction by a.

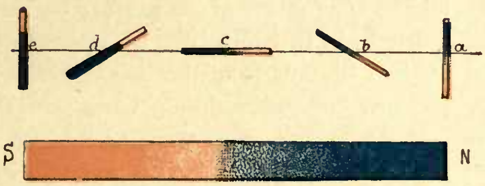

FIG. 5.

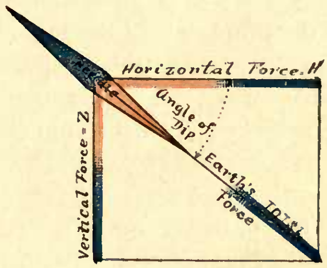

FIG. 6.

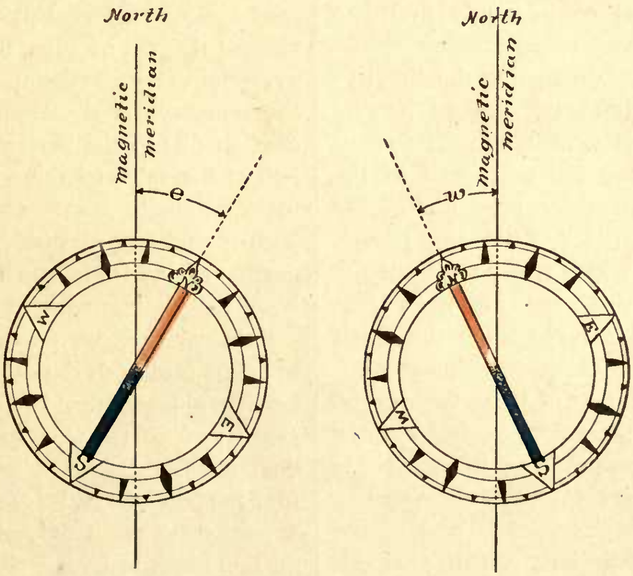

FIG. 7.

e = easterly deviation. w = westerly deviation.

(3) Like poles repel, and unlike poles attract each other.

(4) Induced magnetism is of the opposite kind to the inducing magnetism.

(5) The hard iron in the ship becomes permanently magnetized while building.

(6) The soft iron in the ship has temporary magnetism induced by the earth's magnetism.

(7) We may investigate separately the effect of each kind upon the needle.

37. Forces Producing Semicircular Deviation—Permanent Magnetism of Ship.—Let the heavy lines in Fig. 8 represent a ship heading North while building, so that it has assumed the character of a *permanent* magnet, the poles of the ship being of the same kind of magnetism as the poles of the needle, as indicated by the coloring. As the action of the poles of the magnet and of the ship obeys the same laws that like poles repel and unlike poles attract, the north or red end of the needle need only be considered, the action of the forces on the south poles being entirely in harmony with that of the north pole. In Fig. 8, heavy lines, the north pole of the ship repels that of the needle; but, acting through the center of, and in line with the axis of the needle, it has no deflecting power, and consequently produces no deviation; but it does oppose the attracting force of the earth, thus weakening the directive force of the needle. In Fig. 8, suppose the ship to have swung to a NE. heading. The north pole of the ship repels the north end of the needle and now, not acting in the line of the axis of the needle, has a deflecting power, causing a deviation which increases until the repulsion due to the ship's pole and the attraction due to the earth's force bring the north end of the compass needle to rest in a line coinciding with the resultant of these two forces. This is indicated in the dotted position of the needle. The deviation produced in this case is $x°$ W. on the course NE.

From the foregoing, it is seen that as the ship swings in azimuth from North through East to South, the deviation increases from 0°, reaches a maximum near East, and finally becomes 0° on South; the opposite effect obtaining in the other semicircle. This portion of the semicircular deviation is produced by the action of the hard iron in the ship, this iron having acquired a permanent magnetic character while the ship was building. The remaining portion of the semicircular deviation is produced by vertical soft iron as follows:

38. Portion of Semicircular Due to Vertical Soft Iron.—In Fig. 10, let the direction of the total force of the earth be in the line T, θ being the angle of dip. Resolve this into its components, the vertical one Z, and the horizontal one H. Let AB be a *soft* iron bar. The effect of the action of the vertical component of the earth's force will be to induce magnetism in this bar of opposite polarity to the inducing force, as shown by the color and ends of the bar. The effect of such a bar on the compass needle is to produce a deviation which is 0° when the bar is in the line of the axis of the needle, and a maximum when at right angles, or nearly so, to the axis of the needle; the deviation produced being westerly or easterly in the eastern semicircle, depending upon whether the arrangement is that of Fig. 11 or that of Fig. 12. Study the figures, and note the effect of AB as it moves around the circle.

39. Changes with Change in Latitude.—From the foregoing, it is seen that vertical soft iron acts exactly in a like manner to the permanent magnet of Figs. 8 and 9, and produces a semicircular deviation. As this portion of the semicircular deviation is produced by induction due to the vertical force of the earth, and as the value of this vertical force depends upon the angle of dip, and as the dip changes with a change in latitude, it follows that this portion of the force causing semicircular deviation will change with a change of latitude.

Summarizing, we may say:

Semicircular deviation is produced by the horizontal component of the settled, permanent magnetism of the ship, and by the earth's induction in vertical soft iron of the ship. The first portion of the force causing semicircular deviation is practically constant, the second portion changes with a change in latitude.

40. Quadrantal Deviation. — Quadrantal deviation is a deviation which is easterly in one quadrant and westerly in the next quadrant. It is regular in character and is almost invariably easterly in the NE. and SW. quad-

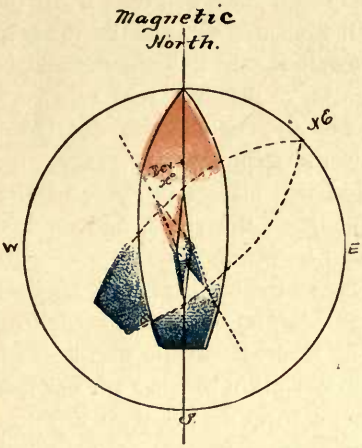

FIG. 8.

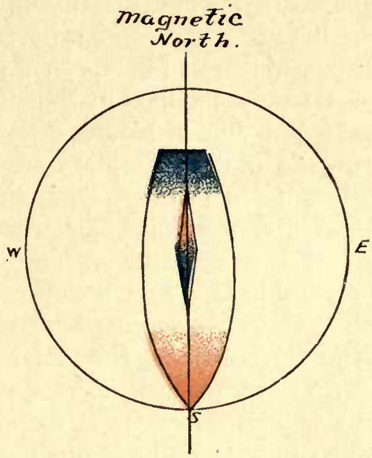

FIG. 9.

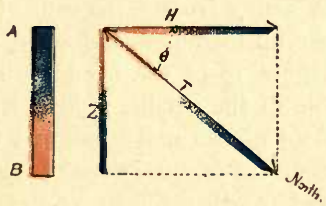

FIG. 10.

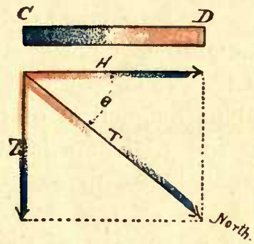

FIG. 13.

T = total force of the earth's magnetism.
H = the horizontal component of T.
Z = the vertical component of T.
θ = angle of dip.

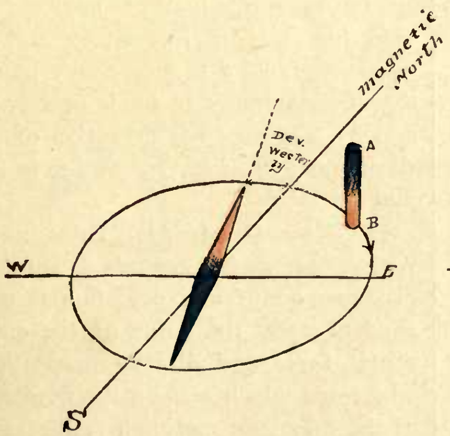

FIG. 11.

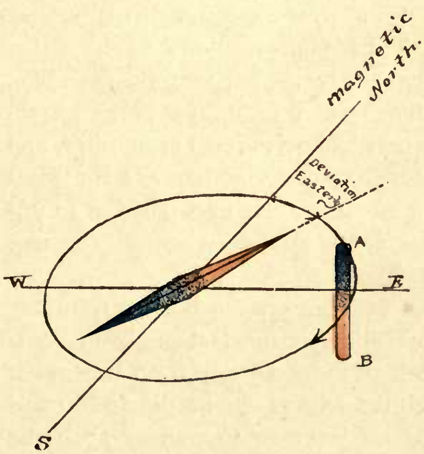

FIG. 12.

rants, and westerly in SE. and NW. quadrants. It arises from induction in horizontal soft iron, as will be seen by the study of the following: Resuming the demonstration of Fig. 10, let *T*, Fig. 13, be the direction of the lines of action of the earth's magnetism and, as before, *Z* its vertical component and *H* its horizontal component. Let *CD* be a bar of soft iron, lying in the magnetic meridian, subject to the inductive action of the horizontal component *H*. Then *CD*, while lying parallel to *H*, *i. e.*, in the magnetic meridian, will assume induced magnetism, as shown by its colored ends. Now refer to Fig. 14. Let *NOS* be the magnetic meridian or the line of action of the horizontal component of the earth's force, *i. e.*, the *H* of Fig. 13, and let *CD* be the bar of Fig. 13. If this bar be swung around through 180° either way, in the horizontal plane, that is, from the first to the third position, the magnetism of the ends *C* and *D* will be found to have changed places; that is, the red of the *D* end will be found to have changed to blue magnetism of opposite polarity. See position 3. There is evidently one position between 1 and 3, the point of just changing from one kind of magnetism to the other, at which the magnetism of the bar is neither red nor blue, that is, zero. This position is half way between the 1st and 3d positions, or at 2d and 4th; in other words, a bar held *at right angles* to the magnetic meridian, or to the line of action of a magnetic force, is not magnetized. For positions intermediate between that parallel to the meridian and that at right angles to it, the amount of magnetism induced in the bar is proportional to the cosine of the angle made by the bar with the meridian. Remembering now that unlike poles attract each other, that like poles repel each other, and that the nearest poles together are the most powerful in effect, we are in a position to understand the action of *CD* when it is swung around a compass.

Referring to Fig. 15, the bar at 1, in the magnetic meridian, is most strongly magnetized, but will produce no deviation because it acts through the axis of the needle and in this position has no leverage to pull or push the needle aside and cause deviation. On the contrary, the sketch shows that the magnetism of the bar will attract the needle to keep it in the meridian, and will thus assist the earth's force. In such a condition the directive force of the needle is said to be increased.

At 2 the bar will not be magnetized so strongly, but will now act upon the pole of the needle with some leverage; the blue of the *C* end will attract the pole of the needle, drawing it to the right, and an easterly deviation will be produced.

At 3 the bar is at right angles to the magnetic meridian and is not magnetized; hence, while the leverage on the needle is greatest, there is no deviation because the bar possesses no magnetic force to act with this leverage. Hence, in passing from 1 to 3 (North to East) the horizontal soft iron bar, under the induction of the earth's magnetism, has produced an easterly deviation attaining a maximum and returning to 0°.

Passing from 3, the ends of the bar begin to take up their new character, and at 4 the red magnetism of the *C* end will attract the blue pole of the needle, pulling it towards it, thus throwing the north point of the needle to the west, producing westerly deviation. At 5, the bar will not produce deviation because of its magnetic force acting through the axis of the needle and thus having no leverage. It will be seen that in this position the directive force of the needle is increased. So, from 3 to 5, there has been produced a westerly deviation starting at 0°, attaining a maximum and returning to 0°.

The same method of analysis shows an easterly deviation from 5 to 7, and a westerly deviation from 7 to 1. It may be easily seen that the maximum deviation occurs near 2, 4, 6 and 8. See now the definition of quadrantal deviation. See Fig. 15a and note to Figs. 14 and 15.

41. Why Quadrantal Does not Change with a Change in Latitude.—The force which produces quadrantal deviation is directly dependent upon the value of the earth's horizontal force and directly proportional to it. The force which acts on the needle to keep it in the magnetic meridian *is* the earth's horizontal force. Hence, as a change occurs in the value of *H*, the force tending to cause quad-

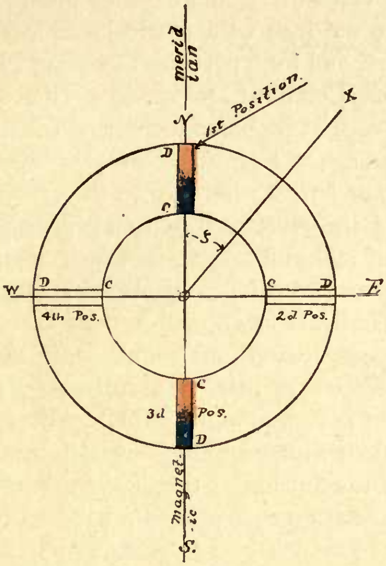

FIG. 14.

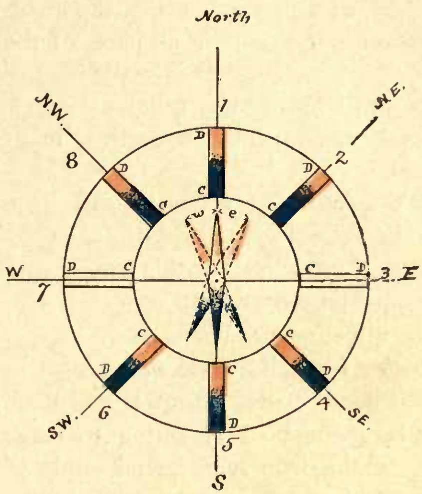

FIG. 15.

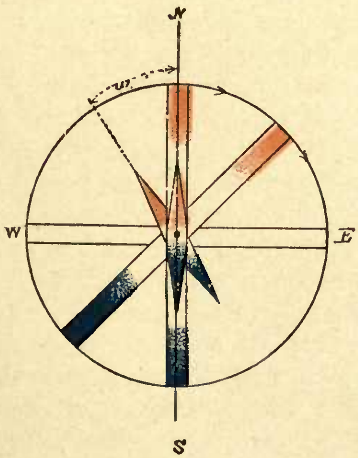

FIG. 15a.

NOTE TO FIGS. 14 AND 15.

If *CD* were to extend through the needle as shown in the sketch Fig. 15a, instead of being ahead of the needle or abaft it as at 1, or at 5 in Fig. 15, the effect on the needle will be opposite from that produced in Fig. 15, *i. e.*, the quadrantal deviation will be westerly from *N* to *E*, easterly from *E* to *S*, westerly from *S* to *W* and easterly from *W* to *N*. This is easily seen by a study of Fig. 15a.

rantal deviation and the force tending to keep the compass true vary in exactly the same proportion. This brings us to the important fact that the quadrantal deviation does not change in value with H, and consequently does not change with a change in latitude. For a particular heading, of a particular ship, the quadrantal deviation is the same in all parts of the world.

This may also be proved as follows:

H = horizontal component of earth's magnetism.

ζ = magnetic azimuth of a bar of soft iron. (See line OX, Fig. 14.)

f = coefficient of induction for this bar.

We then have the following:

H = { Force directing needle. Also the force inducing magnetism in iron lying in the magnetic meridian.

$H \cos \zeta$ = component of H acting to magnetize iron lying at an angle $\zeta°$ with the magnetic meridian.

$f\,(H \cos \zeta)$ = magnetism induced, *i. e.*, deflecting force.

$$\therefore \text{Ratio} \frac{\text{Deflecting force}}{\text{Directive force}} = \frac{fH \cos \zeta}{H} = f \cos \zeta.$$

This shows that the ratio is *independent* of the value of H, and depends upon f and $\cos \zeta$. For the iron of a particular ship f is a constant, and for a particular heading ζ is constant.

42. Constant Deviation.—The constant deviation, as its name implies, is constant for all headings. For all compasses symmetrically situated with reference to the center line of a ship, the constant deviation is imaginary rather than real and arises from instrumental errors, incorrect readings, misplaced lubber's line, etc. It is always small, and in most cases, for compasses situated as above, it is nearly zero. Cases where there is a *real* value of the constant deviation may be found where compasses are not situated in the central fore-and-aft line but to one side of this line, such as a steering compass on each side of a hand-wheel aft.

CHAPTER III.

THE THEORY OF DEVIATION.

By COMMANDER G. W. LOGAN, U. S. N.

(Taken from the *American Practical Navigator* (Bowditch).)

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43. Features of the Earth's Magnetism.—It has already been stated that the earth is an immense natural magnet, with a pole in each hemisphere which is not coincident with the geographical pole; it has also a magnetic equator which lies close to, but not coincident with, the geographical equator.

A magnetic needle freely suspended at a point on the earth's surface, and undisturbed by any other than the earth's magnetic influence, will lie in the plane of the magnetic meridian and at an angle with the horizon depending upon the geographical position.

The magnetic elements of the earth which must be considered are shown in Fig. 16. The earth's *total force* is represented in direction and intensity by the line *AB*. Since compass needles are mechanically arranged to move only in a horizontal plane, it becomes necessary, when investigating the effect of the earth's magnetism upon them, to resolve the total force into two components, which in the figure are represented by *AC* and *AD*. These are known, respectively, as the *horizontal* and *vertical* components of the earth's total force, and are usually designated as H and Z. The angle *CAB,* which the line of direction makes with the plane of the horizon, is called the *magnetic inclination* or *dip,* and is denoted by θ.

It is clear that the horizontal component will reduce to zero at the magnetic poles, where the needle points directly downward, and that it will reach a maximum at the magnetic equator, where the free needle hangs in a horizontal direction. The reverse is true of the vertical component and of the angle of dip.

Values representing these different terms may be found from special charts.

44. Induction—Hard and Soft Iron.—When a piece of unmagnetized iron or steel is brought within the influence of a magnet, certain magnetic properties are immediately imparted to the former, which itself becomes magnetic and continues to remain so as long as it is within the sphere of influence of the permanent magnet. The magnetism that it acquires under these circumstances is said to be *induced,* and the properties of *induction* are

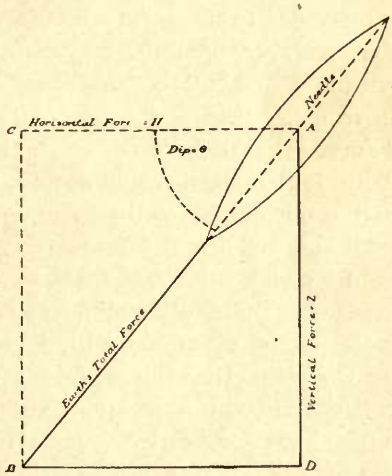

Fig. 16.

such that that end or region which is nearest the pole of the influencing magnet will take up a polarity opposite thereto. If the magnet is withdrawn, the induced magnetism is soon dissipated. If the magnet is brought into proximity again, but with its opposite pole nearer, magnetism will again be induced, but this time its polarity will be reversed. A further property is, that if a piece of iron or steel, while temporarily possessed of magnetic qualities through induction, be subjected to blows, twist-

ing, or mechanical violence of any sort, the magnetism is thus made to acquire a permanent nature.

The softer the metal, from a physical point of view, the more quickly and thoroughly will induced magnetism be dissipated when the source of influence is withdrawn; hard metal, on the contrary, is slow to lose the effect of magnetism imparted to it in any way. Hence, in regarding the different features which affect deviation, it is usual to denominate as hard iron that which possesses retained magnetism of a stable nature, and as soft iron that which rapidly acquires and parts with its magnetic qualities under the varying influences to which it is subjected.

45. Magnetic Properties Acquired by an Iron or Steel Vessel in Building.—The inductive action of the earth's magnetism affects all iron or steel within its influence, and the amount and permanency of the magnetism so induced depend upon the position of the metal with reference to the earth's total force, upon its character, and upon the degree of hammering, bending, and twisting that it undergoes.

An iron bar held in the line of the earth's total force instantly becomes magnetic; if held at an angle thereto, it would acquire magnetic properties dependent for their amount upon its inclination to the line of total force; when held at right angles to the line, there would be no effect, as each extremity would be equally near the poles of the earth and all influence would be neutralized. If, while such a bar is in a magnetic state through inductive action, it should be hammered or twisted, a certain magnetism of a permanent character is impressed upon it, which is never entirely lost unless the bar is subjected to causes equal and opposite to those that produced the first effect.

A sheet of iron is affected by induction in a similar way, the magnetism induced by the earth diffusing itself over the entire plate and separating itself into regions of opposite polarity divided by a neutral area at right angles to the earth's line of total force. If the plate is hammered or bent, this magnetism takes up a permanent character.

If the magnetic mass has a third dimension, and assumes the form of a ship, a similar condition prevails. The whole takes up a magnetic character; there is a magnetic axis in the direction of the line of total force, with poles at its extremities and a zone of no magnetism perpendicular to it. The distribution of magnetism will depend upon the horizontal and vertical components of the earth's force in the locality and upon the direction of the keel in building; its permanency will depend upon the amount of mechanical violence to which the metal has been subjected by the riveting and other incidents of construction, and upon the nature of the metal employed.

46. Causes that Produce Deviation.—There are three influences that operate to produce deviation; namely, (a) *subpermanent magnetism,* (b) *transient magnetism induced in vertical soft iron,* and (c) *transient magnetism induced in horizontal soft iron.* Their effect will be explained.

Subpermanent magnetism is the name given to that magnetic force which originates in the ship while building, through the process explained in the preceding article; after the vessel is launched and has an opportunity to swing in azimuth, the magnetism thus induced will suffer material diminution until, after the lapse of a certain time, it will settle down to a condition that continues practically unchanged; the magnetism that remains is denominated *subpermanent.* The vessel will then approximate to a permanent magnet, in which the north polarity will lie in that region which was north in building, and the south polarity (that which exerts an attracting influence on the north pole of the compass needle), in the region which was south in building.

Transient magnetism induced in vertical soft iron is that developed in the soft iron of a vessel through the inductive action of the vertical component only of the earth's total force, and is transient in nature. Its value or force in any given mass varies with and depends upon the value of the vertical component at the place, and is proportional to the sine of the dip, being a maximum at the magnetic pole and zero at the magnetic equator.

Transient magnetism induced in horizontal soft iron is that developed in the soft iron of a vessel through the inductive action of the hori-

zontal component only of the earth's total force, and is transient in nature. Its value or force in any given mass varies with and depends upon the value of the horizontal component at the place, and is proportional to the cosine of the dip, being a maximum at the magnetic equator and reducing to zero at the magnetic pole.

The needle of a compass in any position on board ship will therefore be acted upon by the earth's total force, together with the three forces just described. The poles of these forces do not usually lie in the horizontal plane of the compass needle, but as this needle is constrained to act in a horizontal plane, its movements will be affected solely by the horizontal components of these forces and its direction will be determined by the resultant of those components.

The earth's force operates to retain the compass needle in the plane of the magnetic meridian, but the resultant of the three remaining forces, when without this plane, deflects the needle, and the amount of such deflection constitutes the deviation.

47. Classes of Deviation.—Investigation has developed the fact that the deviation produced as described is made up of three parts, which are known respectively as *semicircular, quadrantal,* and *constant* deviation, the latter being the least important. A clear understanding of the nature of each of these classes is essential for a comprehension of the methods of compensation.

48. Semicircular deviation is that due to the combined influence, exerted in a horizontal plane, of the subpermanent magnetism of a ship and of the magnetism induced in soft iron by the vertical component of the earth's force. If we regard the effect of these two forces as concentrated in a single resultant pole exerting an attracting influence upon the north end of the compass needle, it may be seen that there will be some heading of the ship whereon that pole will lie due north of the needle and therefore produce no deviation; now consider that, from this position, the ship's head swings in azimuth to the right; throughout all of the semicircle first described an easterly deviation will be produced, and, after completing 180°, the pole will be in a position diametrically opposite to that from which it started, and will again exert no influence that tends to produce deviation. Continuing the swing, throughout the next semicircle the direction of the deviation produced will be always to the westward, until the circle is completed and the ship returns to her original neutral position. From the fact that this disturbing cause acts in the two semicircles with equal and opposite effect, it is given the name of *semicircular* deviation.

In Fig. 3, Chapter I, a curve is depicted which shows the deviations of a semicircular nature separated from those due to other disturbing causes, and from this the reason for the name will be apparent.

49. Returning to the two distinct sources from which the semicircular deviation arises, it may be seen that the force due to subpermanent magnetism remains constant, regardless of the geographical position of the vessel; but since the horizontal force of the earth, which tends to hold the needle in the magnetic meridian, varies with the magnetic latitude, the deviation due to subpermanent magnetism varies inversely as the horizontal force, or as $\frac{1}{H}$. This may be readily understood if it is considered that the stronger the tendency to cling to the direction of the magnetic meridian, the less will be the deflection due to a given disturbing force. On the other hand, that part of the semicircular force due to magnetism induced in vertical soft iron varies as the earth's vertical force, which is proportional to the sine of the dip; its effect in producing deviation, as in the preceding case, varies inversely as the earth's horizontal force—that is, inversely as the cosine of the dip; hence, the ratio representing the change of deviation arising from this cause on change of latitude is $\frac{\sin \theta}{\cos \theta}$, or $\tan \theta$.

If, then, we consider the change in the semicircular deviation due to a change of magnetic latitude, it will be necessary to separate the two factors of the deviation and to remember that the portion produced by subpermanent magnetism varies as $\frac{1}{H}$, and that due to vertical

induction as tan θ. But for any consideration of the effect of this class of deviation in one latitude only, the two parts may be joined together and regarded as having a single resultant.

50. If we now resume our former assumption, that all the forces tending to produce semicircular deviation are concentrated in a single pole exerting an attracting influence upon the north pole of the compass, we may consider a line to be drawn joining that theoretical pole with the center of the compass, then the angle made by this line with the keel line of the vessel, measured from right ahead, around to the right, is called the *starboard angle*. From this it follows that the disturbing force producing semicircular deviation may be considered to have the same effect as a single

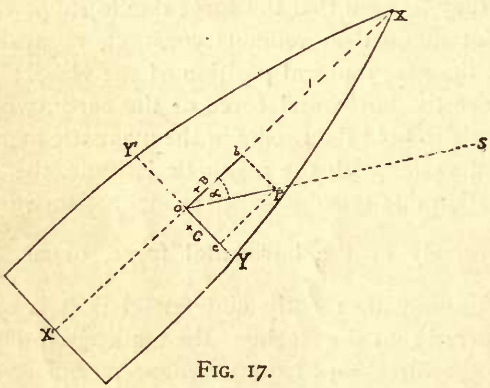

FIG. 17.

magnet whose center is in the vertical axis of the compass, and whose *south* pole (attracting to the north pole of the compass) is in the direction given by the starboard angle; if, therefore, a magnet be placed with its center in the vertical axis of the compass, its *north* (or repelling) pole in the direction of the starboard angle, and its distance so regulated that it exerts upon the compass a force equal to that of the ship's combined subpermanent magnetism and vertical induced magnetism, the disturbing effect of these two forces will be counterbalanced, and, so far as they are concerned, the compass deviations will be corrected, provided that the ship does not change her magnetic latitude.

51. It is evident that the force of the single magnet may be resolved into two components —one fore-and-aft, and one athwartship; in this case, instead of being represented by a single magnet with its south pole in the starboard angle, the semicircular forces will be represented by two magnets, one fore-and-aft and the other athwartship, and compensation may be made by two separate magnets lying respectively in the directions stated, but with their north or repelling poles in the position occupied by the south or attracting poles of the ship's force.

Figure 17 represents the conditions that have been described. If O be the center of the compass, XX' and YY', respectively, the fore-and-aft and athwartship lines of the ship, and OS the direction in which the attracting pole of the disturbing force is exerted, then XOS is the *starboard angle,* usually designated α. Now, if OP be laid off on the line OS, representing the amount of the disturbing force according to some convenient scale, then Ob and Oc respectively represent, on the same scale, the resolved directions of that force in the keel line and in the transverse line of the ship. Each of these resolved forces will exert a maximum effect when acting at right angles to the needle, the athwartship one when the ship heads North or South by compass, and the longitudinal one when the heading is East or West. On any other heading than those named, the deviation produced by each force will be a fraction of its maximum, whose magnitude will depend upon the azimuth of the ship's head. The maximum deviation produced, therefore, forms in each case a basis for reckoning all of the various effects of the disturbing force, and is called a *coefficient.*

The coefficient of semicircular deviation produced by the force in the fore-and-aft line is called B, and is reckoned as positive when it attracts a north pole toward the bow, negative when toward the stern; that produced by the athwartship force is C, and is reckoned as positive to starboard and negative to port. These coefficients are expressed in degrees.*

* It should be remarked that in a mathematical analysis of the deviations, it would be necessary to distinguish between the *approximate coefficients,* B and C, here described, as also A, D, and E, to be mentioned later, and the *exact coefficients* denoted by the corresponding capital letters of the German alphabet.

Referring again to Fig. 17, it will be seen that

$$\tan \alpha = \frac{Oc}{Ob},$$

or (what may be shown to be the same thing)

$$\tan \alpha = \frac{\sin C}{\sin B};$$

and when the maximum deviations are small, this becomes

$$\tan \alpha = \frac{C}{B}.$$

Since the starboard angle is always measured to the right, it will be seen that, for positive values of *B* and *C*, α will be between 0° and 90°; for a negative *B* and a positive *C*, between 90° and 180°; for negative values of both *B* and *C*, between 180° and 270°; and for a positive *B* and a negative *C*, between 270° and 360°.

52. The coefficient *B* is approximately equal to the deviation on East, or to the deviation on West with reversed sign, or to the mean of these two. Thus, in the ship having the table of deviations previously given (Art. 20, Chapter I), *B* is equal to $-19° 30'$, or to $-17° 30'$, or to $\frac{1}{2}(-19° 30' - 17° 30') = -18° 30'$.

The coefficient *C* is approximately equal to the deviation on North, or to the deviation on South with reversed sign, or to the mean of these two. In the example given, *C* is equal to $-0° 00'$.

53. The value of the subpermanent magnetism remaining practically constant under all conditions, it will not alter when the ship changes her latitude; but that due to induction in vertical soft iron undergoes a change when, by change of geographical position, the vertical component of the earth's force assumes a different value, and in such case the correction by means of one permanent magnet or a pair of permanent magnets will not remain effective. If, however, by series of observations in two magnetic latitudes, the values of the coefficients can be determined under the differing circumstances, it is possible, by solving equation, to determine what effect each force has in producing the semicircular deviation; having done which, the subpermanent magnetism can be corrected by permanent magnets after the method previously described, and the vertical induction in soft iron can be corrected by a piece of vertical soft iron placed in such a position near the compass as to produce an equal but opposite force to the ship's vertical soft iron. This last corrector is called a *Flinders bar.*

Having thus opposed to each of the component forces a corrector of magnetic character identical with its own, a change of latitude will make no difference in the effectiveness of the compensation, for in every case the modified conditions will produce identical results in the disturbing and in the correcting force.

54. Quadrantal deviation is that which arises from horizontal induction in the soft iron of the vessel through the action of the horizontal component of the earth's total force. Let us consider, in Fig. 18, the effect of any piece of soft iron which is symmetrical with respect to the compass—that is, which lies wholly within a plane passing through the center of the needle in either a fore-and-aft or an athwartship direction. It may be seen (a) that such iron produces no deviation on the cardinal points (for on North and South headings the fore-and-aft iron, though strongly magnetized, has no tendency to draw the needle from a north-and-south line, while the athwartship iron, being at right angles to the meridian, receives no magnetic induction, and therefore exerts no force; and on East and West headings similar conditions prevail, the athwartship and the fore-and-aft iron having simply exchanged positions); and (b) the

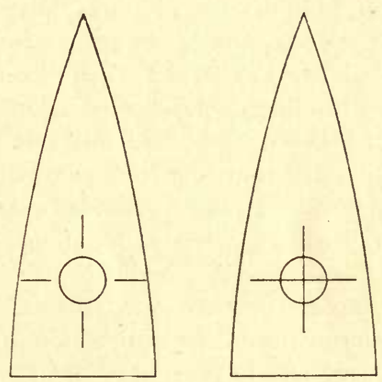

Fig. 18.

direction of the deviation produced is opposite in successive quadrants. The action of unsymmetrical soft iron is not quite so readily apparent, but investigation shows that part of its effect is to produce a deviation which becomes zero at the inter-cardinal points and is of opposite name in successive quadrants. From the fact that deviations of this class change sign every 90° throughout the circle, they gain the name of *quadrantal deviations.* One of the curves laid down in the Napier diagram (Fig. 3, Chapter I) is that of quadrantal deviations, whence the nature of this disturbance of the needle may be observed.

55. All deviations produced by soft iron may be considered as fractions of the maximum deviation due to that disturbing influence; and consequently the maximum is regarded as a coefficient, as in the case of semicircular deviations. The coefficient due to symmetrical soft iron is designated as *D,* and is considered positive when it produces easterly deviations in the quadrant between North and East; the coefficient of deviations arising from unsymmetrical soft iron is called *E,* and is reckoned as positive when it produces easterly deviations in the quadrant between NW. and NE.; this latter attains importance only when there is some marked inequality in the distribution of metal to starboard and to port, as in the case of a compass placed off the midship line.

56. *D* is approximately equal to the mean of the deviations on NE. and SW.; or to the mean of those on SE. and NW., with sign reversed; or to the mean of those means. In the table of deviations given in Art. 20, Chapter I, D is equal to $\frac{1}{2}(-3° 00' + 21° 00') = +9° 00'$; or to $\frac{1}{2}(+24° 30' - 2° 00') = +11° 15'$; or to $\frac{1}{2}(+9° 00' + 11° 15') = +10° 07'$. By reason of the nature of the arrangement of iron in a ship, *D* is almost invariably positive.

E is approximately equal to the mean of the deviations on North and South, or to the mean of those on East and West with sign reversed, or to the mean of those means. In the example, E is equal to $\frac{1}{2}(\pm 0° 00' \pm 0° 00') = -0° 00'$, or to $\frac{1}{2}(+19° 30' - 17° 30') = +1° 00'$, or to $\frac{1}{2}(-0° 00' + 1° 00') = +0° 30'$.

57. Quadrantal deviation does not, like semicircular, undergo a change upon change of magnetic latitude; being due to induction in horizontal soft iron, the magnetic force exerted to produce it is proportional to the horizontal component of the earth's magnetism; but the directive force of the needle likewise depends upon that same component; consequently, as the disturbing force exerted upon the needle increases, so does the power that holds it in the magnetic meridian, with the result that on any given heading the deflection due to soft iron is always the same.

58. Quadrantal deviation is corrected by placing masses of soft iron (usually two hollow spheres in the athwartship line, at equal distances on each side of the compass), with the center of mass in the horizontal plane of the needle. The distance is made such that the force exerted exactly counteracts that of the ship's iron. As the correcting effect of this iron will, like the directive force and the quadrantal disturbing force, vary directly with the earth's horizontal component, the compensation once properly made will be effective in all latitudes, provided the compass needles are short and, consequently, exercise little or no induction on the quadrantal correctors.

With compasses such as the U. S. Navy standard 7½-inch liquid compass, the needles of which are long and powerful, it will usually be found that the position of the spheres must be changed with change of latitude. This may be accounted for by the magnetism induced in the spheres by the compass needles at the same time and in the same manner as the earth's force. In this case the quadrantal correcting force is the resultant of the constant force due to the induction of the needles in the spheres and the variable force (the earth's horizontal force, *H,* varying with change in magnetic latitude) due to the induction of the earth in the spheres. This resultant of these two forces is a variable force, and, after a given quadrantal deviation is corrected in one latitude by this force, the balance will be changed upon going into another latitude and the correction will fail to hold good.

In practice, the quadrantal deviation due to unsymmetrical iron is seldom corrected; the correction may be accomplished, however, by placing the soft iron masses on a line which

makes an angle to the athwartship line through the center of the card.

59. Constant deviation is due to induction in horizontal soft iron unsymmetrically placed about the compass. It has already been explained that one effect of such iron is to produce a quadrantal deviation, represented by the coefficient *E;* another effect is the *constant* deviation, so called because it is uniform in amount and direction on every heading of the ship. If plotted on a Napier diagram, it would appear as a straight line parallel with the initial line of the diagram.

60. Like other classes of deviation, the effect of the disturbing force is represented by a coefficient; this coefficient is designated as *A,* and is considered *plus* for easterly and *minus* for westerly errors. It is approximately equal to the mean of the deviations on any number of equidistant headings. In the case previously given, it might be found from the four headings, North, East, South, and West, and would then be equal to $\frac{1}{4}(-0^\circ 00' - 19^\circ 30' \pm 0^\circ 00' + 17^\circ 30') = -0^\circ 30'$; or from all of the twenty-four headings, when it would equal $+0^\circ 56'$.

For the same reason as in the case of *E,* the value of *A* is usually so small that it may be neglected; it only attains a material size when the compass is placed off the midship line, or for some similar cause.

61. Like quadrantal deviation, since its force varies with the earth's horizontal force, the constant deviation will remain uniform in amount in all latitudes.

No attempt is made to compensate this class of error.

62. Coefficients.—The chief value of coefficients is in mathematical analyses of the deviations and their causes. It may, however, be a convenience to the practical navigator to find their approximate values by the methods that have been given, in order that he may gain an idea of the various sources of the error, with a view to ameliorating the conditions, when necessary, by moving the binnacle or altering the surrounding iron. The following relation exists between the coefficients and the deviation:

$$d = A + B \sin z' + C \cos z' + D \sin 2z' + E \cos 2z',$$

where d is the deviation, and z' the ship's heading by compass, measured from compass North.

63. Mean Directive Force.—The effect of the disturbing forces is not confined to causing deviations; it is only those components acting at right angles to the needle which operate to produce deflection; the effect of those acting in the direction of the needle is exerted either in increasing or in diminishing the directive force of the compass, according as the resolved component is northerly or southerly.

It occurs, with the usual arrangement of iron in a vessel, that the mean effect of this action throughout a complete swing of the ship upon all headings is to reduce the directive force; that is, while it varies with the heading, the average value upon all azimuths is *minus* or southerly. The result of such a condition is unfavorable from the fact that the compass is thus made more "sluggish," is easily disturbed and does not return quickly to rest, and a given deflecting force produces a greater deviation when the directive force is reduced. The usual methods of compensation largely correct this fault, but do not entirely do so. It is therefore the case that the mean combined horizontal force of earth and ship to north is generally less than the horizontal force of the earth alone; but it is only in extreme cases that this deficiency is serious.

64. Heeling Error.—This is an additional cause of deviation that arises when the vessel heels to one side or the other. Heretofore only those forces have been considered which act when the vessel is on an even keel; but if there is an inclination from the vertical, certain new forces arise, and others previously inoperative become effective. These forces are (a) the vertical component of the subpermanent magnetism acquired in building; (b) the vertical component of the induced magnetism in vertical soft iron, and (c) the magnetism induced by the vertical component of the earth's total force in iron which, on an even keel, was horizontal. The first two of these disturbing causes are always present, but, when the ship is upright, have no tendency to produce deviation, simply exerting a downward pull on one of the

poles of the needle; the last is a new force that arises when the vessel heels.

The maximum disturbance due to heel occurs when the ship heads North or South. When heading East or West there will be no deviation produced, although the directive force of the needle will be increased or diminished. The error will increase with the amount of inclination from the vertical.

65. For the same reason as was explained in connection with semicircular deviations, that part of the heeling error due to subpermanent magnetism will vary, on change of latitude, as $\frac{1}{H}$, while that due to vertical induction will vary as tan θ. In south magnetic latitude the effect of vertical induction will be opposite in direction to what it is in north.

66. The heeling error is corrected by a permanent magnet placed in a vertical position directly under the center of the compass. Such a magnet has no effect upon the compass when the ship is upright; but since its force acts in an opposite direction to the force of the ship which causes heeling error, is equal to the latter in amount, and is exerted under the same conditions, it affords an effective compensation. For similar reasons to those affecting the compensation of *B* and *C*, the correction by means of a permanent magnet is not general, and must be rectified upon change of latitude.

THE EXACT COEFFICIENTS.

By LIEUT.-COMMANDER HARRIS LANING, U. S. N.

67. In Chapter II, Commander L. M. Nulton has shown us the causes that produce each of the various deviations that go to make up the total deviation. In Arts. 50-55 (inclusive), in this chapter, we have learned that the maximum value of each one of the various deviations is—when expressed in degrees, minutes, and seconds—designated by a letter of the alphabet, and is known as the approximate coefficient. *A* is the approximate coefficient for the constant deviation; *B*, for the deviation produced by the combined force of the subpermanent magnetism and the induced magnetism in vertical soft iron acting in the fore-and-aft line; *C*, for the deviation produced by the subpermanent magnetism and the induced magnetism in vertical soft iron acting in the athwartship line; *D*, for the deviation produced by the induced magnetism in horizontal soft iron symmetrically placed with reference to the compass; and *E*, for the deviation produced by the induced magnetism in horizontal soft iron unsymmetrically placed with reference to the compass. These approximate coefficients are always expressed in degrees, minutes, and seconds.

Though any one of the various deviations named above is caused by the combination of several magnetic forces, each acting from a different point, these several forces may be considered as concentrated in a single magnetic pole which exerts on the compass needle a push or pull equal to the combined push or pull of the several forces. If the force concentrated in the single pole be measured, its measured value, or strength, is called the *exact coefficient.* Exact coefficients are designated by the letters of the German alphabet that correspond to the English letters that represent (in degrees, minutes, and seconds) the errors they produce. Thus the force represented by the exact coefficient $\mathfrak{A}$ produces the deviation expressed by the approximate coefficient *A;* the force represented by the exact coefficient $\mathfrak{B}$ produces the deviation expressed by the approximate coefficient *B;* the force represented by the exact coefficient $\mathfrak{C}$ produces the deviation expressed by the approximate coefficient *C;* the force represented by the exact coefficient $\mathfrak{D}$ produces the deviation expressed by the approximate coefficient *D;* and the force represented by the exact coefficient $\mathfrak{E}$ produces the deviation expressed by approximate coefficient *E*.

The unit of measure for these exact coefficients is not a fixed unit, but is expressed in the terms of the *mean force of the earth and ship to north.* It will be seen that if the force be measured in any of the ordinary *fixed* units of work, the values of all the exact coefficients will vary with the magnetic latitude, since the induced magnetism varies with the latitude. If, however, we measure the force represented by the exact coefficients with a unit that varies with the magnetic latitude, we find that the value of the exact coefficients that measure in-

duced magnetism will remain constant, because the relation between the induced magnetism and the cause of it remains constant. The coefficients 𝔅 and ℭ will not, however, remain constant, since each is partly made up of sub-permanent magnetism. Having found the values of the exact coefficients in terms of "mean force to north," these values, with the exception of 𝔅 and ℭ, remain constant, since they are in reality only the ratio between the force producing the error and the mean force to north, both of which change in the same ratio with a change ot magnetic latitude.

68. The values ol both the *exact* and the *approximate* coefficients can be calculated by certain methods and formulæ which are deduced and may be studied in Muir's *Navigation and Compass Deviation* and in other complete works on the mathematical theory of the deviation of the compass. A knowledge of this theory is perhaps desirable, but it is not essential to the practical navigator. The determination and use of the coefficients, and of other terms and symbols used in compass work, are, however, a part of a navigator's regular duties, and a knowledge of what they are and of how to determine their values is necessary for any naval officer intrusted with navigating a ship.

The value of *A, B, C, D,* and *E,* for any compass on any ship, may be obtained by what is known as an *analysis* of the compass deviations. For this work, special forms are supplied to each ship by the Navy Department. This form (a copy of which is shown in this chapter) is self-explanatory. Having used the first page of the form to determine the approximate coefficients, we use the second page to determine the value of the exact coefficients and the value of λ.

In addition to the exact coefficients, there is also a coefficient that expresses the proportion of the mean horizontal force northward of the earth and ship to the earth's horizontal force (that is, the force on shore unaffected by outside influences). This coefficient is called λ and, once known for a ship, will often aid materially in compass work. It may be computed by the formula

$$\lambda = \frac{H'}{H} \times \frac{\cos \delta}{1 + \mathfrak{B} \cos z - \mathfrak{C} \sin z + \mathfrak{D} \cos 2z - \mathfrak{E} \sin 2z}$$

In the above formula, δ is the deviation on the magnetic course, z the azimuth of the ship's head measured eastward from the correct magnetic north. H' is the horizontal component of the total force of earth and ship to north. H is the horizontal component of the earth to north. $\frac{H'}{H} = \frac{T^2}{T'^2}$, in which T is the time of n vibrations of a small horizontal magnetic needle on shore, in a place free from local magnetic disturbances, and T' the time of the same number of vibrations of the same needle with its center in the exact place occupied by the center of compass needle when the compass is in place, the ship being on magnetic heading z, on which the deviation is δ.

The exact coefficients are found from the analysis, while δ and z are known. $\frac{T^2}{T'^2}$ must be obtained in a special way. To obtain the value of T and of T', an instrument known as the *horizontal force instrument* is supplied to all ships. It consists of a cylindrical brass case, with a removable glass cover, mounted on a rectangular base which is provided with spirit levels and has levelling screws underneath. Inside the brass case is a horizontal circle, graduated to degrees, in the center of which is a pivot that supports a small lozenge-shaped magnetic needle on which is carried an adjustable sliding weight that is used to counteract the dip. The needle is capable of vibrating freely in the horizontal plane.

To find T (the time of n vibrations on shore), select on shore a level spot free from local attraction, level the instrument, and orient it (that is, turn the instrument in azimuth until the needle, when not vibrating, points to 0° on the graduated scale). By means of a small magnet draw the needle aside about 20°, and then remove the magnet to such a distance that it will not further affect the needle. The needle will then be vibrating. As the needle passes the 0 line the first time "mark" the time or start the stop watch. As the needle passes the 0 line the second time count "one"; at the next passage count "two"; and so on till the count of "ten," when the time is noted or the watch is stopped. The interval of time will be the time required to make ten vibra-

N. Eq. 10.

Analysis of Deviations of the............Compass No.........................,

Place of Observation,..; Latitude,........................

Table I.—Computation of Coefficients *B* and *C*.

(1) Ship's Head by.......... Compass No.........	(2) Deviation. Easterly+ Westerly−	(3) Ship's Head by.......... Compass No.........	(4) Deviation. Easterly+ Westerly−	(5) Half sum of Cols. (2) and (4).	(6) Half sum of Cols. (2) and (4) [changing sign in Col. (4)]. *Semicircular Deviation.*	(7) Computation of *B*. Multipliers.	(7) Computation of *B*. Products of Col. (6) by Multipliers.	(8) Computation of *C*. Multipliers.	(8) Computation of *C*. Products of Col. (6) by Multipliers.
°	° ′	°	° ′	° ′	° ′		° ′		° ′
0	....	180	....	....	....	0	....	1	....
15	....	195	....	....	....	S_1	....	S_5	....
30	....	210	....	....	....	S_2	....	S_4	....
45	....	225	....	....	....	S_3	....	S_3	....
60	....	240	....	....	....	S_4	....	S_2	....
75	....	255	....	....	....	S_5	....	S_1	....
90	....	270	....	....	....	1	....	0	....
105	....	285	....	....	....	S_5	....	$-S_1$	....
120	....	300	....	....	....	S_4	....	$-S_2$	....
135	....	315	....	....	....	S_3	....	$-S_3$	....
150	....	330	....	....	....	S_2	....	$-S_4$	....
165	....	345	....	....	....	S_1	....	$-S_5$	....

This form is adapted to a computation from observations on 24 equidistant compass headings. It may be used for 12 or 8 equidistant observations by omitting the intermediate headings, but the divisors for finding *A*, *B*, and *C* must be 3 or 2, respectively, and those for finding *D* and *E* must be $\frac{3}{2}$ or 1, respectively.

Sum of + terms = + ...	+ ....
Sum of − terms = −	− ....
Divisor 6		6	
B = ...	*C* = ...

Table II.—Computation of Coefficients *A*, *D*, *E*.

(9) Upper half of Col. (5), Table I.	(10) Lower half of Col. (5), Table I.	(11) Half sum of Cols. (9) and (10). *Constant Deviation.*	(12) Half sum of Cols. (9) and (10) [changing sign in Col. (10)]. *Quadrantal Deviation.*	(13) Computation of *D*. Multipliers.	(13) Computation of *D*. Products of Col. (12) by Multipliers.	(14) Computation of *E*. Multipliers.	(14) Computation of *E*. Products of Col. (12) by Multipliers.
° ′	° ′	° ′	° ′		° ′		° ′
....	....	....	....	0	....	1	....
....	....	....	....	S_2	....	S_4	....
....	....	....	....	S_4	....	S_2	....
....	....	....	....	1	....	0	....
....	....	....	....	S_4	....	$-S_2$	....
....	....	....	....	S_2	....	$-S_4$	....

Sum of + terms = + ...	Sum of + terms = + ...	+ ....
Sum of − terms = −	Sum of − terms = −	− ....
Divisor 6	Divisor 3	3
A = ...	*D* = ...	*E* = ...

Multipliers for Computing *B*, *C*, *D*, *E*.

$S_1 = .259$

$S_2 = .500$

$S_3 = .707$

$S_4 = .866$

$S_5 = .966$

$S_6 = 1$

$S_0 - 0$

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on board the U. S. S..

Longitude,...................... Date of Observation.. .., 19

Table III.—Computation of Exact Coefficients 𝔄, 𝔅, ℭ, 𝔇, 𝔈.

	A ° ′	B ° ′	C ° ′	D ° ′	E ° ′
Angles	....	....	....	....	....
Sines	....	....	....	....	....
Versines	* * *	....	....	....	* * *

$\mathfrak{A} = \sin A =$..

$\mathfrak{B} = \sin B\ [1 + \frac{1}{2} \sin D + \frac{1}{12} \text{versin}\ B - \frac{1}{4} \text{versin}\ C] + \frac{1}{2} \sin C \sin E$

=..

$\mathfrak{C} = \sin C\ [1 - \frac{1}{2} \sin D + \frac{1}{12} \text{versin}\ C - \frac{1}{4} \text{versin}\ B] + \frac{1}{2} \sin B \sin E$

$\mathfrak{D} = \sin D\ [1 + \frac{1}{3} \text{versin}\ D] =$..

$\mathfrak{E} = \sin E - \sin A \sin D =$..

For Computation of Lambda.

Ship's Head Mgtc.	By Compass.	T ‡	T′‡	$\lambda = \frac{H'}{H} \times \frac{\cos \delta}{1 + \mathfrak{B} \cos z - \mathfrak{C} \sin z + \mathfrak{D} \cos 2z - \mathfrak{E} \sin 2z} =$
....	....	....	....	....
....	....	....	$\frac{H'}{H} = \frac{T^2}{T'^2}$	....
....	....	....		....
....	....	....	....	....
....	....	....	....	....

(Note what correctors, if any, were in place when deviations were obtained. If compensation is changed, give details of new compensation.)

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Deviations observed by.., ship swung with..........................helm.

Forwarded. ....

...., *U. S. N., Navigator.*

.........................., *U. S. N., Commanding.*

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‡ T′ and T must be obtained in the same general locality.

tions, and is known as T. To insure an accurate value of T, it is customary to take for its value the average time of ten sets of ten vibrations.

To obtain T', similar observations are taken on board the ship. The horizontal force instrument is set up so that the center of the needle will occupy the exact place usually occupied by the center of the compass, which, with all correctors, has been removed to a safe distance. Each ship is supplied with a brass table, the spindle of which is set in the central vertical tube of the compass binnacle, where it is easily adjusted for height to bring the needle of the horizontal force instrument to its correct place when placed on the table. To get the exact position of the horizontal force needle, the use of a centering batten is necessary. The centering batten is a rectangular bar of hard wood, perfectly straight, $12\frac{3}{4}$ in. long by $\frac{3}{4}$ in. wide and $\frac{1}{2}$ in. thick, having a triangular tenon at each end $\frac{1}{2}$ in. long, to fit in the wyes in the compass chamber of the U. S. Navy Type VI binnacle, and having vertically through its center a brass pointer, $\frac{1}{8}$ in. in diameter and pointed at its end, projecting $\frac{3}{4}$ in. below the under face of the batten, the pointer having a screw head and a threaded shank, by which it is screwed flush into the batten. Place the tenons of the batten in the wyes of the binnacle, and by raising or lowering the brass table and moving the horizontal force instrument bring the point of the pivot of the instrument up to the point of the brass pointer on the batten. Secure the table in this position, level the instrument, and then take the time of ten vibrations as on shore. If it is found that the needle comes to rest before making ten vibrations, or so nearly so as to make the time uncertain, take five vibrations and double the resulting time. Do not pull the needle over to 60° or 90° to get vibrations.

Having found the values of T and T' as described above, we substitute them in the formula $\frac{H}{H'} = \frac{T'^2}{T^2}$ and get the value of $\frac{H}{H'}$ to substitute in the equation given above for λ. Having completed all the work laid out in the form, we have all the information we can get from an analysis.

An analysis is not absolutely necessary in compensating compasses, as compasses can be compensated without an analysis; but if we can get an opportunity to analyse we should do so, for the data so obtained may be of great service in future compensations. For instance, a ship laid up for repairs and afterwards recommissioned can compensate her compasses before leaving a navy yard, provided λ and the exact coefficients are known, as they would be if the location of the compass had not been changed and the iron around it was the same as before. Also, by an analysis of compass deviations on similar ships we are frequently able to get data from which we may partially compensate the compasses of a new ship before leaving the navy yard. In any event the Navy Regulations require that an analysis of deviations for each compass on board ship be made at regular intervals.

CHAPTER IV.

THE PRINCIPLES OF THE CORRECTION OF THE DEVIATION.

By COMMANDER L. M. NULTON, U. S. N.

69. Preliminary.—If the compass needle is pushed or pulled aside from the correct position by certain magnetic forces, the effect of these forces may be overcome by applying other magnetic forces which push or pull in opposition, and thus bring the needle back to its place as fast as those forces which produce deviation tend to push or pull it out of place. Or, to better express it, if the magnetic forces producing deviation are opposed by equal but opposite magnetic forces, the forces tending to produce deviation are neutralized, and the needle swings in its correct position under the influence of the earth alone.

As has been shown in the preceding pages, the forces causing deviation are those of the magnetism existing permanently, or temporarily, in the ship's iron or steel. The neutralizing forces are produced by special magnets, permanent and temporary, placed in positions from which they oppose the forces of the ship and thus leave the compass needle free to point correctly.

Generally speaking, the permanent magnetism of the ship is opposed, or neutralized, by artificial permanent magnets, and the induced, temporary, or transient magnetism is neutralized by soft iron correctors, so placed that the induction of the earth's magnetism in these correctors is opposite in kind or effect upon the compass from that of the soft iron of the ship itself.

70. Elements of Correction Considered Separately.—Just as the effect of each kind of iron on the compass was considered separately, so the correction of each element of the deviation may be separately considered.

71. Semicircular.—Remembering that the semicircular deviation is composed of two parts, the correction of that part produced by the permanent magnetism of the hard iron in the ship is made by permanent magnets, and that part produced by soft iron is corrected by soft iron correctors.

72. Correction of Portion of Semicircular Due to Permanent Magnetism.—As introductory to this correction, it may be well to consider the expressions "the poles of the ship" and "the poles of the permanent magnetism of the ship."

In Fig. 19, let the coloring represent the magnetic character of a particular ship. All the red magnetism will act together, as a whole, at one point, its resultant or center of magnetism, and this point we will call the pole of the red magnetism. The blue will act similarly as if concentrated at one point, and this point will be the blue pole of the ship. These two points are called the *poles of the ship*. For a ship built under the condition shown in Fig. 19, the red pole may be indicated as at *P*, and the blue pole as at *P'*. In Fig. 19, the magnetism indicated is that of the entire set of forces of the ship, *i. e.*, of the permanent and transient magnetism combined. We may, however, separate these and investigate either, so that for purposes of illustration Fig. 19 may be used to represent only the permanent magnetism of the ship while we study that portion. In this case, *P* and *P'* would represent the *poles of the permanent magnetism of the ship*. In Figs. 20 to 25 are indicated the poles of the permanent magnetism of ships built with their heads in the following directions: North, Northeast, East, Southeast, South, and Northwest.

Suppose it is desired to correct that portion of the deviation arising from the permanent magnetism in a ship built, for example, with her head Northwest. Fig. 25 indicates the location of the poles of the element of the mag-

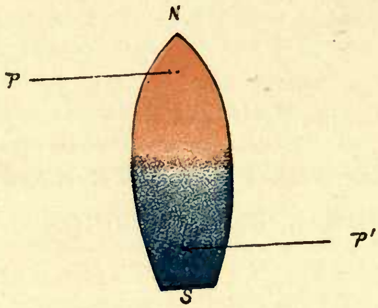


FIG. 19.

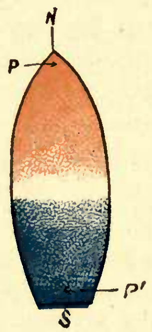


FIG. 20.

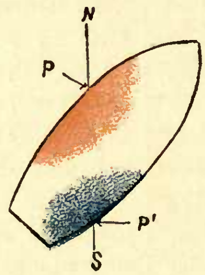


FIG. 21.

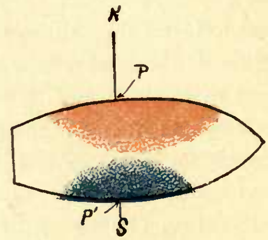


FIG. 22.

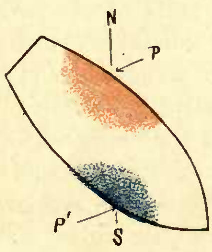


FIG. 23.

FIG. 24.

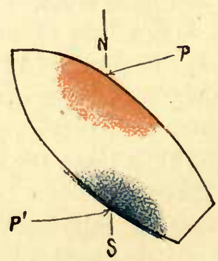


FIG. 25.

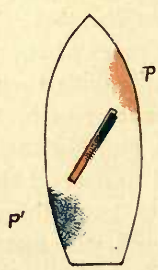


FIG. 26.

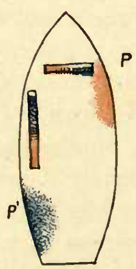


FIG. 27.

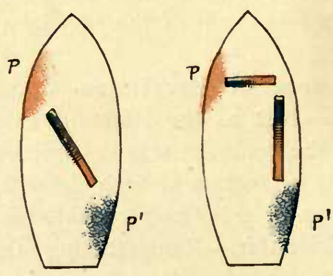


FIG. 28.

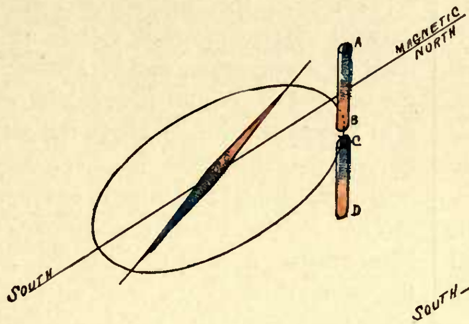


FIG. 29.

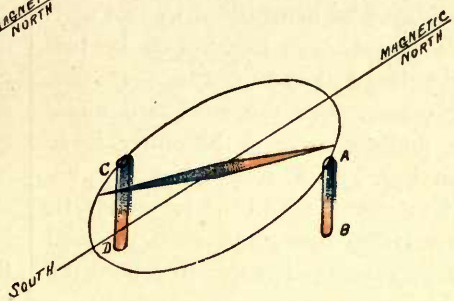


FIG. 30.

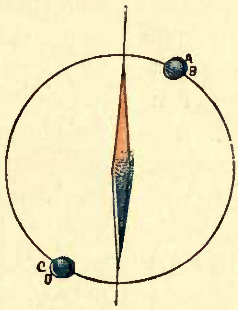
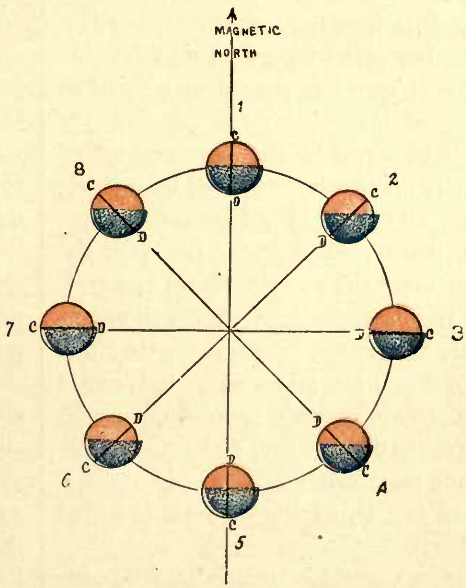


FIG. 31.

FIG. 32.



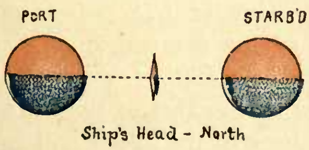


FIG. 34.

FIG. 33.

netism it is desired to correct, and it is easily seen that they may be neutralized by one artificial magnet placed as in Fig. 26, or by two such magnets placed as in Fig. 27.

In Fig. 26, known as the *starboard angle method,* one magnet corrects the entire force *PP′*, while in Fig. 27 *PP′* is considered as resolved into its components in the fore-and-aft, and the athwartship lines, and each artificial magnet corrects one of these components. This is known as the *rectangular method.*

Had the ship's head been Northeast in building (Fig. 21), the correction would have been as indicated in Fig. 28.

The magnets used for correction of this portion of the semicircular deviation may be solid, round, or flat bar magnets, or bundles of small magnets bound together to act as one magnet. In some cases they are placed in specially constructed holders, or trays, in the binnacles; in other cases, they are tacked down to the deck, or secured overhead near the compass. In each and every case, the principles explained in the foregoing are strictly followed, and this element of the magnetic forces of the ship corrected.

73. Correction of that Portion of the Semicircular Deviation Due to Vertical Soft Iron.—Referring to Fig. 11, it is evident that the effect of *AB* would be neutralized by placing a similar soft iron bar, as at *CD,* Fig. 29. And that the bar *AB* of Fig. 12 may be corrected by a soft iron bar placed at *CD,* as in Fig. 30.

The results obtained by the arrangement of Fig. 30 may be made a little clearer by looking at the needle and bars in a horizontal plane through the needle, as in Fig. 31. Here the blue dots represent the end of *AB* on one side, and *CD* on the opposite side, of the diameter of the circle. Suppose, in Fig. 31, that one position of *AB* and *DC* be chosen. It is easily seen that as *AB,* in moving around the circle, attracts or repels the needles, *CD* acts equally in the opposite manner.

Such a bar as *CD,* of Figs. 29-31, is called a *Flinders bar.*

AB, in Fig. 30, could be neutralized by putting *CD* directly over it end to end; but it is to be remembered that *AB* is an imaginary bar representing the magnetism of the ship's vertical soft iron, while *CD* is an actual bar used as a corrector, and is actually placed by the compass. To put it over *AB* would bring it in an awkward place above the compass card, and cause considerable inconvenience in taking bearings, fitting the binnacle cover, etc.

The resultant of the forces which the Flinders bar is used to correct is generally in the center line of the ship, so that nearly all compasses using this bar have it placed in the central fore-and-aft line of the ship, either forward or abaft the compass; forward, to correct a condition represented by Fig. 11; abaft, to correct the condition represented by Fig. 12. See, again, Figs. 29 and 30.

In many ships this bar is not used, the entire semicircular deviation being corrected by the permanent magnets of Figs. 26 and 27. It is easily seen that such a correction is perfect for one latitude only, that in which the correction was made, and that the deviation will change with a change in latitude, because the entire semicircular corrected by the one set of magnets is, as before stated, composed of two elements: one which changes with a change of latitude, and another which does not change with the latitude.

74. Correction of the Quadrantal Deviation.—The quadrantal deviation may be corrected by any arrangement of soft iron which, under the influence of the earth's magnetism, produces a result opposite to that produced by the bar *CD* of Figs. 14 and 15. This correction is generally made by the use of soft iron spheres, and the action of these spheres will be investigated before proceeding farther.

Let the bar *CD* of Fig. 14 be replaced by a sphere *CD,* as in Fig. 32, and let this sphere be revolved through 360°, taking the successive positions 1, 2, 3, etc., to 8, Fig. 33.

As the diameter *CD* swings around, the character of the magnetism at *C* or *D* will change, and at 5, Fig. 33, will have become reversed just as was that of the bar *CD* of Fig. 14. The shape of the sphere is, however, such that no matter in which direction the diameter *CD,* Fig. 33, may be, the effect is that of a ball of soft iron, always maintaining the characteristic of having its northern half of red magnet-

ism and its southern half of blue magnetism. In other words, the northern and southern hemispheres are always of the same magnetic character, with their poles north and south, regardless of how the sphere is revolved. The effect is the same as moving around in a circle, parallel to itself, a magnet of the character shown in Fig. 33.

This magnet is produced by the induction of the earth's magnetism, and, if properly placed, its force may be used to oppose the effect upon the compass of other induced magnetism of the soft iron of the ship, *i. e.,* it may be used to counteract the effect of the bar *CD,* of Fig. 14, in producing deviation.

For this purpose, two spheres, one on each side of the compass needle, as shown in Fig. 34, are used. Their action may be illustrated as follows:

Take the position 2 of Fig. 15, in which the ship is heading northeast, and place the spheres in position as they would ordinarily be mounted on board ship. See Fig. 35. As in Fig. 15, the result of *CD* acting alone would be to pull the needle to the position *e,* thus producing an easterly deviation. The result of the spheres acting by themselves would be to pull the needle to the position *w,* and produce a westerly deviation. The action of the spheres is thus opposed to the action of the bar *CD,* and if the spheres are large enough and placed close enough they may be made to entirely correct the action upon the needle of the bar *CD* or its equivalent.

So far, this explanation has applied to the particular case represented in Fig. 35; but a clear conception of the principles involved, applied to the study of Fig. 36, will show that the spheres oppose, neutralize, or correct *CD* in all positions of the ship's head.

The spheres to correct quadrantal deviation, such as would be produced by conditions represented by *CD* of Fig. 15, the conditions ordinarily existing on board ship, are placed one to starboard and one to port on the 'thwartship line, passing through the center of the compass needle.

If conditions represented by Fig. 15a existed, the spheres would be placed on the fore-and-aft center line of the ship, one forward and one abaft the binnacle. Such conditions are not usually found on board ships of present construction, so that the quadrantal correctors are usually found one to starboard and one to port of the compass, and their effect on the compass needle varied by moving them toward or away from the compass.

In compasses which have large and powerful needles, these needles, when close to the spheres, will induce magnetism in the spheres at the same time and in the same manner as the earth's force. In this case, the quadrantal correcting force is the resultant of the permanent force due to the induction of the needles in the spheres and the variable force due to the induction of the earth in the spheres. The resultant of these two forces is a variable force, and when a given quadrantal deviation is corrected in one latitude by this force, the balance will be disturbed and the correction fail to hold good upon going to another latitude. If, however, the needles are so small, and so far from the spheres as to not appreciably affect them, the quadrantal deviation once corrected should remain corrected, practically, for all latitudes.

75. Heeling Error.—If a ship whose compass has been corrected be heeled to one side, and while so heeled be swung in azimuth, it will be found that the equilibrium of compensation (correction) has been disturbed, and that there now exists on some headings deviations which did not exist when the ship was upright. Furthermore, it will be found that if the ship be brought to an upright position and again swung in azimuth these deviations will have disappeared. The deviation brought into existence during heeling is called the *heeling deviation,* or *heeling error.*

In all of the preceding discussion of the causes of deviation, the ship has been considered as in an upright position and the discussion has proceeded on the following assumptions: (1) That such bars as *CD* of Figs. 14, 15, and 15a have been in a horizontal plane; (2) that the effect of vertical induction in vertical soft iron, such as *AB,* Figs. 11 and 12, has acted at points other than directly under the center of the compass needle; and (3) that the permanent magnetism of the ship has acted only in a horizontal plane.

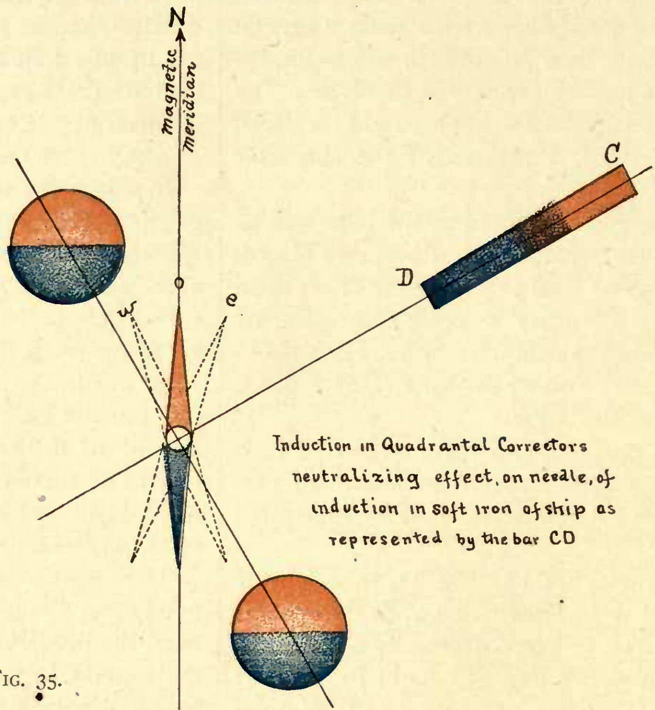

N
magnetic meridian
C
D
w
e
Induction in Quadrantal Correctors neutralizing effect, on needle, of induction in soft iron of ship as represented by the bar CD

FIG. 35.

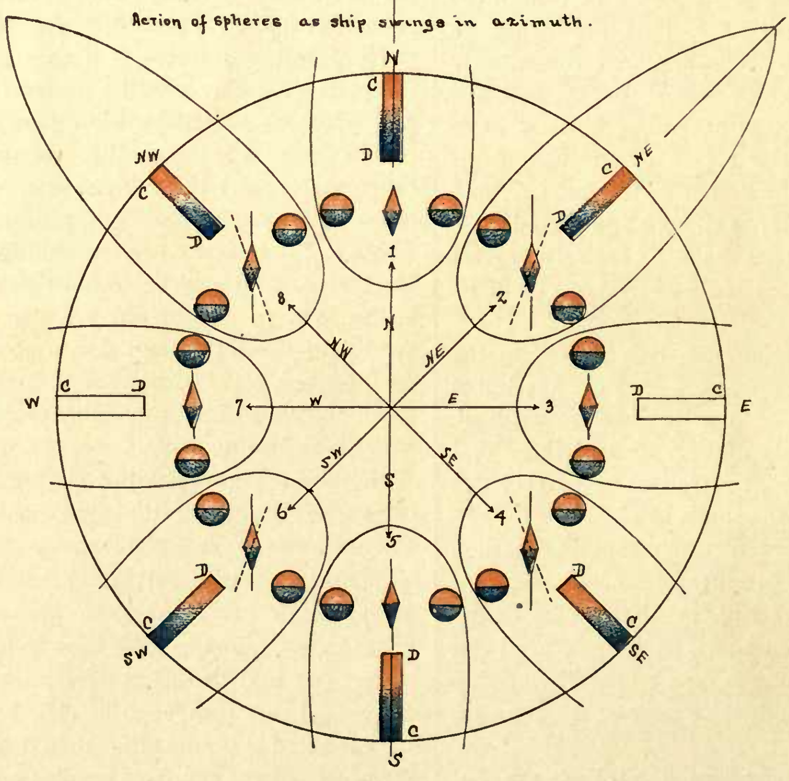

Action of spheres as ship swings in azimuth.
N
C
D
NW
NE
1
2
3
4
5
6
7
8
N
NW
NE
W
E
SW
SE
S
W
E
SW
SE
S

FIG. 36.

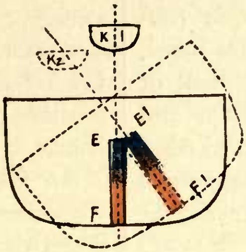


FIG. 37.

Effect of vertical component of permanent magnetism, ship heading North and heeled to port and to starboard.

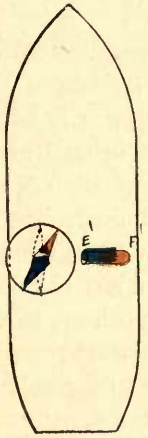


FIG. 38.
Heeled to port.

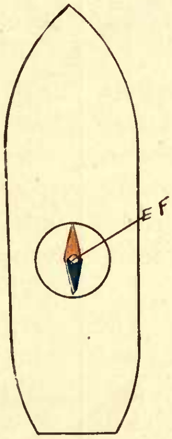


FIG. 37a.
Upright.

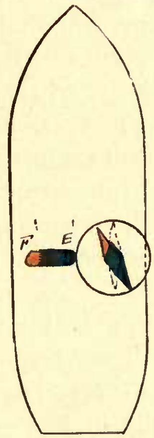
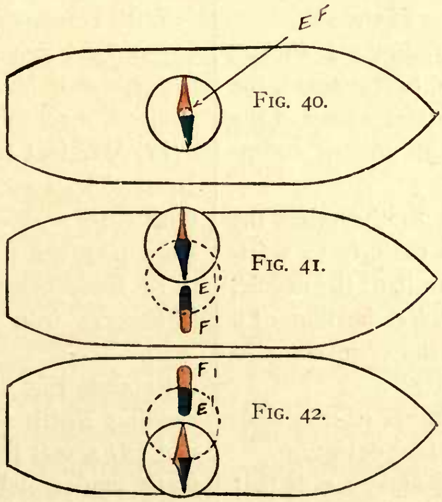


FIG. 39.
Heeled to starboard.



On even FIG. 40. keel.

Heeled FIG. 41. to port.

Heeled FIG. 42. to starboard.

Effect of vertical component of permanent magnetism, ship heading East and heeled to port and to starboard.

As a matter of fact, that portion of the permanent magnetism which has been considered as acting only in the horizontal plane, has been merely the horizontal component of the permanent magnetism of the ship, and there is yet to be considered that vertical component of the ship's permanent magnetism which acts directly under the center of the compass.

When the ship is upright, this force has no effect in producing deviation. When the ship heels, this force no longer acts vertically beneath the center of the compass, but to one side of the compass needle, and consequently, in certain positions, will produce deviations as long as the ship remains heeled.

This may be illustrated as follows: In Figs. 37 and 37a, let *EF* represent a vertical component of permanent magnetism acting directly under the center of the compass, the ship being in an upright position heading North. In this position *EF* is ineffective in producing deviation.

Now let the ship be heeled to port. The compass bowl will move from K_1 to K_2, and *EF* will move to *E'F'*. The situation is projected horizontally in Fig. 38. It is evident from an inspection of Fig. 38, that *EF*, now in the position *E'F'*, is at right angles to the axis of the compass needle and exerts a pull on it producing, as shown, a deviation of the needle to the high, or windward, side of the ship.

An inspection of Fig. 39 shows a similar result when the ship is heeled to starboard, the deviation of the needle again being toward the high side of the ship, although now of an opposite sign from that in Fig. 38.

In heeling from one side to the other the deviation has changed from easterly to westerly, and if the swing in azimuth, of the needle, synchronizes with the rolling, *i. e.*, heeling, of a ship, violent oscillations of the compass card may be produced.

This is one test of the presence of a heeling error, or force producing heeling deviation.

Referring again to Figs. 38 and 39, note that with the ship heading north *EF*, when the ship is heeled, swings to the side of the needle at right angles to its axis, and is capable of producing on north or south courses its maximum effect.

Referring now to Fig. 40, let the ship be headed East on an even keel, and from this position be heeled first to port and then to starboard, as in Figs. 41 and 42.

An inspection of these figures shows that while heeled *EF* may increase or decrease the directive force of the needle, but it acts in the same plane as the axis of the needle and through its center, thus possessing no power to deflect it horizontally. On easterly and westerly courses, *EF* produces no deviation.

This element then produces a deviation semicircular in character, being a maximum on North and South, and zero on East and West.

76. Vertical Induction in Vertical Soft Iron.—If we endow *EF* with the characteristics of soft iron instead of hard iron, Figs. 37-42 also illustrate the effect (in north latitude) of vertical induction in vertical soft iron immediately below the compass.

The two forces just considered are, at any one geographical position, so mixed as to make it impossible to separate them.

With reference to the coloring of *EF*, Fig. 37, as permanent magnetism, the upper end may be blue or red, depending upon where the ship was built, how she was heading when built, and in which part of the ship the compass is located.

With reference to its coloring as representing vertical induction in vertical soft iron, the upper end is blue in north magnetic latitudes and red in south magnetic latitudes.

77. Vertical Induction in Transverse Soft Iron.—The two forces just considered combine with a third force to produce what is known as the principal heeling error. This third force arises from vertical induction in transverse iron as, for example, the deck beams.

Suppose Fig. 43 to be an end view of a ship heading North (in North magnetic latitude), and *CD* a soft iron deck beam in a horizontal plane immediately below the compass. This beam is, with the ship heading North, magnetic, at right angles to the magnetic meridian, and is not magnetized (see Figs. 14 and 15a).

and consequently produces no effect on the compass needle which is shown end on at L.

Let the ship be heeled to port, as in Fig. 44. This beam now ceases to be horizontal, becomes magnetized, and has a vertical component DZ, which is the result of induction in CD by the vertical component of the earth's force. This force now acts at one side of the compass needle, at right angles to its axis, and produces a deviation.

beams not continuous, *i. e.,* beams in wake of hatches. This force thus produces a deviation which is zero on East and West, and a maximum on North and South.

78. Principal Heeling Error.—The combined action of the three forces just discussed causes the principal heeling error.

It is to be noted that they are all a maximum on North and South, are zero on East and West, and are all due to vertical forces. Being

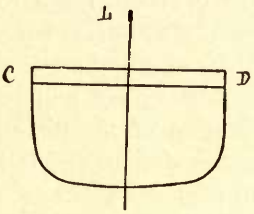


FIG. 43.

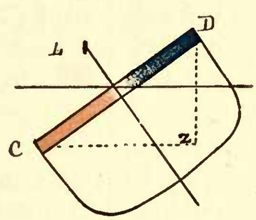


FIG. 44.

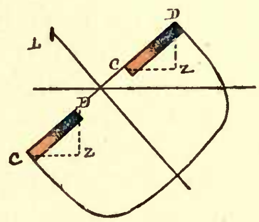


FIG. 45.

Ship heading North. Effect of vertical induction (in North latitude) in transverse soft iron.

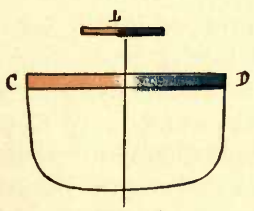


FIG. 46.

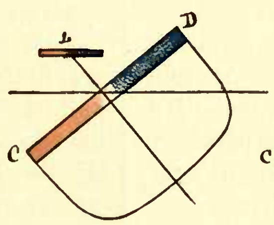


FIG. 47.

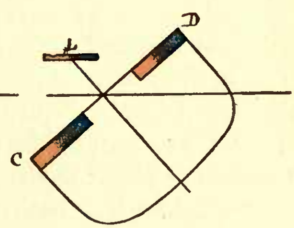


FIG. 48.

Ship heading East. Effect of induction in transverse soft iron. North latitude.
In connection with Figs. 43-46, study Figs. 10, 13, 14, and 15a.

Consider, again, this ship, in Fig. 46, as being upright and heading East magnetic. CD now lies in the magnetic meridian, is parallel to the compass needle, and is in the same vertical plane with it. It will be magnetized both in an upright position and while heeled; but lying in the same vertical plane, it will not tend to move the needle out of that plane, and hence produces no deviation. Figs. 45 and 48 represent

due to vertical forces, they are corrected by a vertical magnet placed directly under the center of the compass needle while the ship is upright. They are usually, in a practical sense, considered as one force and corrected by one permanent magnet, so arranged that it may be raised, lowered, or it ends reversed, to meet the necessities arising in going from one magnetic hemisphere to the other.

CHAPTER V.

THE PRACTICAL CORRECTION OF THE DEVIATION.

By COMMANDER G. W. LOGAN, U. S. N.

(Taken from the *American Practical Navigator* (Bowditch).)

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79. In the course of explanation of the different classes of deviation, occasion has been taken to state generally the various methods of compensating the errors that are produced. The practical methods of applying the correctors will now be explained.

80. Order of Correction.—The following is the order of steps to be followed in each case. It is assumed that the vessel is on an even keel, that all surrounding masses of iron or steel are in their normal positions, all correctors removed, and the binnacle is one in which the semicircular deviation is corrected by two sets of permanent magnets at right angles to each other.

1. Place quadrantal correctors by estimate.
2. Place the heeling magnet in its tube, North end up in North magnetic latitudes, and lower it to the bottom.
3. Correct the semicircular deviations
4. Correct the quadrantal deviation.
5. Swing ship for residual deviations.

A Flinders bar can be put in place permanently only after observations in two latitudes. In cases of excessive deviation due to vertical induction in soft iron, when no data for placing the Flinders bar are available, it will be preferable to correct all but about ten degrees by Flinders bar and the remainder by the semicircular magnets, rather than to correct all by the magnets. The compensation may not be accurate in this case, but it is more nearly so than it would be by not using the Flinders bar, and it may be accurately completed whenever the necessary observations are made.

81. The ship is first placed on some magnetic cardinal point. If North or South, the only force (theoretically speaking) which tends to produce deflection of the needle will be the athwartship component of the semicircular force, whose effect is represented by the coefficient C. If East or West, the only deflecting force will be the fore-and-aft component of the semicircular force, whose effect is represented by the coefficient B. This will be apparent from a consideration of the direction of the forces producing deviation, and is also shown by the equation connecting the terms (where A and E are zero):

$$d = B \sin z' + C \cos z' + D \sin 2z'.$$

If the ship is headed North or South, z' being equal to 0° or 180°, the equation becomes $d = \pm C$. If on East or West, z' being 90° or 270°, we have $d = \pm B$.

This statement is exact if we regard only the forces that have been considered in the problem, but experience has demonstrated that the various correctors, when in place, create certain additional forces by their mutual action, and in order to correct the disturbances thus accidentally produced, as well as those due to regular causes, it is necessary that the magnetic conditions during correction shall approximate as closely as possible to those that exist when the compensation is completed; therefore the quadrantal correctors should first be placed on their arms at the positions which it is estimated that they will occupy later when exactly located. An error in the estimate will have but slight effect under ordinary conditions. It should be understood that the placing of these correctors has no corrective effect while the ship is on a cardinal point. Its object is to create at once the magnetic field with which we shall have to deal when compensation is perfected.

This having been done, proceed to correct the semicircular deviation. If the ship heads North or South, the force producing deflec-

tion is, as has been stated, the athwartship component of the semicircular force, which is to be corrected by permanent magnets placed athwartships; therefore enter in the binnacle one or more such magnets, and so adjust their height that the heading of the ship by compass shall agree with the magnetic heading. When this is done, all the deviation on that azimuth will be corrected.

Similarly, if the ship heads East or West, the force producing deviation is the fore-and-aft component of the semicircular force, and this is to be corrected by entering fore-and-aft permanent magnets in the binnacle and adjusting the height so that the deviation on that heading disappears.

With the deviation on two adjacent cardinal points corrected, the semicircular force has been completely compensated. Next correct the quadrantal deviation. Head the ship NE., SE., SW., or NW. The coefficients B and C having been reduced to zero by compensation, and $2z'$, on the azimuths named, being equal to 90° or 270°, the equation becomes $d = \pm D$. The soft-iron correctors are moved in or out from the positions in which they were placed by estimate until the deviation on the heading (all of which is due to quadrantal force) disappears. The quadrantal disturbing force is then compensated.

82. Determination of Magnetic Headings. To determine when the ship is heading on any given magnetic course, and thus to know when the deviation has been corrected and the correctors are in proper position, four methods are available:

(a) Swing the ship and obtain by the best available method the deviations on a sufficient number of compass courses to construct a curve on the Napier diagram for one quadrant, and thus find the compass headings corresponding to two adjacent magnetic cardinal points and the intermediate intercardinal point, as North, NE., and East, magnetic.* Then put the ship successively on these courses; noting the corresponding headings by some other compass; and when it is desired to head on the various magnetic azimuths during the process of correction, the ship may be steadied upon them by the auxiliary compass. Variations of this method will suggest themselves, and circumstances may render their adoption convenient. The compass courses corresponding to the magnetic directions may be obtained from observations made with the auxiliary compass itself, or while making observations with another compass the headings by the auxiliary may be noted and a curve for the latter constructed, as explained in Art. 22, and the required headings thus deduced.

(b) By the methods explained in the *American Practical Navigator,* ascertain in advance the true bearing of the sun at frequent intervals during the period which is to be devoted to the compensation of the compasses; apply to these the variation and obtain the magnetic bearings; record the times and bearings in a convenient tabular form; set the watch accurately for the local apparent time; then when it is required to steer any given magnetic course, set that point of the pelorus for the ship's head and set the sight vanes for the magnetic bearing of the sun corresponding to the time by watch. Maneuver the ship with the helm until the sun comes on the sight vanes, when the azimuth of the ship's head will be that which is required. The sight vanes must be altered at intervals to accord with the table of times and bearings.

(c) Construct a table showing times and corresponding magnetic bearings of the sun, and also set the watch, as explained for the previous method. Then place the sight vanes of the azimuth circle of the compass at the proper angular distance to the right or left of the required azimuth of the ship's head; leave them so set and maneuver the ship with the helm until the image of the sun comes on with the vanes. The course will then be the required one. As an example, suppose that the table shows that the magnetic azimuth of the sun at the time given by the watch is 87°, and let it be required to head magnetic North; when placed upon this heading, therefore, the sun must bear 87° to the right, or east, of the direction of the ship's head; when steady on

* This is all that is required for the purposes of compensation, but if there is opportunity it is always well to make a complete swing and obtain a full table of deviations, which may give interesting information of the existing magnetic conditions.

any course, turn the sight vane to the required bearing relative to the keel. If on 349°, for example, turn the circle to 76°; leave the vane undisturbed and alter course until the sun comes on. The magnetic heading is then North, and adjustment may be made accordingly.

(d) When ranges are available, they may be utilized for determining magnetic headings.

83. Summary of Ordinary Corrections.—To summarize, the following is the process of correcting a compass for a single latitude, where magnets at right angles are employed for compensating the semicircular deviation and where the disturbances due to unsymmetrical soft iron are small enough to be neglected:

First: All correctors being clear of the compass, place the quadrantal correctors in the position which it is estimated that they will occupy when adjustment is complete. The navigator's experience will serve in making the estimate, or, if there seems to be no other means of arriving at the probable position, they may be placed at the middle points of their supports.

Second: Steady the ship on magnetic North, East, South, or West, and hold on that heading by such method as seems best. By means of permanent magnets alter the indications of the compass until the heading coincides with the magnetic course. In heading North, magnets must be entered N. ends to starboard to correct easterly deviation, and to port to correct westerly, and the reverse if heading South. If heading East, enter N. ends forward for easterly deviations and aft for westerly, and the reverse if heading West. (Binnacles differ so widely in the methods of carrying magnets that details on this point are omitted. It may be said, however, that the magnetic intensity of the correctors may be varied by altering either their number or their distance from the compass; generally speaking, several magnets at a distance are to be preferred to a small number close to the compass.)

Third: Steady the ship on an adjacent magnetic cardinal point and correct the compass heading by permanent magnets to accord therewith, in the same manner as described for the first heading.

Fourth: Steady the ship on an intercardinal point (magnetic) and move the quadrantal correctors away from or toward the compass, keeping them at equal distances therefrom, until the compass and magnetic headings coincide.

84. The compensation being complete, the navigator should proceed immediately to swing ship and make a table of the residual deviations. Though the remaining errors will be small, it is seldom that they will be reduced to zero, and it must never be assumed that the compass may be relied upon without taking the deviation into account. Observations on eight equidistant points will ordinarily suffice for this purpose.

85. To Correct Semicircular Deviation with a Single Magnet.—In certain binnacles provision is made for correcting the semicircular deviation by a single magnet (or series of magnets) in the starboard angle, the magnet tray having motion in azimuth as well as vertically. In this case the process of correcting semicircular deviation is somewhat different from that described for correction by rectangular magnets. Either of the two following methods may be employed:

(a) By computation determine the starboard angle. An approximate method for doing this is given in Chapter III, Art. 51, and a more exact one may be found in works treating this subject mathematically. Head the ship on a cardinal point (magnetic); enter the magnets in the tray and revolve it until their N. ends lie at an angular distance from ahead (measured to the right) equal to the starboard angle; raise or lower the tray until the deviation disappears.

(b) Head the ship on a cardinal point (magnetic), enter the magnets, and turn the tray to an East-and-West position, the N. ends in such direction as will tend to reduce the deviation; raise or lower the tray until the deviation disappears. Alter course 90° and head on an adjacent magnetic cardinal point; observe the amount of deviation that the compass shows; correct half of this by altering the starboard angle and the other half by raising or lowering the tray. Return to first course, note deviation, and correct one-half in each way, as before.

Continue the operation, making a series of trials until the deviations disappear on both headings, when the compensation will be correct. This operation may be considerably hastened by finding the first position of the magnets from a rough calculation of the starboard angle (Chapter III, Art. 51).

86. Correcting the Heeling Error.—The heeling error may be corrected by a method involving computation, together with certain observations on shore. A more practical method, however, is usually followed, though its results may be less precise. The heeling corrector is placed in its vertical tube, N. end uppermost in north latitudes, as this is almost invariably the required direction. The ship being on a course near North or South and rolling, observe the vibrations of the card, which, if the error is material, will be in excess of those due to the ship's real motion in azimuth; slowly raise or lower the corrector until the abnormal vibrations disappear, when the correction will be made for that latitude; but it must be readjusted upon any considerable change of geographical position.

In making this observation care must be taken to distinguish the vessel's "yawing" in a seaway, from the apparent motion due to heeling error; for this reason it may be well to have an assistant to watch the ship's head and keep the adjuster informed of the real change in azimuth, by which means the latter may better judge the effect of the heeling error.

In the case of a sailing-vessel, or one which for any reason maintains a nearly steady heel for a continuous period, the amount of the heeling error may be exactly ascertained by observing the azimuth of the sun, and corrected with greater accuracy than is possible with a vessel which is constantly rolling.

87. Flinders Bar.—The simplest method that presents itself for the placing of the Flinders bar is one which is available only for a vessel crossing the magnetic equator. Magnetic charts of the world show the geographical positions at which the dip becomes zero; that is, where a freely suspended needle is exactly horizontal and where there exists no vertical component of the earth's total magnetic force. In such localities it is evident that the factor of the semicircular deviation due to vertical induction disappears, and that the whole of the existing semicircular deviation arises from subpermanent magnetism. If, then, when on the magnetic equator, the compass be carefully compensated, the effect of the subpermanent magnetism will be exactly opposed by that of the semicircular correcting magnets. Later, as the ship departs from the magnetic equator, the semicircular deviation will gradually acquire a material value, which will be known to be due entirely to vertical induction, and if the Flinders bar be so placed as to correct it, the compensation of the compass will be general for all latitudes.

In following this method it may usually be assumed that the soft iron of the vessel is symmetrical with respect to the fore-and-aft line and that the Flinders bar may be placed directly forward of the compass or directly abaft it, disregarding the effect of components to starboard or port. It is therefore merely necessary to observe whether a vertical soft iron rod must be placed forward or abaft the compass to reduce the deviation, and, having ascertained this fact, to find by experiment the exact distance at which it completely corrects the deviation.

The Flinders bar frequently consists of a bundle of soft iron rods contained in a case, which is secured in a vertical position near the compass, its upper end level with the plane of the needles; in this method, the distance remaining fixed, the intensity of the force that it exerts is varied by increasing or decreasing the number of rods; this arrangement is more convenient and satisfactory than the employment of a single rod at a variable distance.

88. When it is not possible to correct the compass at the magnetic equator there is no ready practical method by which the Flinders bar may be placed. The operation will then depend entirely upon computation, and as a mathematical analysis of deviations is beyond the scope laid out for this work, the details of procedure will not be gone into; the general principles involved are indicated, and students seeking more must consult the various works that treat the subject fully.

It has been explained that each coefficient of semicircular deviation (B and C) is made up

of a subpermanent factor varying as $\frac{1}{H}$ and of a vertical induction factor varying as $\tan\theta$. If we indicate by the subscripts s and v, respectively, the parts due to each force, we may write the equations of the coefficients:

$$B = B_s \times \frac{1}{H} + B_v \times \tan\theta,$$

and

$$C = C_s \times \frac{1}{H} + C_v \times \tan\theta.$$

Now if we distinguish by the subscripts 1 and 2 the values in the first and in the second position of observation, respectively, of those quantities that vary with the magnetic latitude, we have:

$$B_1 = B_s \times \frac{1}{H_1} + B_v \times \tan\theta_1,$$

$$B_2 = B_s \times \frac{1}{H_2} + B_v \times \tan\theta_2;$$

and

$$C_1 = C_s \times \frac{1}{H_1} + C_v \times \tan\theta_1,$$

$$C_2 = C_s \times \frac{1}{H_2} + C_v \times \tan\theta_2.$$

The values of the coefficients in both latitudes are found from the observations made for deviations; the values of the horizontal force and of the dip at each place are known from magnetic charts. Hence we may solve the first pair of equations for B_s and B_v, and the second pair for C_s and C_v; and having found the values of these various coefficients, we may correct the effects of B_s and C_s by permanent magnets in the usual way, and correct the remainder—that due to B_v and C_v—by the Flinders bar.

Strictly, the Flinders bar should be so placed that its repelling pole is at an angular distance from ahead equal to the "starboard angle" of the attracting pole of the vertical induced force, this angle depending upon the coefficients B_v and C_v; but since, as before stated, horizontal soft iron may usually be regarded as symmetrical, C_v is assumed as zero and the bar is placed in the midship line.

89. To Correct Adjustment on Change of Latitude.—The compensation of quadrantal deviation, once properly made, remains effective in all latitudes;* but unless a Flinders bar is used, a correction of the semicircular deviation made in one latitude will not remain accurate when the vessel has materially changed her position on the earth's surface. With this in mind the navigator must make frequent observations of the compass error during a passage and must expect that the table of residual deviations obtained in the magnetic latitude of compensation will undergo considerable change as that latitude is departed from. The new deviations may become so large that it will be found convenient to readjust the semicircular correcting magnets. This process is very simple.

When correctors at right angles are used, provide for steadying the ship, by an auxiliary compass or by the pelorus, upon two adjacent magnetic cardinal points. (See Art. 82, above.) Put the ship on heading North or South (magnetic), and raise or lower the athwartship magnets, or alter their number, until the deviation disappears; then steady on East or West (magnetic) and similarly adjust the fore-and-aft magnets. Swing ship for a new table of residual deviations.

When correctors in the starboard angle are used, arrange as before for heading on two adjacent cardinal magnetic courses. Steady on one of these; observe amount of compass error; correct half by changing the starboard angle and half by raising or lowering magnets. Steady on the adjacent cardinal point and repeat the operation. Continue until adjustment is made on both headings; then swing for residual deviations.

* This is true only when the quadrantal correctors are far enough from the powerful magnets of the compass to prevent the magnets of the compass itself from inducing magnetism in the correctors. If the correctors are sufficiently near the needles to cause mutual induction to be set up, a disturbing force will be introduced that is constant for all latitudes, depending as it does upon the amount of magnetism in the compass needles. But since it is resisted by a quadrantal correcting force which depends on the earth's magnetic induction, and which, therefore, varies with the magnetic latitude, the compensation will in this case be disturbed by change in magnetic latitude and will not be universal.

CHAPTER VI.

DIRECTIONS FOR USE OF COMPENSATING BINNACLES WITH FORE-AND-AFT AND ATHWARTSHIP MAGNET CORRECTORS AND QUADRANTAL SPHERES, ETC.

(Copy of circular issued by the Navy Department.)

90. A compass mounted in a binnacle of the above type may be corrected for deviations by following the instructions given below.

91. The vessel should be on an even keel. Secure all movable local masses in the vicinity of the compass in the positions they will invariably occupy when at sea.

92. All binnacles should be exactly on the midship line and should be so solidly secured as to avoid any chance of movement. The compasses should be in the center of the binnacles. To center a compass in its binnacle, with ship heading north or south, or nearly so put compass in place and adjust its position by the screws at the ends of the outer gimbal ring knife edges, until no change of heading by compass is observed as the heeling magnet is raised and lowered, the vessel being on an even keel. Secure the compass in this position by setting in on the screws to prevent any sliding back and forth athwartships.

93. The lubber's line of the compass should be exactly in the fore-and-aft plane, and that it is so should be carefully verified. This is best done by sighting with the azimuth circle on straight edges erected on the midship line at some distance forward and abaft the compass.

94. The lubber's line of each pelorus should also be checked up, either by comparison of simultaneous bearings of a distant object taken from compass and pelorus, or by computing from known dimensions taken from the ship's plans the angle which the flagstaff or jackstaff should bear from the fore-and-aft line through the pelorus and verifying this by observation.

TO PLACE THE SHIP'S HEAD UPON ANY MAGNETIC POINT OF THE COMPASS AT SEA.

95. A convenient method of finding the proper direction to lay the ship's head by an uncorrected compass at sea, to correspond with any magnetic point, is as follows:

1. Select beforehand the locality and date on which the compass is to be corrected, and choose certain intervals of local apparent time to cover the operation.

2. With the selected latitude and declination, pick out from the azimuth tables, or the azimuth diagram, the sun's true bearing for the local apparent times selected. Apply the variation for the locality to the true bearings and obtain the magnetic bearings of the sun, observing the rule that easterly variation must be applied to the *left* and westerly variation to the *right* of the true to obtain magnetic bearing. Make a curve on cross-section paper in which the ordinates are minutes of local apparent time and the abscissæ degrees of magnetic azimuth. Cross-section paper for this purpose may be found in the back of the Compass Record Book.

3. On the date of observation proceed to the locality previously decided upon and set the watch to local apparent time. Suppose it is desired to head the ship North, magnetic.

Knowing the magnetic bearing of the sun at any watch time, as taken from the curve, turn the azimuth circle until the angle between the reflecting prism opposite the mirror and the lubber's line of the compass equals the angle between the sun's magnetic bearing and magnetic North. Turn the ship to bring the sun's reflection exactly in the vertical slit opposite the mirror, and hold it there by the helm. At the instant of time selected, the ship's head will be North, magnetic. A mark should be given to the helmsman at the instant when the ship is on magnetic North, in order that he may note the heading by steering compass and steady on it. The angle at which the azimuth circle is set may be read from the scale of degrees

marked on its inner beveled edge, noting that the lubber's line is continued as a score on the rim of the compass bowl. In a similar manner the ship may be headed on any other magnetic course, as the following example will illustrate:

To Head 45° Magnetic.—Having decided upon correcting the compass between the hours of 7 a. m. and 10 a. m., local apparent time, and having a curve prepared covering these times and the locality selected, we will suppose that the ship arrives at this locality, and that it is desired to head 45°, magnetic, at 7 a. m., local apparent time. An inspection of the curve gives the sun's magnetic bearing for this time as, say, 99° 15′, or 54° 15′ to the right of 45°. Turn the azimuth circle until the reflecting prism opposite the mirror is 54° 15′ to the right of the score on the rim of the compass bowl forward. Turn the ship until the reflection of the sun is thrown exactly into the vertical slit and hold it there by the helm until 7 a. m. by watch time, at which instant the ship will be heading 45° magnetic.

4. The pelorus may also be used for this purpose, by setting the dial to the magnetic heading selected, setting the sight vanes to correspond with the magnetic bearing of the sun for the selected local apparent time, and then turning the ship to bring the sight vanes on the sun. It is better, however, to take bearings of the sun from the compass when possible.

TO COMPENSATE.

96. Approximate Preliminary Compensation.—1. The first step in compensation of the compass is to correct approximately the quadrantal deviation and the heeling error, in the order named. This is necessary because a material factor in the deviation may be caused by the induction in quadrantal spheres set up by the magnet correctors, and it is essential that the semicircular correction, which is the largest and most important one, should be made when the magnetic conditions approximate as nearly as possible to those when the compensation is complete.

2. Place the quadrantal spheres on the arms and secure them at the middle position; or if the proper position is approximately known, secure them more accurately.

3. Place the heeling magnet in its tube, North end up in North magnetic latitude, unless some foreknowledge demands the reverse, and lower it to the bottom.

97. Semicircular Deviation.—*To correct semicircular deviation:* 1. Head the vessel North magnetic, by any compass whose deviation is known or by the method described above.

If the compass shows easterly deviation, enter one or more athwartship magnets, North or red ends to starboard. Move the magnets up or down until the compass points North.

If the compass shows westerly deviation, enter the athwartship magnets with North or red ends to port. Raise or lower them until the compass points North.

Or, head the vessel South, magnetic; enter the athwartship magnets North or red ends to port to correct easterly deviation, or to starboard to correct westerly deviation.

2. Next head the vessel East, magnetic. If easterly deviation is shown, enter the fore-and-aft magnets with North or red ends forward; if westerly deviation is shown, enter the fore-and-aft magnets with North ends aft. Raise or lower the magnets until the compass points East.

Or, head the vessel West, magnetic; enter the fore-and-aft magnets North ends aft to correct easterly deviation, or North ends forward to correct westerly deviation.

3. As the ship is steadied on each magnetic course, a mark is given to an assistant at each compass, and the compasses should all be brought to the same reading, the change to the next course not being made until each assistant reports ready.

4. In using semicircular corrector magnets, divide them equally on each side of the vertical axis of the binnacle. It is better to use a greater number of magnets at a distance than a smaller number near the compass.

98. Quadrantal Deviation.—*To correct quadrantal deviation:* 1. Having corrected the semicircular deviation by the foregoing methods, next head the vessel on a magnetic intercardinal point; and if deviation is shown, move the spheres in or out until the compass points correctly.

2. Steady on each course as before, long enough for all compasses to be corrected.

3. If the spheres over-correct when placed at the outer limits of the arms, smaller spheres should be used. Note that one sphere will correct half as much as two of the same size. If the spheres under-correct when close in, larger ones are needed.

4. Quadrantal spheres should from time to time be tested for polarity. Select a time when the ship's head is steady, preferably alongside the dock. Run the spheres in on the arms as far as possible and note the headings by compass. Then turn one sphere at a time successively through 90° on its own axis until it has been completely rotated, noting after each turn of 90° if any deflection of the compass has been produced. Should a deflection of more than 45′ be apparent during the rotation of a sphere, that sphere should be reannealed by heating to a dark heat only, covering with ashes and allowing to cool slowly.

(It should be noted that a compass from which bearings of the sun can be taken may be corrected by raising or lowering the magnets, or moving the spheres, until the sun bears as it should, in which case the compensation is correct, even if the ship's head is one or two degrees on either side of the desired magnetic heading. With an azimuth circle mounted on the steering compass, it may be corrected by having the helmsman keep on heading North, by the compass in front of him, or whatever heading is desired, regardless of the work of correcting, and bringing the sun to bear as it should by raising or lowering the magnets, or moving the spheres.)

99. Errors in Compensation.—1. In compensating by the method described, certain errors are possible, and they should be guarded against by the navigator.

2. By removing all deviation on one heading, a real constant deviation, if there is any, although removed on this heading, will be doubled on the opposite heading.

3. The curve of magnetic bearings may be in error, due to errors of calculation or in the assumed variation. The azimuth circle may be inaccurate. In either of these two cases an error is caused, due to the fact that the compass is compensated on one heading for an apparent deviation which does not really exist, an apparent deviation of double this amount being thereby caused on the opposite heading.

4. It is therefore advisable, after compensating on three headings as described above, to check up on the opposite headings, removing one-half of any apparent deviation remaining on each heading. The result will be that the real constant deviation, if any, and the apparent deviation, previously taken out on the first headings, will now be left uncompensated as they should be.

100. Another Method of Compensation.—1. Regardless of its magnetic bearing, if a distant object can be brought to bear the same by compass for all headings, that compass will be accurately compensated. This fact forms the basis for a method of compensation proposed by Lieutenant R. A. Koch, U. S. Navy, which eliminates the errors mentioned in Art. 99, above. By this method a bearing of a distant object is first taken by the compass to be corrected, with the ship steadied on North by compass. The ship is then headed South by compass and a bearing of the same object is taken. The athwartship magnets are raised and lowered until the bearing of the distant object is half-way between the two bearings observed on North and South, respectively. There should then remain no deviation on South except the real constant deviation, which it is desired to leave uncompensated. Compensation is completed on East or West, and then on one of the intercardinal points, by causing the distant object to bear the same as on South. The sun may be used as the distant object, making allowance for its change of bearing between observations, for which purpose a curve of change of bearings on cross-section paper is used. (A full description of this method is given in Chapter VIII of this book.)

101. Swinging for Residuals.—1. Swing ship for residual deviations, taking observation on at least eight points. Either readjust the correctors, proceeding as above, or use the residual deviations to run on.

The vessel should invariably be swung for a final table of deviations at the earliest oppor-

tunity after compensation. Check all courses steered by frequent azimuths.

102. Heeling Error.—1. The heeling magnet may be approximately placed, at any time when shore observations are available, by the following method: Hang the heeling magnet to the chain and lower it to the bottom of the tube, North end up (in North magnetic latitudes). Place the heeling adjuster * in the binnacle, in the position of the compass needle, with the movable weight at λa. a is the reading of the scale when the needle was level on shore. If λ is not known, it may be assumed at .8 for ordinarily well-placed compasses. Pull the magnet up until the needle comes horizontal; then lower about two inches and secure it.

2. When a vessel at sea rolls moderately, the presence of heeling error will be shown by a marked vibration of the compass card of more or less amplitude, depending upon the amount of force producing the heeling error. North or South by compass is the most favorable course to steer to observe this effect.

To correct the heeling error, under these circumstances, the heeling magnet being North end up (in North magnetic latitudes) in the central vertical tube and at the bottom, steer North or South by compass and observe the vibrations of the card as the vessel rolls from side to side. Raise the heeling magnet until the vibrations disappear. The amount of vibration should be determined by taking bearings of a distant object as the vessel rolls, and not by watching the lubber's line. In case there is no distant object to observe as the vessel rolls, it is a very good plan to have an intelligent assistant standing close to the observer at the compass, the duty of this assistant being to watch the ship's head (*not* the compass) and to call out "starboard" or "port," indicating the direction of yawing. With such an assistant there is no difficulty for the man at the compass to distinguish between motions of the card due to heeling error and those due to change of azimuth of the ship's head. In correcting by this method, it is best to leave a slight amplitude of vibration to avoid over-correction.

3. The heeling magnet will be at the proper height in the tube when no sensible disturbance of the card occurs as the vessel changes her inclination while maintaining a steady course.

The following method of correcting the heeling error at sea can be used as convenience affords: Choose a time when the vessel heels steadily when on a northerly or southerly course (not more than 45° from North or South). Take an azimuth of sun, moon or star and find the deviation due to heel, knowing the deviation on the same course when the vessel is upright. Correct the error due to heel by moving the magnet up or down in its tube, with proper pole uppermost.

4. If raising the heeling magnet from the bottom of the tube aggravates the heeling error, either the wrong pole is uppermost or the heeling error is so small that the maximum effect of the heeling magnet constitutes an over-correction.

5. If the heeling magnet is raised close to the top of the tube after the compensation of the semicircular and quadrantal deviation is made, it will probably induce magnetism in the quadrantal spheres which will require further compensation by the magnets.

103. Flinders Correction.—1. After a ship has assumed her permanent magnetic character, the compensation may be completed, if desired, by placing a Flinders bar, at those compass stations where the influence of magnetism induced in vertical soft iron, such as a mast, or smokepipe, is excessive.

*The heeling adjuster is a small brass box provided with levels and levelling screws, mounting on a horizontal axis a needle which is free to vibrate in the vertical plane, its tendency to dip being counteracted by a small sliding platinum weight whose distance from the axis of suspension may be measured by a scale on the glass cover. There is a small glass window in each end provided with an index line to mark the horizontal plane. Without the small weight, the needle before being magnetized was exactly balanced, so the weight is intended to balance the vertical magnetic force ashore or on board. If a denotes the distance between the movable weight and the center of the needle when the needle is exactly balanced on shore, then when the instrument is set up on board, in the magnetic meridian, and in the place occupied by the center of the compass needle, the movable weight should be at that reading of the scale $= \lambda a$.

2. Owing to the fact that the resultant of the forces which this bar is used to correct is generally in the center line of the ship, it is customary to install it in a holder attached to the binnacle in the vertical midship fore-and-aft plane of the vessel, and on the side of the binnacle opposite the vertical soft iron causing deviation. Should this bring the bar in front of the binnacle door, the binnacle may be turned around with its door in the opposite direction.

3. In the absence of data, all but about ten degrees deviation on magnetic East or West should be corrected by the Flinders bar, the balance by the permanent semicircular corrector magnets. Where semicircular deviation on magnetic East or West does not greatly exceed 10°, a Flinders bar is not seriously needed.

4. When a vessel is on the magnetic equator, no deviation can be caused by the ship's vertical soft iron, as the Earth's vertical force is zero. All semicircular deviation is therefore due to the ship's permanent magnetism and may be corrected by the semicircular corrector magnets. Any deviation that arises on the East and West points thereafter, on change of magnetic latitude, is due to the effects of induction in the ship's vertical soft iron and may be corrected by the Flinders bar.

5. To compensate, first remove the heeling magnet, noting its correct position; then compensate, using the Flinders bar. Then replace the heeling magnet in its correct position, and complete the compensation with the permanent semicircular magnets. It is to be noted that the Flinders bar is parallel to the heeling magnet and close to it, so that the heeling magnet will introduce induced magnetism in the Flinders bar. If the position of the heeling magnet is subsequently changed, it will be necessary to correct the compensation with the semicircular magnets; and it should be noted that although the heeling error is compensated on North or South, the error caused in the compensation by shifting the heeling magnet would be a maximum on East or West.

6. The Type II Flinders bar is 2 inches in diameter, and its total length of 24 inches is cut into one length of 12 inches, one length of 6 inches, one length of 3 inches, one length of 1½ inches, two lengths of ¾ inch. The bar as installed can therefore be varied in length to produce the desired effect. About one-twelfth of the length of the bar used should project above the compass needles, this being arranged by replacing the missing lengths by wooden blocks of the same dimensions.

7. The Type I Flinders bar consists of a number of soft-iron rods each ½ inch in diameter and 40 inches long. Any number of rods from one to seven may be used, provided they are arranged symmetrically with reference to the midship fore-and-aft line of the vessel. The holder is so designed as to allow the greatest number of symmetrical combinations to be made.

8. A Flinders bar, once installed, may be regarded as part of the permanent structure of the ship, provided it is made of perfectly soft iron. It is recommended, however, that in all cases it be carefully watched to see that it does not take up magnetism from the shock of gun fire, vibration, etc.; and it would be well during target practice to remove the bar to some point as far as possible from the shock of gun fire, being careful to lay it on its side.

9. Should a Flinders bar be found to have picked up magnetism, it should be reannealed, or the magnetism may be removed, or much reduced, by holding the bar in a direction at right angles to the lines of force—East and West magnetic—and hammering it with a piece of wood.

104. Continuous Correction.—1. Every effort should be made to keep at least the standard maneuvering and steering compasses magnetic. This is especially necessary when working in the fleet at maneuvers, etc., but it is always easier to keep the compass correct than to keep the deviation table at hand and apply the correction.

The following method was originally proposed by Captain Roy C. Smith, U. S. Navy. It has been somewhat added to by Commander George C. Day, U. S. Navy, and has been used successfully in the Atlantic Fleet.

After the first compensation, steady the ship on North (or South) and move the athwartship magnets up exactly one inch, noting, by

the bearing of a distant object or of the sun, the amount and direction of the effect on the compass. After the compass has settled down and the observation been made, return the magnets to the correct position and note if the compass returns to the correct heading. Then lower the needles exactly one inch and record the effect as before. Then head the ship East (or West) and take the same observations with the fore-and-aft magnets. Then head an intercardinal point and observe the effect of moving the spheres in and out one inch from their correct position.

It is then advisable to check the results by repeating the observations on the opposite headings, but, if carefully taken under good conditions, there should be no difference except in the direction of the effect produced.

The record would take this form:

Date.......... Lat.......... Long..........
$H =$ $\theta =$

On N.: Raising *C* magnets (6) 1 in. (from 9.85 to 8.85) makes 12° 30′ easterly deviation; .1 in. makes 1° 15′ easterly. Lowering *C* magnets (6) 1 in. (from 9.85 to 10.85) makes 10° 15′ westerly deviation; .1 in. makes 1° 2′ westerly.

On E.: Raising *B* magnets (2) 1 in. (from 10.45 to 9.45) makes 8° 15′ westerly deviation; .1 in. makes 0° 50′ westerly. Lowering *B* magnets (2) 1 in. (from 10.45 to 11.45) makes 6° 30′ easterly deviation; .1 in. makes 0° 40′ easterly.

On NE.: Moving spheres *in* 1 in. (from 10.6 to 9.6) makes 4° 15′ westerly deviation; .1 in. makes 0° 25′ westerly. Moving spheres *out* 1 in. (from 10.6 to 11.6) makes 3° 20′ easterly deviation; .1 in. makes 0° 20′ easterly.

If now, after a change of latitude, it is found that there is 1° 45′ easterly deviation on East, it is evident that raising the *B* magnets .2 will exactly correct it, and three careful observations on two adjacent cardinal points and an intercardinal point are enough to make an accurate recompensation. Opportunity for this is usually found during fleet tactics, with no loss of time and with little trouble.

It is, of course, better to get observations both on N. and S. and on E. and W. and take the mean result; and this is necessary if the value of the variation is uncertain, as is too often the case.

Every opportunity should, of course, be taken to check up the deviation, and it is not intended that the use of this method should cause any change in this regard.

Whenever the position of any corrector is changed, the new position, together with the date, latitude and longitude, and values of *H* and *θ*, should be noted on one of the blank sheets of the Compass Record.

For the position of the quadrantal spheres, it will probably be found practical to construct a curve, using the distance from the center of the needle and the value of *H* as coördinates, that will suffice to keep the quadrantal deviation approximately zero.*

On board the *Connecticut,* for instance, the position of the one sphere on the standard compass varied from about 10″ at the magnetic equator to about 12″ at Rockland, Me., and by keeping it on the position called for by the curve the quadrantal deviation was kept at nothing.

A curve should also be made, showing the proper position of the heeling magnet for changes in *Z,* and the magnet changed accordingly.

In the course of a cruise, the positions of all correctors will gradually become known for each magnetic latitude, or approximately for each latitude, and may be so plotted in a smooth curve. It is advisable to make the corrections by this curve on change of latitude, in order to carry out the principle of continuous correction, checking the resulting deviations as opportunity offers. This involves less probable error than if the correctors should be left in their old position until a new swing could be made.

* The necessity for changing the positions of the spheres for a change of magnetic latitude may be explained as follows: "Due to mutual induction between the compass needles and the quadrantal spheres, a quadrantal deviation is caused. The amount of the disturbing force causing this deviation will be constant in all magnetic latitudes, depending as it does upon the amount of magnetism in the compass needles; but since it is resisted by a quadrantal correcting force which depends upon the earth's magnetic induction, and which therefore varies with the magnetic latitude, the compensation will not be universal."

CHAPTER VII.

COMPASS CORRECTION BY THE AZIMUTH METHOD, AND A NEW MANNER OF COMPUTING THE FLINDERS BAR CORRECTION.

BY COMMANDER J. B. PATTON, U. S. N.

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105. The following method of correcting compasses has been used by the writer during four or five years of sea experience in charge of compasses. It applies to compasses so situated that bearings can be taken with the azimuth circle.

The "azimuth method" of getting a ship on the desired magnetic heading is simpler and more practical than the "lubber's point" method generally used in the navy. Being simpler, it promotes accuracy by enabling the observer to concentrate on the most important point, *which is to get correct azimuth observations.* We all know the delay and confusion caused by trying to make the helmsman keep the vanes of a distant pelorus pointed at the sun.

The most common errors are due to an unsteady compass card. In such cases the mean of several observations should be taken.

106. To Correct *B*, *C*, and *D*, with Permanent Magnets and Quadrantal Spheres.—1. *Preparation:* Select time and place, using method of azimuths of the sun. Select a time when the magnetic bearing of the sun is one or two points from magnetic East or West, otherwise the mast or smoke-pipe may prevent your getting observations on those headings. On this coast, where the variation is westerly, the proper time, in winter, would be in the morning; in the summer, late in the morning, or late in the afternoon. Do not use the pelorus in correcting.

2. Set watch to local apparent time. Get from chart or tide book, or by observation on shore, the variation of the compass. From the sun's azimuth tables obtain the sun's true azimuth at intervals during the hours selected. Apply the variation and obtain the corresponding magnetic azimuths. Then, on cross-section paper, plot a curve of times and magnetic azimuths. Reference to this curve will show the sun's magnetic azimuth at any moment. A table showing the magnetic azimuth for each ten minutes will do as well as the curve.

The variation from chart may be 1° or 2° in error. *This will not affect the compass correction,* but to obtain the correct residual deviations, the variation should be known more exactly.

3. See that all preparations are made and assistants properly instructed, so that you will have nothing to delay you when the time comes to correct. See that the mechanism of the binnacle is in good order, moving parts working freely and not blocked with paint. Put a little oil under the azimuth circle, and see that the latter fits snugly on the bowl. See that awnings, etc., are clear, and that iron masses near compass are in their usual sea condition, and ship is on an even keel.

4. Place heeling corrector at bottom of tube, and North (red) end up in North latitude. If you have any previous information as to its proper location, place it accordingly. It is best to set it by means of the heeling adjuster, see paragraph 25.

5. Place quadrantal correctors at middle of slot. If you have any previous information as to their proper location, place them accordingly.

6. Give watch and curve to an assistant and tell him to keep you informed continually, without your having to ask him, as to the magnetic azimuth of the sun as shown by curve.

7. Station a quartermaster at the compass being corrected and tell him to conn the helmsman.

107. 8. *To Correct C:* Tell quartermaster to head North (or South) by the compass being corrected. (All courses refer to the compass

being corrected.) When the ship is within about 5° of North note the sun's azimuth by compass roughly, apply magnetic azimuth mentally, and obtain rough deviation. With athwartship tray near bottom of binnacle, put in athwartship magnets to reduce deviation, remembering that the blue end of magnet will attract the North point of compass. One magnet for each five degrees' deviation will be an approximation.

Caution the quartermaster to keep the ship headed North (the magnets, of course, will have moved the compass off the North heading). When again headed about North note the deviation roughly and by adding more magnets, or by moving the tray, reduce it to nearly zero.

Now take very careful observations and by moving the tray reduce the deviation to zero. Do not delay until the quartermaster gets exactly on North, and do not allow him to bother you by saying " on," or " not quite on," etc.

The value of this method is that you do not look at the lubber's point until you have removed all the deviation, and then you note the heading, and if the ship is heading about North (say N. 2° E.), you can safely say there is no deviation on North. Of course, a moment later, you can check it when you come on North exactly.

9. Tell quartermaster to head South (or North). After being on that heading about ten minutes, *note the deviation very carefully* (say it is +4°). *Move athwartship magnets so as to reduce it one-half* (to +2°). Check this very carefully. (If you should head North again, a deviation of +2° should appear.) Look out for lost motion in the magnet trays.

This constant deviation is the sum of the error in variation used, plus *A*, plus *E*. *A* includes instrumental errors in the azimuth circle. (Lubber's point errors are not involved when correcting by this method.)

108. 10. *To Correct B:* Now head East (or West) and proceed as at North, putting in fore-and-aft magnets to *reduce the deviation to to zero.*

11. Then head West (or East) and *note deviation carefully. Move fore-and-aft magnets so as to reduce it one-half.* This residual is due to error in variation, plus *A,* minus *E*.

(If you cannot get bearings of sun on both East and West on account of smoke-pipe being in the way, assume E to be zero and adjust on one of these headings, leaving an apparent deviation (+2°) *as on South.)*

109. 12. *To Correct D:* Now head NE. (or NW., SE. or SW.) and move spheres so as to *reduce deviation to zero.* It is best to use quadrantal correctors large enough to correct from the middle or outer end of slot. It is better to over-correct than under-correct. (See discussion below under " Interference of Correctors.")

13. Then change course eight points (say to NW.) and *note deviation carefully. Reduce it one-half by moving the spheres. (It is usually sufficient to correct on only one intercardinal point and leave a residual equal to the mean residual on North, East, South and West.)*

This residual deviation is due to error in variation, plus *A*. The residual deviation on NE. and NW. mathematically, is a mean of those on N., S., E. and W. The compass is now corrected for *B, C,* and *D, in spite of the fact that the variation used may have been in error.* The apparent residuals on North and South should be equal, those East and West equal, and those on all intercardinal points equal, when the correctors are properly set. *If you had to move the spheres materially, then recorrect on N. and S.*

110. Residuals.—14. You have now recorded the apparent residual deviations on South, West, and Northwest. Put the ship on the other five cardinal and intercardinal points and note and record the apparent residual deviations carefully. *Remember that it is important to get a correct azimuth of the sun, but not important to have the ship headed on precisely the desired point at that time.*

Of course, the ship must be accurately headed if you are noting the deviations of other compasses by comparison.

15. *Table of Residual Deviations:* (a) If the variation used was obtained by accurate observation on shore, then the apparent residuals obtained in paragraph 14 are the correct deviations, and are due to the effect of *A* and *E,* where *A* includes constant errors in the azimuth circle.

(b) If there is any doubt about the accuracy of the variation, then assume *A* to be zero, and all the apparent residuals must be corrected by a constant quantity. To do this, *add algebraically to each deviation a quantity that will make the deviation curve symmetrical with regard to the North and South line.* In other words, subtract the *mean* residual from each residual.

16. *The Coefficient A:* If the coefficient *A* is deduced from a set of deviations it will contain any error made in the variation assumed when swinging ship. If no variation is assumed, but the ship is swung by the method of steaming on a magnetic range, the error of that magnetic range will be included. If swung by the method of reciprocal bearings, the results will be too inexact to be of value. I doubt if in recent times any ship has been swung by such a method. With a well located compass the value of *A* is much less than the probable variation error when the latter is taken from the chart.

17. Therefore, *if you use variation from chart (unchecked) in correcting and swinging for residuals, consider A zero, and correct residuals as described in paragraph 15(b).* But if you have a reliable coast survey record of the local variation, or if you have checked the chart by setting up a compass on shore and taking an azimuth of the sun for variation, then accept the results as described in paragraph 14 for your residual deviation table.

111. Compasses With Large Deviations.—18. If you start with a compass with large deviations, say over 10°, proceed as follows to make an approximate correction before proceeding with final correction. Head on any cardinal point and correct approximately to less than 5°. Change course eight points and correct again. Then change to an intercardinal point and correct with the quadrantal spheres approximately. (See paragraphs 8, 10 and 12). If deviation on East or West is over 45° the directive force on North or South may be reversed. Therefore correct on East or West first.

112. Correction Alongside Dock.—*Approximate Correction of Compass of New Ship or of Compass That Has Been Changed in Position on a Ship.*—19. Prepare binnacle and correctors as mentioned before, pars. 3, 4 and 5.

20. Note on chart some well-defined distant object (d. o.) a mile or more away, and note carefully its magnetic bearing from the ship's dock, using parallel rulers. Note from the chart the line of bearing of the face of the dock. This gives you the ship's heading (magnetic) —say it is about WNW. Note roughly the general direction of North (magnetic) and West (magnetic) and NW. (magnetic).

21. At the proper stage of tide you can slack lines and can point the ship about West. With azimuth circle, note bearing of distant object (d. o.) by compass, and apply the magnetic bearing mentally and obtain roughly the deviation. Put in fore-and-aft magnets to reduce it. Repeat the operation until deviation is zero and ship's head is about West *by compass.* (See pars. 8 and 10.)

22. At slack water get a tug to pull the bow or stern out till ship's head points about North (magnetic). Observe azimuth of distant object (d. o.) and compare it mentally with the magnetic bearing taken from chart and obtain deviation. Put in athwartship magnets, and proceed to reduce it to zero, keeping the ship's head about North *by compass.* (See par. 8.)

23. By use of lines or tugs now head NW., note deviation and correct with the quadrantal correctors until it is zero and ship heads about NW. *by compass.* The above method was used on a ship having deviations up to 60° and the residual deviation was less than 3°. Total time of operation about two hours.

113. Remarks. — The residuals obtained while compensating are usually more exact than those taken by a hurried swinging ship afterwards.

The compass cannot be trusted to remain correct and must be checked by daily azimuths.

When deviations appear it is often better to readjust than to swing ship.

The first adjustment should be on North and South, as there is less interference by smokestack, etc., than on East and West.

The use of the pelorus or many assistants is not recommended.

Observations of the sun by the mirror on the azimuth circle are much more accurate than observation of terrestrial objects by the azi-

muth circle vanes. Bear in mind the effect of hot smoke-pipes and stray electric currents.

Do not use a *single* quadrantal sphere as it is subject to induction from the heeling magnet and horizontal magnets, causing semicircular deviation.

In correcting take plenty of time, say ten minutes on each heading, in order to let the induced magnetism establish itself.

114. Correction of the Heeling Error.— The heeling error is greatest on North and South, and is zero on East and West courses.

It is usually greatest in high North latitudes, and usually draws the North point of needle to windward (that is, "uphill"). It decreases gradually to zero at some place south of the equator. Farther south it changes sign and draws the North point of needle to leeward.

The quadrantal deviation being corrected, the heeling error is caused by the vertical subpermanent magnetism represented by R and an induced force kZ, which varies with Z. These usually act together north of the magnetic equator, and opposed south of the equator. At some point not far south of the equator they neutralize each other, and farther south the effect of kZ predominates. The error is therefore greater in North latitude than South latitude.

It is corrected by a vertical magnet under the compass, red end up in the North latitude, and blue end up in the far South latitude. Its position must be changed for different latitudes and it disturbs the Flinders correction, so that after shipping it or moving it the deviation on East and West should be recorrected.

24. *To Correct Heeling Error:* When the ship is on a northerly or southerly course and rolling, and during the rolls the North point of needle is observed to go to windward, the heeling magnet is raised in the tube to correct it, care being taken not to over-correct. (Use it sparingly, as it interferes with other correctors.)

Then head East and West and correct with the fore-and-aft magnets any deviation that may have been caused by the heeling magnet inducing magnetism in the Flinders bar.

25. The general effect of the heeling magnet is to neutralize the vertical subpermanent force R, and the variable vertical force kZ, that is, the remaining vertical force should be the same at the binnacle as it is on shore.

This may be done by means of the heeling adjuster, as described in the text-books. Balance the heeling adjuster on shore, then set it up on the binnacle, and move the heeling magnet until the vertical force is the same as on shore, the quadrantal deviation having been first completely corrected.

If the heeling error is corrected in *an average North latitude,* it should be fairly satisfactory for all usual latitudes without moving the magnet.

The above rules are satisfactory and convenient for practical use. The method of using the heeling adjuster to make the vertical force at the compass the same as the vertical force on shore, is used by professional compass adjusters in New York.

For those who wish to be more exact, it may be stated that there is a third cause of heeling error. When the ship is headed North or South, and heeled over, the upper edge of the deck and upper end of deck beams have blue magnetism induced in them by the earth's vertical force, which tends to draw the North point of compass to windward. It happens that this force is corrected partially (or possibly entirely) by the quadrantal spheres.

The text-book method of correcting exactly, is to balance the heeling adjuster needle on shore. Then calling the distance of the balance weight a, the heeling adjuster is placed on the binnacle, and the weight is shifted to a new distance $a \times \lambda$, and the heeling magnet is raised until the needle balances (the quadrantal deviation having been corrected). The value of λ used should be deduced from data obtained after the spheres are in place and after the Flinders bar is shipped.

Quadrantal Correctors.—The fore-and-aft dimension of the sphere is detrimental. Discs or rings set athwartships would be better than spheres. The ideal correctors would be iron crosses, set vertically and athwartships. The horizontal arms would correct the quadrantal deviation (D) and would tend to correct the heeling error due to tilted deck beams. The vertical arms, if of suitable length, would correct (kZ) the force causing heeling error due to vertical soft iron. If, then, the vertical

force (R) due to hard iron be corrected with the heeling magnet in the usual way, the total heeling error would possibly be correct for all latitudes.

115. To Correct the Semi-Circular Deviation on East and West by Means of Permanent fore-and-aft Magnets and the Flinders Bar.—26. With the ship on the *magnetic* equator, correct on East and West with permanent fore-and-aft magnets.

27. Then leave the equator and any deviation that may appear on those headings, correct with a Flinders bar (heeling magnet out). Then put in the heeling magnet if required, and recorrect with fore-and-aft magnets any deviation on East or West that was caused by the introduction of the heeling magnet. Then correct any quadrantal deviation caused by the Flinders bar. (See pars. 44 and 45.)

28. *To Compute the Correction for P:* As ships may not often go to the magnetic equator, the equatorial correction can be computed as follows, from simple observations taken in two latitudes, say New York and Vera Cruz:

Obtain from chart portfolio No. 1 the vertical force (Z) chart No. 111, B. A. 3613. (If not available, get horizontal force and magnetic dip charts and compute Z.) ($Z = H \tan \theta$.)

At the high latitude:

Let Z_1=vertical force (chart).
d_1=distance in inches of fore-and-aft magnets from compass needles after correcting on East and West.

At the low latitude:

Z_2=vertical force (chart).
d_2=distance of fore-and-aft magnets after recorrecting on East and West.

Let d_3 equal the distance the fore-and-aft magnets would have to be placed if ship were on the equator.

29. The formula is based on the law that the correcting effect of the magnet is proportional, inversely, to the cube of its distance from the needles. The *distance* being the *diagonal distance* from the end of the magnet to the end of the needles. The vertical scale on the central column of the binnacle gives the vertical distance, and this distance must be translated into the correct diagonal distance, and the computed d_3 must be translated back into the vertical scale distance. This law was tested on the navy binnacle and found very exact.

The half length of the magnet is two inches and the half length of the needles is three inches, so that the corrected diagonal distance is $= \sqrt{d^2+4+9} = \sqrt{d^2+13}$.

The following table may be used in correcting *d:*

Vertical scale distance	Correct diagonal distance	Vertical scale distance	Correct diagonal distance
7″	7.87	13″	13.49
8″	8.77	14″	14.46
9″	9.70	15″	15.43
10″	10.63	16″	16.40
11″	11.57	17″	17.38
12″	12.53	18″	18.36

The vertical scale distance may be used directly in the formula and give good results if the latitudes are separated over 20°.

30. *Case I. U. S. S. Alpha:* Corrected compass on East and West in New York and Vera Cruz, and recorded $d_1=9$ inches, and $d_2=10$ inches.

New York $Z_1=.55$ $d_1=9''$
d_1 (corrected) $= 9.7''$
Vera Cruz $Z_2=.35$ $d_2=10''$
d_2 (corrected) $=10.63''$

Substitute in formula (1)

$$d_3^{\,3} = \frac{(Z_1-Z_2)d_1^{\,3}\,d_2^{\,3}}{d_1^{\,3}Z_1 - d_2^{\,3}Z_2} \qquad (1)$$

$$d_3^{\,3} = \frac{(.55-.35)913\times 1202}{913\times .55 - 1202\times .35} = 2691.$$

d_3 (corrected) $= \sqrt[3]{2691} = 13.9$.

d_3 (vertical scale) $= 13.9 - .48 = 13.42$.

Now set fore-and-aft magnet tray at 13.42 inches (the computed equatorial distance) and correct the remaining deviation on East and West with the Flinders bar (heeling magnet being out). Then put in heeling magnet, and recorrect on East and West with fore-and-aft magnets any deviation caused by induction of heeling magnet in the Flinders bar. Then correct with the spheres any quadrantal deviation caused by the Flinders bar. If the spheres were moved materially, recorrect on North and South. (See pars. 44 and 45.)

31. *Case II. U. S. S. Beta:* If, when you substitute in formula (1), the denominator

yields a *negative quantity* your computed value of d_3 will be *negative. This means that the fore-and-aft magnet must be reversed end for end.* Then set the tray at the computed distance, and proceed as in Case I.

32. *Case III. U. S. S. Beta:* If, when correcting in the second latitude, the fore-and-aft magnet must be reversed end for end to what it was in the first latitude, proceed as in Case I, except the formula is changed slightly; that is, both terms in the denominator are positive and must be added. Compute d_3 and set the tray at d_3 *with the poles of the fore-and-aft magnets in the same direction as at the low latitude.* Then proceed as in Case I.

Z is always taken as positive, unless second latitude is across the magnetic equator; in that case call Z_2 negative.

33. If the two latitudes are not far separated, the Flinders correction may be only an approximation. In that case consider the bar a permanent part of the ship, and on the next voyage obtain new values for d_1, d_2 and d_3, care being taken to have the heeling magnet in the same place for each set of observations.

34. The binnacle scale for d extends from 7 inches to 18 inches. If, after final adjustment, the fore-and-aft tray is too close to the needles (say less than 10 inches) then add more magnets and recorrect with the tray lower down. If the value obtained for d_3 is greater than 18 inches, remove half the magnets and set tray at $d_3 \times \sqrt[3]{1/2}$, or remove two-thirds of the magnets and set tray at $d_3 \times \sqrt[3]{1/3}$.

This rule will not be exact, unless all the magnets have the same strength, which is unusual.

There is usually lost motion in the screw of the tray, and in its final position it should be forced down by hand.

The magnets should be grouped symmetrically about the scale index pointer on the tray.

116. The Flinders Bar Correction.—35. The Flinders bar should be fitted on the compass to prevent the large change in the semicircular deviation (principally on East and West) due to a change in magnetic latitude.

In practice we cannot realize the full theoretical value of the Flinders bar, and prevent all change, but the change can be reduced to one or two degrees, which is a great convenience.

There is an unaccountable prejudice against this corrector. It reminds one that not very long ago there was a prejudice against "doctoring" a compass with magnets of any kind, preferring to let the compass have its "natural deviation."

The fore-and-aft force producing semicircular deviation is in absolute units: $\lambda HB' = P + cZ$. (a)

P represents the force due to subpermanent magnetism, and when corrected by a permanent fore-and-aft magnet, is permanently neutralized for all latitudes.

cZ represents that part due to induction in vertical iron (for instance, a smoke-pipe) by the vertical component (Z) of the earth's magnetism.

Z is zero at the magnetic equator and increases to .6 near the magnetic poles.

On crossing the magnetic equator Z changes sign and causes the second term (cZ) in equation (a) to become subtractive. In other words, the smoke-pipe had blue magnetism induced at the top while in North latitude, and has red magnetism at the top in South latitude. If cZ acts with P on one hemisphere, it will be opposed in the other hemisphere.

The problem is to ascertain the magnitude and sign of these two parts of the fore-and-aft force, and to correct the force P with a fore-and-aft permanent magnet, and to correct the force cZ with a vertical rod of iron (Flinders bar) placed on the opposite side of the compass form the disturbing vertical iron (c).

The rod will have magnetism induced in it, which will vary as Z, and if of proper size will neutralize the variable force cZ in all latitudes.

36. The same reasoning will apply to the force $\lambda HC' = Q + fZ$ acting in an athwartship line. An athwartship Flinders bar may be fitted, or the bar may be placed in the resultant angle of cZ and fZ. But this is not recommended, as the athwartship force is fairly constant and the Flinders bar is best on the center line.

37. On the *Culgoa* the following results were obtained (Flinders bar unshipped). (Record being incomplete, table is partly computed.)

	Z	Uncorrected Deviation on East	Distance of F and A Magnets to correct
New York........	+.55	—29°	8.3″ blue end fwd.
Equator (magnetic).	0.	—10°	11.4″ " " "
Magellan St.......	—.325	—2°	18″ " " "
Melbourne........	—.57	+4°	17″ red " "

This shows that P and cZ were acting together in North latitude, and opposed in South latitude. At Magellan Straits they were opposed and almost neutralizing each other. At Melbourne cZ predominated, causing easterly deviation.

Some ships have these forces opposed in the northern latitude, and if no Flinders bar is used, will have to reverse the direction of the fore-and-aft magnets on arriving at a high North latitude.

In the *Culgoa,* the fore-and-aft magnets were set at 11.4″, blue end forward, and the remainder of the deviation corrected with a Flinders bar. The change in deviation on East when going from South to North latitude was less than 3°.

38. The following is quoted from the valuable compass reports made by Commander W. C. Cole, U. S. N., navigator of the *Kansas,* in 1908:

This compass (standard) shows normal conditions, and the compensation has been made practically universal. The change in the residual deviation between Punta Arenas and Magdalena Bay (before target practice) being so small that the error on any point did not exceed 1°. Athwartship, as well as fore-and-aft, Flinders bars were used in this compensation, though the former was small size.

It is believed that when the Flinders bar is of suitable material, there is small chance of magnetism of any great strength. The advantages derived from a well-placed Flinders bar are so important that they greatly overbalance the possibility of magnetization of the bar.

39. The relation of these forces is shown by the following formulæ:

At a high latitude (L_1), correct on East with fore-and-aft magnets and note distance in inches of magnets from compass needles (d_1).

Recorrect at a low latitude (L_2) and note distance of magnets from needles (d_2).

At L_1 let Z_1=vertical force (chart).
d_1=distance of magnets (observed).

At L_2 let Z_2=vertical force (chart).
d_2=distance of magnets (observed).

Let d_3=distance of magnets to correct if ship were at equator (compute).

The formulæ are easily deduced from the fundamental formula $\lambda HB'=P+cZ$, and the law that the correcting effect of the magnet is inversely proportional to the cube of its distance from the needles.

40. *Cases I and II:*

$$\frac{P}{P+cZ_2}=\frac{d_2^3}{d_3^3} \qquad \frac{P}{P+cZ_1}=\frac{d_1^3}{d_3^3};$$

hence,

$$d_3^3=\frac{(Z_1-Z_2)d_1^3\,d_2^3}{(d_1^3\,Z_1-d_2^3\,Z_2}. \qquad (1)$$

41. *Case III:* P and cZ opposed, and in one latitude, $cZ>P$.

$$\frac{P}{P-cZ_2}=\frac{d_2^3}{d_3^3} \qquad \frac{P}{cZ_1-P}=\frac{d_1^3}{d_3^3};$$

hence,

$$d_3^3=\frac{(Z_1-Z_2)d_1^3\,d_2^3}{d_1^3\,Z_1+d_2^3\,Z_2}. \qquad (2)$$

42. To obtain the magnetic latitude where $P=-cZ$ and deviation is zero:

$$Z_0=\frac{d^3Z}{d^3-d_3^3}. \qquad (3)$$

These Forces can be Shown Graphically (see sketch):

Let EE represent magnetic equator.

Let MM represent magnetic meridian.

Graduate MM from O at equator to .6 near poles to represent the earth's vertical magnetic force, or magnetic latitude (Z).

Graduate OA to some convenient scale to represent, in inches, the distance of fore-and-aft magnets from needles (d).

In two latitudes, observe d_1 and d_2 and compute d_3.

Using the corresponding value of Z (chart), plot the points d_1, d_2 and d_3.

Compute from formula (3) the value of Z_0 for no deviation, and draw line BB.

Draw curve through d_1, d_2 and d_3, and tangent to BB and MM.

Other points on the curve may be computed by the formulæ.

The curve should be repeated symmetrically on the other side of line *BB*.

Diagram of Forces: Draw *OG* at some convenient angle with meridian (about 30°). Where it intersects *BB*, draw line *KK* parallel to meridian. Then *OP* will represent the force *P* in all latitudes, and the abcissæ of *OG* will represent *cZ*.

117. Continuous Correction Without the Use of Flinders Bar.—43. For any magnetic latitude, or value of *Z*, the abcissæ of this curve (*d*) will give the proper setting of the fore-and-aft magnets.

In any latitude *Z*, the shaded portion shows the algebraic sum of *P* and *cZ*, and the distance to the *d* curve shows setting of magnets to correct it.

118. Interference of Correctors.—44. *Induction of Compass Needles:* Adjacent soft iron will attract the nearest end of the compass needles, and cause quadrantal deviation. The needle is a magnet, either end of which would attract and pick up a soft iron slug. It induces magnetism of opposite polarity in the soft iron and thereby attracts it.

The Quadrantal Spheres: If these are nearer than 13 inches (center to needles) from the needles, they will be affected, causing a $-D$. The quadrantal deviation is usually due to a $+D$, and the induction would therefore assist in correcting it, but it is not desired, as such a correction would not hold for all latitudes, nor would it assist in correcting the heeling error. The spheres should therefore be large enough to correct from a distance of 13 or more inches.

The athwartship subpermanent force *Q* and the athwartship magnets placed to correct it both act together to set up an induced magnetism in the spheres, causing (possibly 5°) semicircular deviation on North and South. That is why in making the final correction on North and South, the spheres must be in approximately their final position.

Flinders Bar: This bar, if full sized, and in the designed position, will receive needle induction and will give several degrees' quadrantal deviation.

The effect is due to a $+D$, which is opposed to the $-D$, caused by the needles' induction in the spheres, so that the situation is improved by the Flinders bar, and we need not worry about the quadrantal deviation caused by this bar.

45. *Heeling Magnet:* The heeling magnet causes a serious induction in the Flinders bar, causing semi-circular deviation of the *P* type, which should be corrected by the fore-and-aft magnets.

If the position of the heeling magnet were never changed, this would not be objectionable. If the position of the heeling magnet is changed, then recorrect on East and West.

119. 46. *Remarks:* The popular objection to a Flinders bar is that it may become permanently magnetized. The objection is not valid, except with the light Mark I rods. As long as they stay in their case they are not apt to have any sudden change. It is almost impossible to hammer any magnetism in the heavy Mark II bar. The Mark I rods will pick up magnetism if held in the meridian and struck. They can be tested as follows for polarity:

The ship being on a steady heading, stand the rod on deck vertically with the top end near the East point of compass and note bearing of distant object.

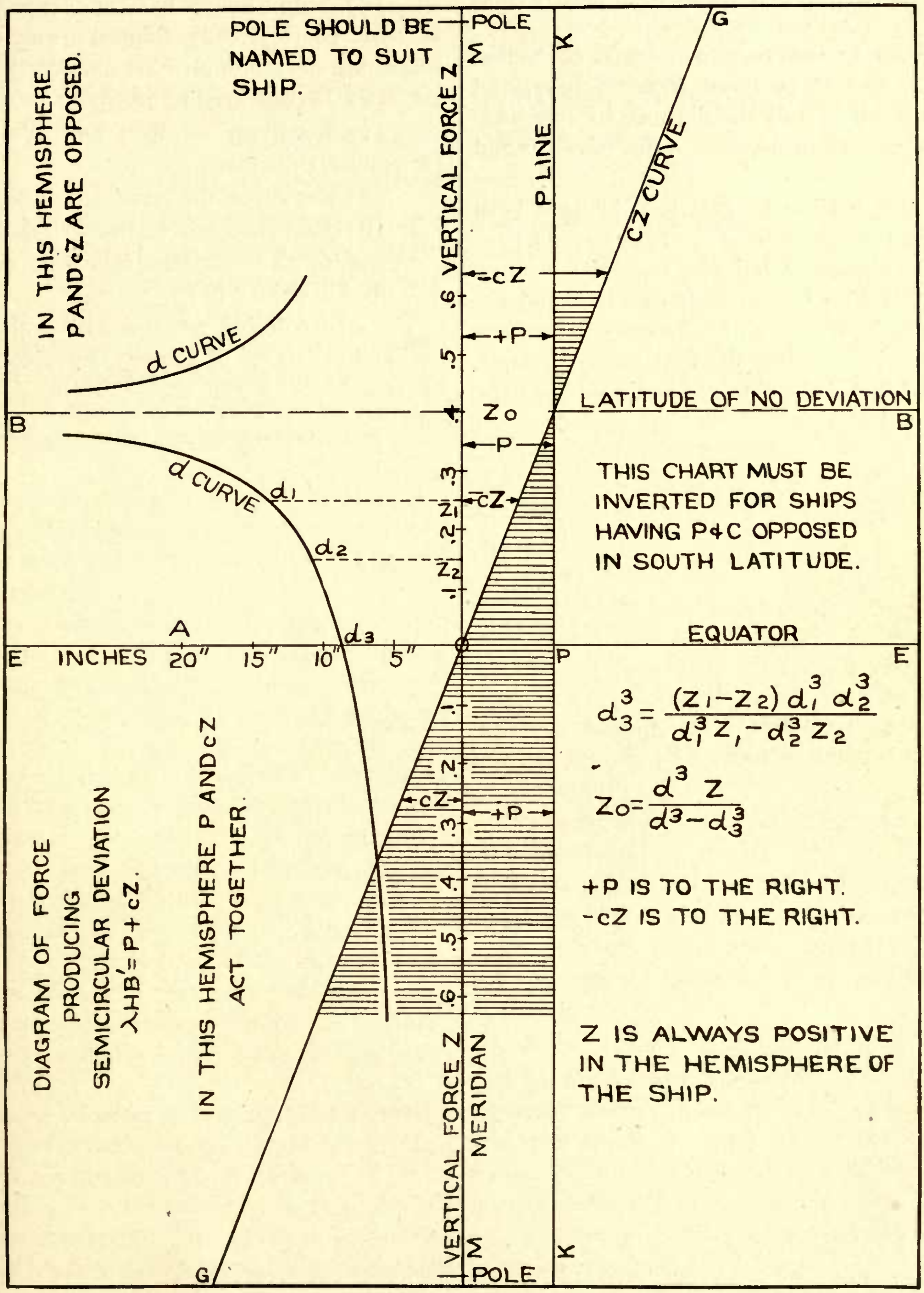
Reverse the rod end for end, and again note bearing of distant object. The end that attracted the North end of needle most has blue magnetism in it. It can be taken out by pointing that end North and rapping it a little.

47. The writer has noted, but has not verified, that on approaching the equator the induced magnetism in the Flinders bar would appear to leave promptly, while that in the smoke-pipe would leave tardily. If this is true, it would argue that the Flinders bar should be made of the same material as the smoke-pipe. All bars should be machined as the surface scale is magnetic.

During the cruise of the fleet around the world, many of the navigators fitted Flinders bars and made most favorable reports about them.

120. Summary.—48. The following is recommended for a new ship:

1. Make approximate correction of *B*, *C* and *D* at the dock.


IN THIS HEMISPHERE P AND cZ ARE OPPOSED.
POLE SHOULD BE NAMED TO SUIT SHIP.
POLE
M
K
G
VERTICAL FORCE Z
P LINE
cZ CURVE
-cZ
+P
d CURVE
LATITUDE OF NO DEVIATION
B
Zo
B
-P
THIS CHART MUST BE INVERTED FOR SHIPS HAVING P&C OPPOSED IN SOUTH LATITUDE.
d CURVE
d1
Z1
-cZ
d2
Z2
A
d3
EQUATOR
E
INCHES
20″
15″
10″
5″
P
E
$d_3^3 = \frac{(Z_1 - Z_2)\, d_1^3\, d_2^3}{d_1^3 Z_1 - d_2^3 Z_2}$
$Z_0 = \frac{d^3\, Z}{d^3 - d_3^3}$
-cZ
+P
+P IS TO THE RIGHT.
-cZ IS TO THE RIGHT.
DIAGRAM OF FORCE PRODUCING SEMICIRCULAR DEVIATION
$\lambda HB' = P + cZ.$
IN THIS HEMISPHERE P AND cZ ACT TOGETHER.
VERTICAL FORCE Z
MERIDIAN
Z IS ALWAYS POSITIVE IN THE HEMISPHERE OF THE SHIP.
M
K
G
POLE

2. It is best to use spheres large enough to correct at a distance of 13 inches or more. Procure a Flinders bar, Mark II. If convenient, set heeling magnet by means of heeling adjuster. (See par. 25.)

3. When underway, make careful correction of *B, C* and *D* (without Flinders bar), and make record of (d) the distance of fore-and-aft magnets from needles. (See pars. 10 and 11.)

4. Place heeling magnet if it has not been done, and if ship is rolling. (See par. 24.)

5. On change of latitude, recorrect on East and West with fore-and-aft magnets, and obtain (d) the distance of fore-and-aft magnets from needles. After the first target practice, d_1 and d_2 should be obtained again. (See pars. 10, 11 and 33.)

6. (a) Compute d_3.

(b) Take out heeling magnet.

(c) Set fore-and-aft magnet tray at d_3.

(d) Ship Flinders bar (or change the bar as required if already shipped), and correct remaining deviation on East and West.

(e) Replace heeling magnet.

(f) Recorrect on East and West with fore-and-aft magnets.

(g) Recorrect the quadrantal deviation.

(h) Recorrect on North and South.

In making all corrections, follow the methods described in pars. 1 to 13.

The writer desires to acknowledge the courtesy and assistance of Lieut. Commander C. T. Owens, U. S. N., in charge of the Compass Office.

CHAPTER VIII.

SIMPLIFIED METHODS OF COMPASS CORRECTION.

By LIEUTENANT R. A. KOCH, U. S. N.

121. The method which is here to be described has worked successfully for two years with the compasses of the *Castine* and all the submarine flotilla. The German and Greek letters, ordinarily used, are here done away with, and thus the biggest bugbear of compass work is eliminated, the constant *A* being the only coefficient given real consideration in this method.

We consider that any compass is properly corrected when a distant object can be made to have the same compass bearings for all headings of the ship.

122. To Compensate the Compass.—Note the change of bearing of the sun for every twenty minutes, using the azimuth tables, the approximate local apparent time, the latitude (correct to a degree), and the date of the month as arguments. A curve of the sun's change of bearing is then plotted on cross-section paper. A reference to the azimuth tables shows that an error of a few minutes in time, of a degree in latitude, or even of a day or so in date, makes practically no change in the rate of change of bearing of the sun, though of course, with such erroneous data, there is a decided error in the actual bearing of the sun; but with the actual bearing we are not now concerned.

Problem.—Correct all compasses of a vessel, and swing for residuals in latitude 40° 20′ N., λ 70° W., about 3.00 p. m. on April 27.

Procedure.—1. Set watch to local apparent time approximately. For example, if watch had been keeping 75th meridian mean time, as would be probable, set it ahead twenty minutes, thus making it 70th meridian mean time, and then apply the equation of time.

2. Pick out from the azimuth tables, using 40° as latitude, and the column nearest the day of month—April 28—bearings of the sun at twenty minute intervals, viz.:

Time.	Bearing of sun.	Change of bearing per 20 minutes
3.20	106° 10′	.....
3.40	102° 14′	3° 56′
4.00	98° 34′	3° 40′
4.20	95° 05′	3° 29′

Using cross-section paper, taking ordinates as times, and abscissæ as degrees—unnumbered as yet—now draw in the curve *ABC* (see Fig. A).

3. Now head the ship North. Using the azimuth circle, take a very accurate bearing of sun; in this case it equals 246° 30′ at 3.22. Put the helm over and swing to South. Plot point *X*, with this data, on Fig. A, close to the change-of-bearing curve, now marking the degree line at *A* as 246°, and also giving values to the abscissæ.

4. Steady on South. Bearing of the sun is found to be 245° 30′ at 3.29. Plot this as point *Y*. Draw *XX′* parallel to *ABC*. *X′*, therefore, represents the sun's bearing if headed on North at 3.29. Now draw a curve parallel to *ABC* and through the point *Z*, which is half-way between *Y* and *X′*.

5. Now, using watch and curve, raise or lower the athwartship magnets until the sun bears as it should. Then there will be no deviation, and South by compass will be correct south. All the other compasses are then made to read south in the usual manner.

6. Correct on East, and then on Northeast, in the same manner.

7. Now head the ship North and take a bearing. If this bearing differs from that given by the curve, one half of the difference has been caused by over compensation on South and this should be corrected at once by raising or lower-

ing the athwartship magnets until the difference is reduced one-half.

Now take a new bearing and plot the difference between it and the curve. Next swing the ship on every fourth point and take bearings on each, plotting the difference between these bearings and those shown by the curve. Draw a curve through the mean of the points thus plotted. This curve is the curve of zero residual deviations. When swinging for residuals if the observed bearing is greater than the bearing given by the curve the deviation is Westerly, and if less the deviation is Easterly.

Residuals may be due to a real *constant* error or to errors in the instruments. To find if the azimuth circle (the only instrument used) has an error take a bearing of the sun say at 7.00 a. m., and another about three or four hours later, say at 10.30 a. m., the ship being on the same heading for each. If the errors found are the same it is safe to assume that the instrument is accurate and we may use the residuals found above to determine the constant error. If the errors found are not the same, it shows that the mirror does not record accurately for all headings and another and correct azimuth circle should be used. It is advisable to test the circle before compensating rather than after in order that the results of the work of compensating will be more accurate.

When correcting a compass in the usual method by a calculated bearing of the sun, an instrumental error and all errors in calculations tend to give a false constant A. During the short time required for compensating in the method just described—less than one hour—the angle of change of the mirror, or change of its error, should be very little, and, even if the mirror were in error *ten degrees,* the compass would be correct, because the distant object has been made to bear the same all the way around; whereas we know that in the usual method the compass would be corrected to take out the whole error (true constant A, instrumental and magnetic) on one heading, and on the opposite heading the instrumental error plus true constant A error which should not have been taken out will be doubled.

It frequently occurs that an azimuth circle is in error by 2° after it has knocked about ship for a few years.

Mathematical Note on the Above by Commander G. R. Marvell, U. S. N.

$$\tan \delta = \frac{A' + B' \sin z + C' \cos z + D' \sin 2z + E' \cos 2z}{1 + B' \cos z - C' \sin z + D' \cos 2z - E' \sin 2z}.$$

The above is the strict mathematical formula for the deviation, z being ship's head magnetic. If the deviations are less than 20°, this formula can be reduced to (see Muir, p. 121):

$$\delta = A + B \sin z' + C \cos z' + D \sin 2z' + E \cos 2z',$$

where z' is the ship's head per compass.

Let $z' = 0°$, then $\delta_0 = A + C + E$.
Let $z' = 180°$, then $\delta_\pi = A - C + E$.

$$\frac{\delta_0 + \delta_\pi}{2} = A + E. \quad (1)$$

Let $z' = 90°$, then $\delta_{\pi/2} = A + B - E$.
Let $z' = 270°$, then $\delta_{3\pi/2} = A - B - E$.

$$\frac{\delta_{\pi/2} + \delta_{3\pi/2}}{2} = A - E. \quad (2)$$

Let the compass be compensated on N., S., E., and W., and the coefficients B and C have been reduced to zero. Therefore,

$$\delta = A + D \sin 2z' + E \cos 2z.$$

Let $\delta = 45°$. $\delta_{\pi/4} = A + D$. (3)
Let $\delta = 135°$. $\delta_{3\pi/4} = A - D$. (4)
Let $\delta = 225°$. $\delta_{5\pi/4} = A + D$. (5)
Let $\delta = 315°$. $\delta_{7\pi/4} = A - D$. (6)

An inspection of these last show that to compensate for D, (3) and (4), (3) and (6), (4) and (5) or (5) and (6), are the combinations.

123. To Swing for Residuals.—If deviations are small, say not over one-half point then the "lag" of the compass will be constant if the swing of the ship is constant. Note the change in bearing of sun during ten minutes. Plot curve of the change of bearing of sun for this time. Start vessel swinging and, after it has swung through eight points, consider the swing constant.

Example.—1. With data, as in first case, we find the change of bearing from 3.50 to 4.00 to be 2°. Plot curve AB (see Fig. B), and without designating values for ordinates or abscissæ.

2. Head East and put helm hard to starboard. Follow the sun with the azimuth circle. When passing North, take azimuth and time—*i. e.,* 268½° at 3.51. Now, in Fig. B, mark 268° for abscissa at point A and 3.51 for ordinate, and plot N.

3. Take bearings every fourth point and plot NW., W., SW., S., SE., E., and NE.

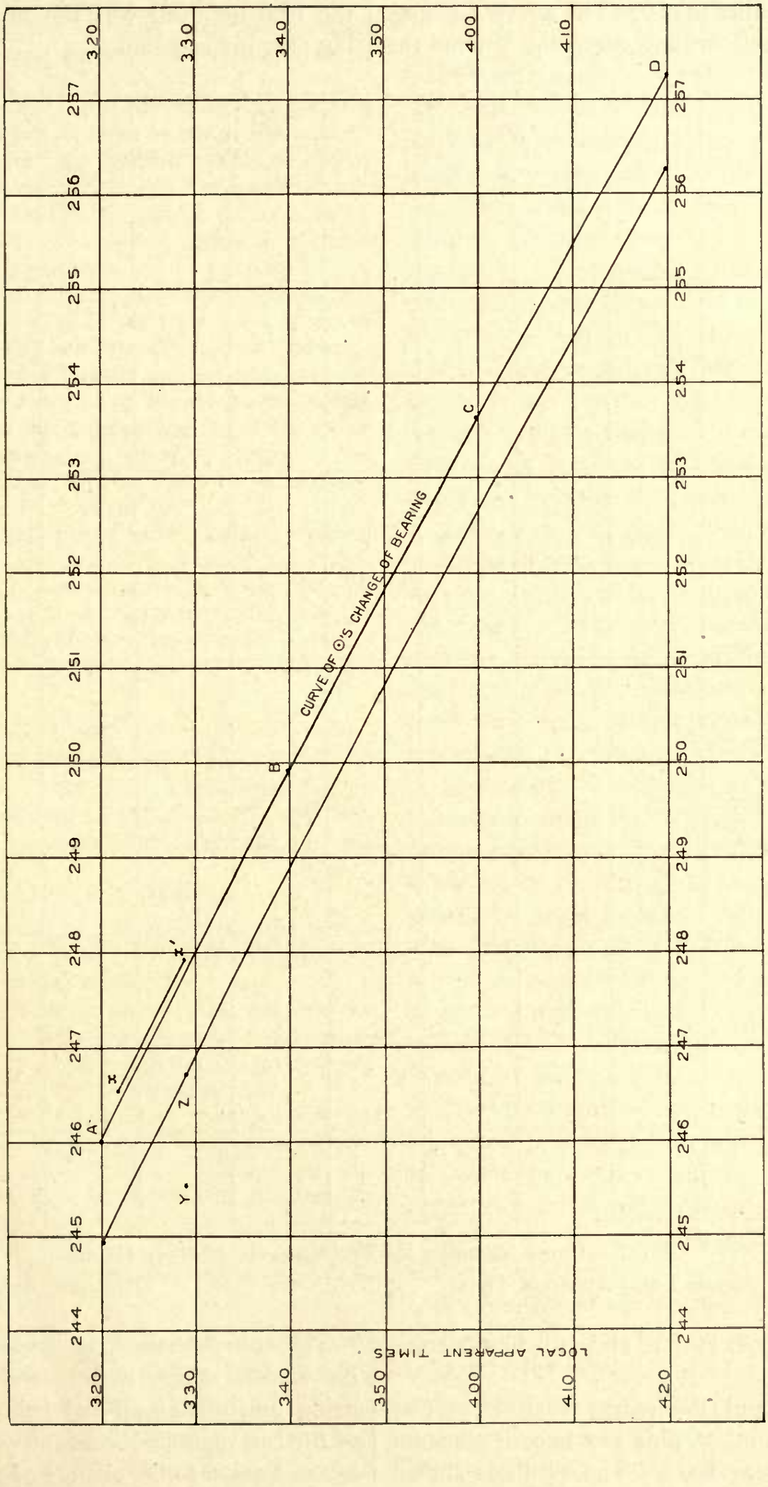


FIG. A.—Curve for Compass Correction.

Abscissæ, Azimuths in Degrees.

Ordinates, Approximate Local Apparent Times.

From the mean of the means between N. and S., E. and W., NW. and SW., SE. and NE., establish the point *X* and through *X* draw the curve *XY* parallel to *AB*. The curve *XY* may be drawn by establishing the point *X* from the

Thus, in the above method, we did not need to know the magnetic bearing of the sun (any distant object could have been used), because the bearing used was the magnetic plus the lag plus the constant.

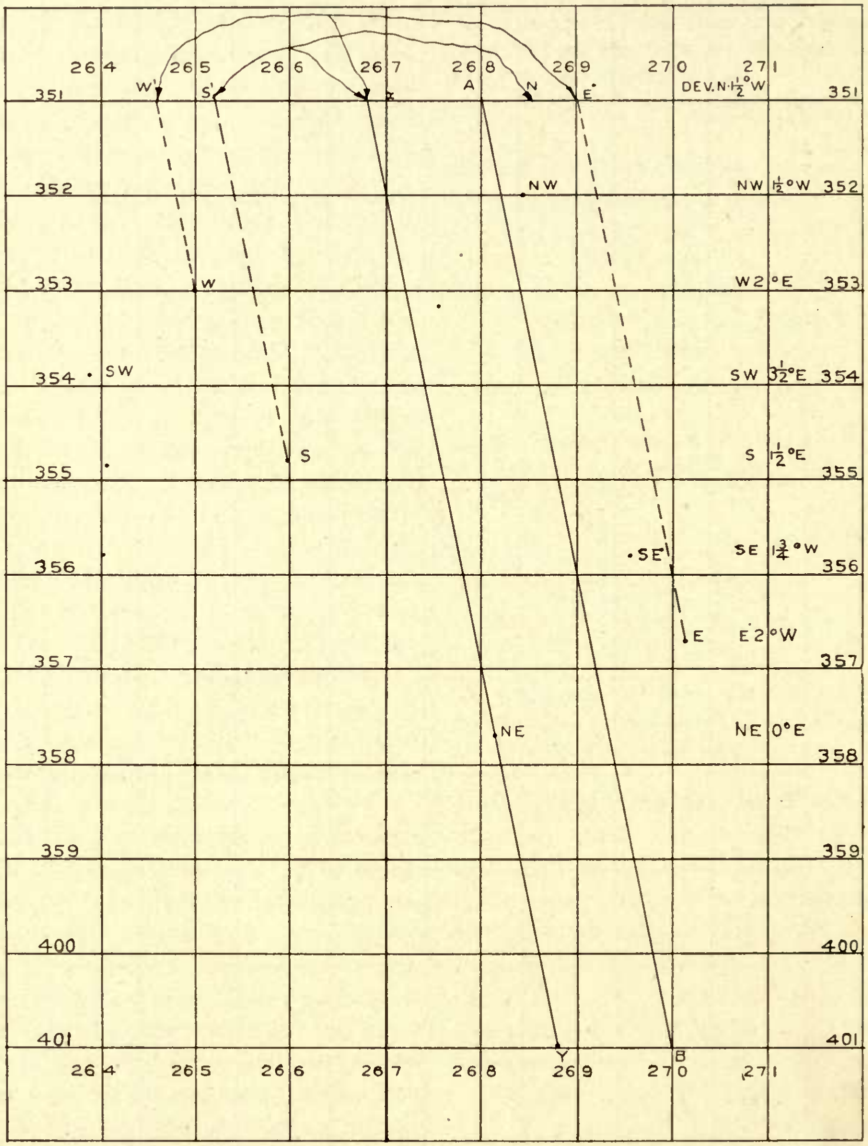


FIG. B.—Curve Swinging for Residuals—Hard Over Helm.

Ordinates, Approximate Local Apparent Times. Abscissæ, Azimuths in Degrees.

mean between N. and S. and still be approximately correct.

4. The amount the points vary from this line is the deviation, plus any known constant the compass may have. The result is shown in Fig. B.

The above method has been proved by trial on various ships with corrected compasses, using uniform speed and helm. The bearing of the sun remained constant, or only varied an amount equal to the change of sun bearing due to time, the bearing being in error the lag.

NOTE ON "LAG" OF COMPASS BY COMMANDER G. R. MARVELL, U. S. N.

The mean directive force of earth and ship in terms of earth's horizontal force as unit is represented by λ, which depends for its value upon the effect of horizontal soft iron, symmetrically arranged about the compass.

Therefore, for any particular heading of the ship there is a certain pull or force on the needle, tending to draw it away from the magnetic meridian, and to bring it to rest at compass North. On another heading there is a similar force, but of different value. If a ship is swung with a constant change of magnetic azimuth, the compass needle will be acted upon by a varying force, so that at any particular magnetic head the deviation will be different from what it would have been if the ship had been steadied on that magnetic head. This difference in deviation may be called *lag*. If the force acting on the compass needle was constant, and the angular velocity of the swing was constant, then the lag would be constant. But in an uncompensated compass the force is variable, therefore the lag is variable.

By the method of compensating described above, the compensation on N. and S. gets rid of C, but leaves A and E; the compensation on E. and W. gets rid of B, but leaves A and E; that on NE. and SE. gets rid of D, but leaves A. The value of the force of earth and ship to magnetic north is given by the formula.

$$F=\lambda\ (1+B'\cos z-C'\sin z+D'\cos 2z-E'\sin 2z).$$

This in terms of earth's horizontal force as unit.

Assume that B', C' and D' have been eliminated by compensation, and the value of $\lambda+E'$ with correctors in place has been found; then the formula reduces to

$$F=\lambda\ (1-E'\sin 2z).$$

If E' is very small, as it is in all centrally located compasses, then the value of F practically remains constant, and therefore the lag is constant.

If the compass is out of the midship's line, and the rods d and b have effect, then the method of compensation, and of finding residual deviations given above is faulty and should not be depended upon.

However, if the deviation has not been entirely removed, the lag will not be constant, for there will remain values for B', C', D' and E' which, when substituted in the formula for force, will give varying values of that force.

The amount of difference in the lag cannot be stated; it may, or it may not, affect the finding of the correct deviation.

124. To Correct Compasses—No Instruments Except Azimuth Circle. No Tables of Information of any Kind.—1. Steady ship on one course; note bearing of sun, and again about ten minutes later; from these two bearings one can tell whether the bearing is increasing or decreasing, and approximate rate. In this case it is noted that the bearing is increasing between 1° and 2° every ten minutes. Call it about 1° for every seven minutes. If no watch is available, note approximately the number of revolutions for 1° change in bearing. All that is necessary is some very rough method of measuring time, and even this is hardly necessary for accurate work.

2. *Procedure.*—Head the ship North by compass and note bearing of sun by compass, say 270°. Then head South by compass and after steadying there two or three minutes again note bearing of sun by compass, say 276°. The time interval between the bearings has been say six minutes, during which time the sun actually changed bearing 1°. At the time of the first bearing (that taken on North heading), had the ship been headed South by compass, the bearing of the sun by compass would have been 275°. The mean of the bearings on North and South at that instant would have been 272½°. Six minutes later, at the time the ship was headed South, the mean of the bearing would have been 273½, and as the observed bearing at that instant was 276° there is on South 2½° Westerly deviation which must be taken out. To do this raise or lower the thwartship magnets until the sun bears between 273½° and 274° by compass and the deviation on South will be removed. The sun should be made to bear nearer 274° by compass than 273½°, since a little time will be consumed in the adjustment, and allowance should be made for the change of bearing of the sun in this time. Next head the ship East and West and following the same procedure find the deviation and correct it with the fore and aft magnets. Next head the ship Northwest and Southwest (or on any two adjacent intercardinal points) and following the same procedure find the deviation and compensate it with the spheres.

On Southwest or Northeast the natural deviation is east; if it is found to be west the compass is overcorrected and it is necessary to move balls out. On Northwest and Southeast natural deviation is west; if found to be east, then compass is overcorrected and we must move the balls out. If the above cannot be

remembered, simply move the balls and find out what happens.

Now put the helm hard over and, after swinging through eight points, take bearings every fourth point, and proceed as in the method of swinging for residuals, with hard-over helm. If the work was accurately performed, it will be found that the bearing all around will be the same, or about $\frac{1}{2}°$ more by the end of the swing, due to change of bearing of sun in the time interval.

125. Flinders Bar Correction.—Flinders bar corrections are best made after compasses have been compensated on the magnetic equator and the additional deviation found on a change of latitude taken out by using the bar. The compensation may also be made from observations of the error in some other latitude than the one compensated in even though the compensation was not made at the magnetic equator. The two methods will be explained.

1. If when in the magnetic equator the compass is compensated and on going North a deviation is found on East or West, a Flinders bar may be used to take out this deviation and the semicircular deviation will then be correct for all latitudes. The Flinders bar should be placed either forward or abaft the compass, as determined by trial, to correct the deviation produced by the change of latitude, and this bar will usually be all that is required, though it is sometimes necessary to put a very weak bar on the side in addition.

2. When the compass has not been compensated on the magnetic equator, the following method of placing the Flinders bar, though not proved by trial, is believed to be correct:

The vertical magnetic force varies as the sine of the magnetic latitude, or to express it differently, the vertical magnetic force varies as the sine of the dip. Suppose a compass has been compensated without using a Flinders bar in a certain magnetic latitude, say 14° 31′, and that there was no deviation remaining on East. The sine of the magnetic latitude where the compensation was made equals $\frac{1}{4}$. Suppose the ship then went to some other magnetic latitude, say 30°, and that it was there found that on East there was a deviation of 2° W. The sine of the new magnetic latitude equals $\frac{1}{2}$. We see that the Flinders bar must be placed on that side of the compass where it will draw the north end of the compass needle to the right and therefore on the forward side. Having secured the holder on the forward side of the binnacle insert rods until a deviation of 2° E. has been produced. The Flinders bar correction will then have been made.

The above method is correct since the pull causing deviation in latitude 30°, sine $\frac{1}{2}$, is twice as much as the pull causing deviation in latitude 14° 31′, sine $\frac{1}{4}$; therefore the deviation caused by the magnetism in vertical soft iron is twice as much in latitude 30° as it is in latitude 14° 31′. Since the difference between the two deviations is 2°, the actual total deviation at latitude 30° is 4°, while at latitude 14° 31′ it was 2°. But the 2° was taken out by magnets at latitude 14° 31′ and the compass was therefore over compensated by 2° in that latitude. Hence the Flinders bar must be so placed as to compensate 4° W. deviation which will leave 2° E. deviation which must be taken out by changing the magnets. The amount the magnets will be changed will be the amount of over compensation in latitude 14° 31′. The two latitudes here assumed were taken to make the explanation simple, but any two latitudes could have been used using tables to get the correct value of the sines.

126. Notes.—When first beginning compass work, the author started with a carefully worked out magnetic curve, but nearly always found that, after compensating on North, the sun's bearing on South was not according to the curve. So, judging this due to mathematical, instrumental variation, or a constant magnetic error, a curve was drawn half-way between the worked out curve and the South compass bearing, and it was found that this curve could be followed all the way around. Then a curve of proper shape only was found to be all sufficient.

If the compass tray is immovable, wires can be added, but do not do so by the bundle. Magnets can even be nailed to the deck. It has been found beneficial to have the compass balls annealed by heating to a dull red and cooling slowly over night, about every six months, as they collect a little permanent magnetism.

The above methods are certainly simple easily taught, form a practical method of compass correction, and eliminate the difficulties ordinarily met with in this work.

CHAPTER IX.

THE FIRST COMPENSATION OF A VESSEL'S COMPASSES AT A SHIP-YARD BEFORE PROCEEDING TO SEA.

(Copy of pamphlet issued by Navy Department.)

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127. Compensation on Two Headings Alongside the Dock.—This can be done with considerable accuracy by observations for directive force on two headings, the only assumptions being that 𝔄 and 𝔈 are zero, which is generally true.

Two headings are available:

(a) When a vessel is in a dry dock or in a dock slip, and, before or afterward, when she is moored along the water front outside the dock or slip.

(b) When a vessel is moored alongside of a dock or sea wall and afterward winded and moored on the opposite heading.

The vessel must not, in either case, be near another iron or steel vessel or in the immediate vicinity of iron or steel structures on shore.

The necessary data are as follows:

T, the mean of ten sets of times of ten vibrations of the horizontal force needle on shore in a place free from local magnetic influences, and not greatly distant from the ship.

T'_1 and T'_2, the means of ten sets of times of ten vibrations of the same needle on board ship in the exact position of the compass needle, taken on each of the two headings of the ship.

Z'_1 and Z'_2, the two headings of the ship by the uncompensated compass.

Z_1 and Z_2, the two corresponding magnetic headings. These can be obtained from a map of the dockyard, or from an azimuth observation, or from reciprocal bearings.

Example, Case a.

$T = 17^s.4$,	$Z_1 = 163° 00'$,
$T'_1 = 19^s.0$,	$Z_2 = 70° 15'$,
$T'_2 = 20^s.65$,	$\delta_1 = 23° 00'$ W.,
$Z'_1 = 186° 00'$,	$\delta_2 = 33° 00'$ E.
$Z'_2 = 37° 15'$,	

By construction* (Plate I), draw OC_1 in the direction of the deviation $(-23° 00')$ on the first heading, and lay off $OC_1 = \frac{H'_1}{H} = \frac{T^2}{T'^2_1} = .838$. Draw OC_2 in the direction of the deviation $(+33° 00')$ on the second heading, and lay off $OC_2 = \frac{H'_2}{H} = \frac{T^2}{T'^2_2} = .71$.

Through C_1 and C_2 draw the lines C_1u and uC_2 in the directions of the magnetic headings Z_1 (163° 00') and Z_2 (70° 15'), respectively, extending them to intersect in u, and at C_1 and C_2 erect perpendiculars to these lines intersecting in v.

Draw uw, bisecting the supplement of the angle between the magnetic courses C_1u and uC_2, and draw vw perpendicular to uw. Produce these lines, if necessary, to intersect ON in D and D'. Bisect DD' at the point P. With P as a center and a radius $PD = PD'$, describe a circle, and through D draw the line DB parallel to the second course uC_2, intersecting the circle in M. Around M draw the figure of a ship with her bow in the direction of the second heading uC_2. Draw MP and MC_2. Then:

$$OP = \lambda = .937,$$
$$PD = PD' = \lambda\mathfrak{D} = .137,$$
$$\mathfrak{D} = \frac{\lambda\mathfrak{D}}{\lambda} = \frac{.137}{.937} = .147,$$
$$MB = \lambda\mathfrak{B} = +.208, \therefore \mathfrak{B} = +.222,$$
$$BC_2 = \lambda\mathfrak{C} = +.326, \therefore \mathfrak{C} = +.348.$$

PM is the direction in which the quadrantal force $\mathfrak{D}$ is pushing on the compass needle and producing the deviation $POM = +6° 00'$.

* For a mathematical demonstration of the correctness of this method, see *Admiralty Manual for the Deviations of the Compass*, 1901, p. 154, Problem 3.

MB is the direction in which the semicircular component $\mathfrak{B}$ is pulling on the needle and producing the deviation $MOB = +11° 00'$.

BC_2 is the direction in which the semicircular component $\mathfrak{C}$ is pulling on the needle and producing the deviation $BOC_2 = +16° 00'$.

MC_2 is the direction in which the total semicircular force $\sqrt{\mathfrak{B}^2 + \mathfrak{C}^2}$ is pulling on the needle and producing the deviation $MOC_2 = +27° 00'$.

OC_2 is the direction taken by the compass needle under the combined influence of the various forces; *i. e.*, the needle has deviated through the angle $POC_2 = +33° 00'$ from magnetic North.

In two heading methods it is generally desirable to compensate the semicircular deviation first, because the quadrantal deviation cannot be accurately compensated on some headings against the pull of the uncompensated semicircular forces.

It should be remembered to compensate the heeling error on that heading of the two which is most nearly East or West. While doing so, the spheres should be placed temporarily at the middle of the arms.

128. To Compensate.—Join OB as well as OM and produce OB, if necessary, to intersect the graduated arc of the dygogram. The deviation due to $\mathfrak{C}$, which is to be compensated by athwartship magnets, is the angle BOC_2 subtended by the line BC_2, and in this case it is positive, or $+16°$. The deviation due to $\mathfrak{B}$, which is to be compensated by fore-and-aft magnets, is the angle MOB subtended by the line MB, and in this case it is positive, or $+11°$. The quadrantal deviation is, as already stated, the angle $POM = +6°$.

With the athwartship magnet tray at the bottom of the chamber, place the C corrector magnets in their tubes, so that, when athwartship, their red ends will be, in this case, to starboard, taking care not to use so many that the compass card will swing more than 16° to the left. Secure the tray with the magnets athwartship and raise it until the card has swung just 16° to the left, or to 53° 15′.

With the fore-and-aft magnet tray at the bottom of the chamber, place the B corrector magnets in their tubes so that, in this case, their red ends are forward, taking care not to use so many that the compass card will swing more than 11° to the left; then raise the tray until the card has swung just 11° to the left, or to 64° 15′. Record the distances of the trays below the compass needles, the number of B and C corrector magnets, and the directions of their red ends; close and lock the chamber door.

Then place the quadrantal corrector spheres at the outer limits on their arms and move them inward until the compass card has swung 6° to the left, or to 70° 15′, which is the magnetic heading. Secure the spheres and record their distance from the compass pivot.

When compensating the semicircular forces it must be borne in mind that accurate compensation is not possible if the corrector magnets lie nearly in the vertical plane through the compass needle, for in such a case it would take a large vertical movement of the magnets to produce an appreciable effect upon the compass card. Therefore the directions of the $\mathfrak{B}$ and $\mathfrak{C}$ forces and of the compass needle, *i. e.*, the directions of the lines MB, BC_2, and OC_2, and the angles which they make with each other must be carefully studied on the dygogram before deciding which semicircular component should be compensated first. Sometimes the compensation of one component will produce an undesirable condition for the compensation of the other, and sometimes it will improve the condition for the other. An illustration of this will be given later.

The dygogram construction is simplified when the two magnetic headings are diametrically opposite, or practically so, as when a ship moored along a dock front is winded and remoored in the opposite direction, provided these headings do not lie in the magnetic meridian or at right angles to it. Should the headings lack one or two degrees of being opposite, they should be assumed to be on the diameter which halves this difference.

Example, Case b.

$T = 17^s.4$,	$\delta_1 = 12° 15'$ E.,
$T'_1 = 15^s.4$,	$\delta_2 = 7° 00'$ W.,
$T'_2 = 24^s.4$,	$Z_1 = 58° 00'$,
$Z'_1 = 45° 45'$,	$Z_2 = 238° 00'$.
$Z'_2 = 245° 00'$,	

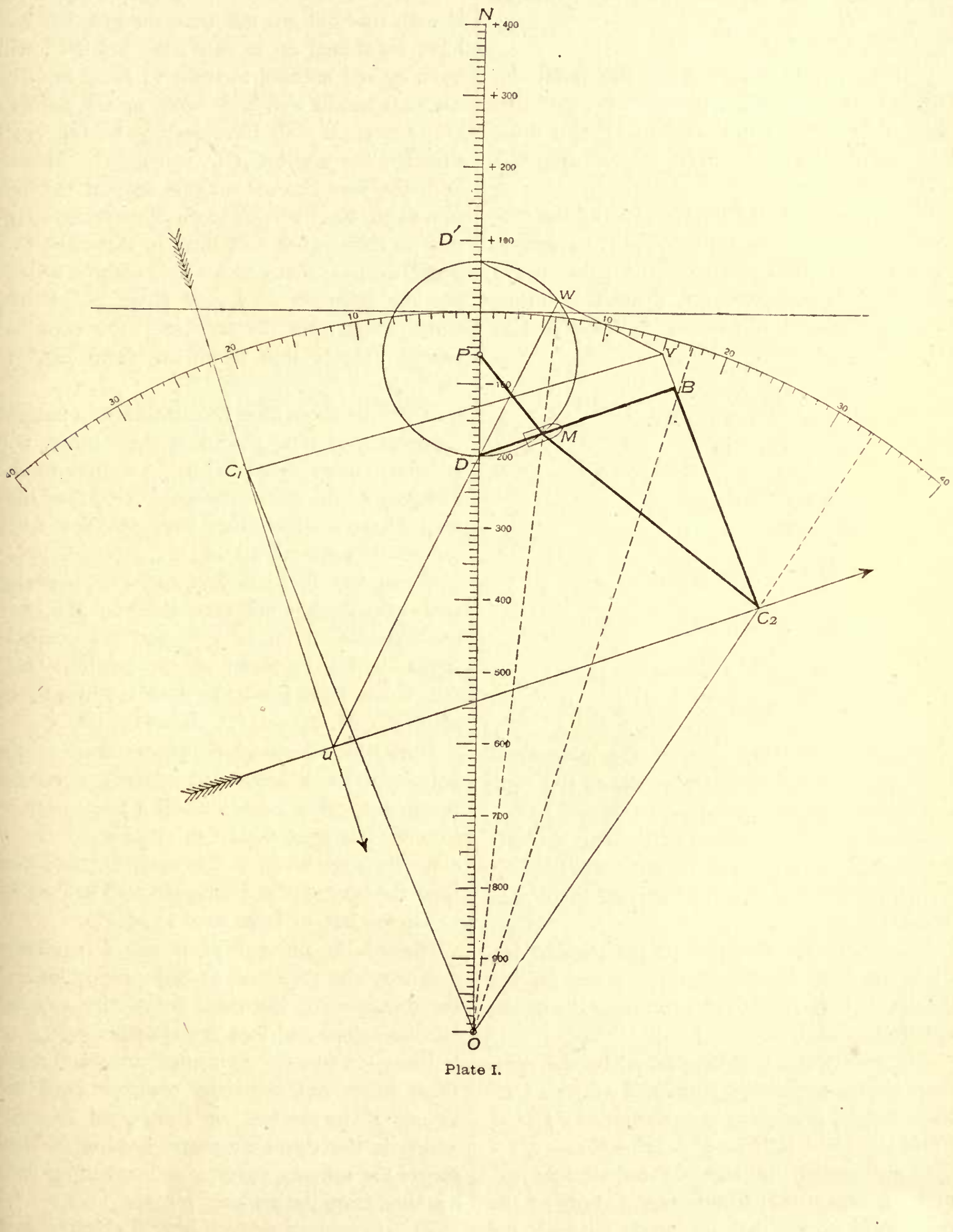
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Plate I.

By construction (Plate II), draw OC_1 in the direction of the deviation $(+12° 15')$ on the first heading, and lay off $OC_1 = \frac{H'_1}{H} = \frac{T^2}{T'^2_1} =$ 1.28. Draw OC_2 in the direction of the deviation $(-7° 00')$ on the second heading, and lay off $OC_2 = \frac{H'_2}{H} = \frac{T^2}{T'^2_2} = .51$.

Join C_1C_2 and bisect it in the point M. Through M draw MD parallel to the keel line (238° 00′), intersecting ON in D, and draw MD' perpendicular to MD, intersecting ON in D'.

Bisect DD' at P, and from C_2 let fall the perpendicular C_2B on MD, produced if necessary. Since C_2 was obtained with the ship on the magnetic heading 238° 00′, draw the outline of a ship around M heading in the direction MD. Then:

$$OP = \lambda = .92,$$
$$PD = PD' = \lambda\mathfrak{D} = .11,$$
$$\mathfrak{D} = \frac{\lambda\mathfrak{D}}{\lambda} = \frac{.11}{.92} = .12,$$
$$MB = \lambda\mathfrak{B} = +.345,$$
$$BC_2 = \lambda\mathfrak{C} = -.225,$$
$$\mathfrak{B} = \frac{\lambda\mathfrak{B}}{\lambda} = +.375,$$
$$\mathfrak{C} = \frac{\lambda\mathfrak{C}}{\lambda} = -.245,$$
$$MC_2 = \lambda\sqrt{\mathfrak{B}^2 + \mathfrak{C}^2} = .41,$$
$$\sqrt{\mathfrak{B}^2 + \mathfrak{C}^2} = \frac{.41}{.92} = .446.$$

PM shows the direction of the quadrantal force pushing the compass needle to the right and producing the deviation $POM = +7°$.

MB shows the direction of the fore-and-aft component of the semicircular force pulling the needle to the left and producing the deviation $MOB = -22°$.

BC_2 shows the direction of the athwartship component of the semicircular force pulling the needle to the right and producing the deviation $BOC_2 = +8°$.

OC_2 shows the direction taken by the compass needle under the combined effort of all these forces, producing a deviation of $POC_2 = POM - MOB + BOC_2 = 7° - 22° + 8° = -7°$.

Compensation is effected as already explained, except that in this case a study of the dygogram shows that the angle between the direction of the athwartship magnets BC_2 and the direction of the compass needle OC_2 is small, but would be increased by compensating the $\mathfrak{B}$ force first. This should therefore be done.

When we shall have compensated the force $\mathfrak{B}$ with fore-and-aft magnets, the line MB will have shortened up to zero; the line BC_2 will have moved parallel to itself to MC_3, and the compass needle will have taken up the position OC_3; *i. e.*, it will have swung to the right through the angle C_2OC_3, or $+25°$. Hence, with the fore-and-aft magnet tray at the bottom of the chamber, place the B corrector magnets in their tubes, red ends, in this case, forward, using as many as possible without swinging the compass card more than 25° to the right; then raise the tray until the card has swung exactly that much, or from 245° to 220°.

It will be noted that the athwartship magnet correctors, if now placed in their tubes, will be much more nearly at right angles to the direction of the disturbed needle OC_3 than they would have been had they been used first when the needle's direction was OC_2.

When the force $\mathfrak{C}$ has been compensated with athwartship magnets, the line MC_3 will have shortened up to zero and the compass needle will have taken up the position OM; *i. e.*, it will have swung to the left through the angle C_3OM, or $-11°$. Hence:

With the athwartship magnet tray at the bottom of the chamber, place the C corrector magnets in their tubes (using a precaution as to their number similar to that used for B magnets), red ends, in this case, to port; then raise the tray until the compass card has swung 11° to the left, or from 220° to 231°.

Record the number of B and C corrector magnets, the direction of their red poles and the distances of the trays below the compass needles; close and lock the chamber door.

Place the spheres upon their arms and move them in or out until the compass card has swung 7° to the left, or from 231° to 238°, which is the ship's magnetic heading. Then secure the spheres, reading and recording their distance from the compass pivot.

The foregoing method would cover a case

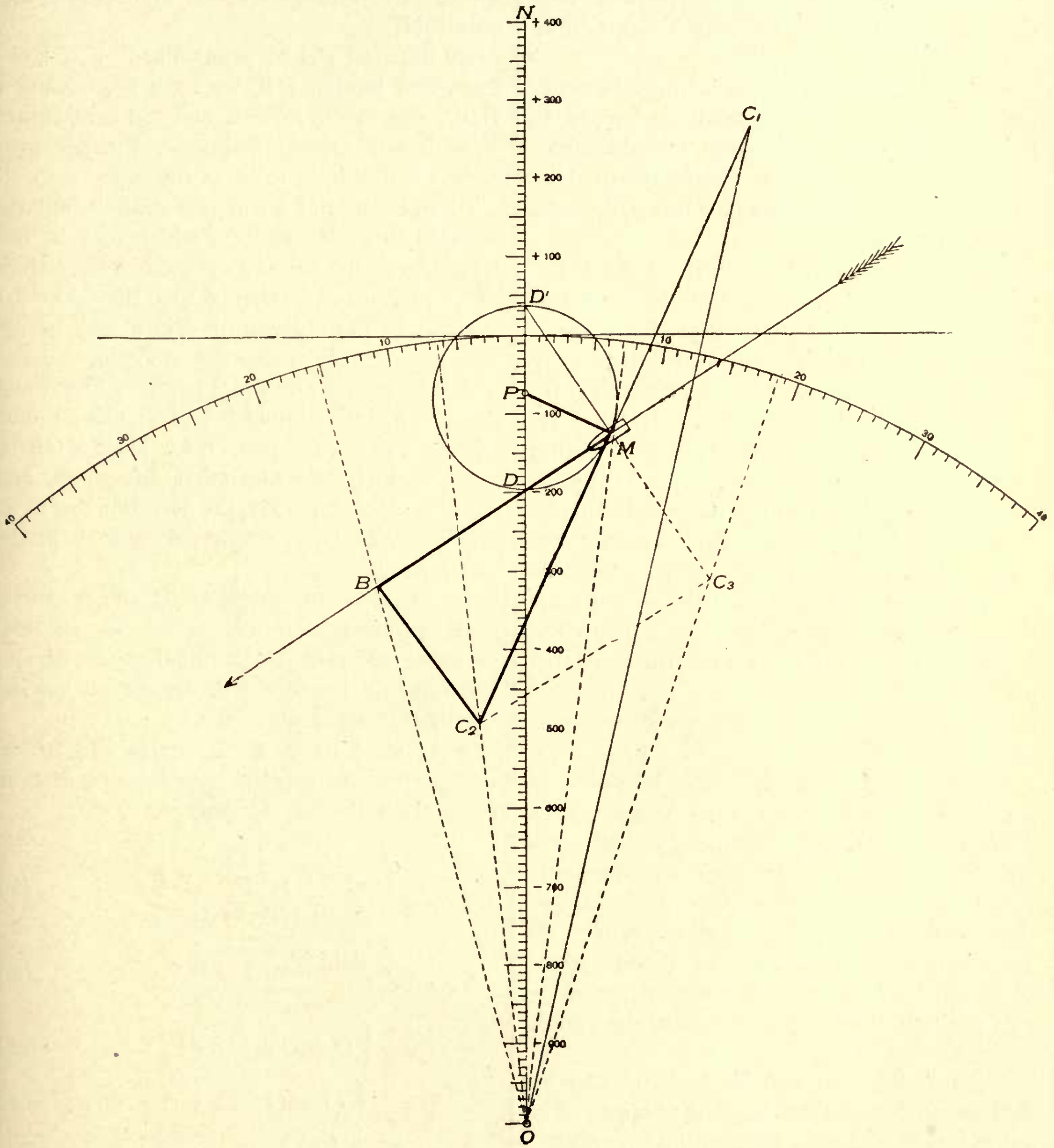
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Plate II.

where either the 𝔅 force or the ℭ force was acting in the direction of the disturbed needle and producing no apparent deviation, *i. e.,* when either MB or BC_2 was coincident in direction with OC_2; for by compensating the other force first, the needle will be made to take up a new position and the coincidence will be destroyed.

Compensation on opposite headings becomes indeterminate if the two headings happen to lie in the magnetic meridian or at right angles to it. These conditions are represented in Plate III, the forces λ𝔅 and λℭ being the same as previously used.

The actual values of λ and 𝔇 cannot be obtained either by construction or by computation. On magnetic East or West the semicircular deviation can be compensated as already explained. On magnetic North or South there is no apparent deviation due to 𝔅. If, however, 𝔅 were compensated, the line BM would shorten up to zero; BC_2 would take up the position MC_3, and the total deviation would change from MOC_2 to MOC_3, or, with the data given, from $-9° \ 30'$ to $-12° \ 30'$. Hence, compensate in this case with B correctors until the total deviation becomes $-12° \ 30'$; then compensate with C correctors until the deviation becomes zero.

This is all that can be done with any certainty.

The quadrantal spheres should be placed in position by estimate based upon records of the placing of spheres at a compass station similarly situated in a similar ship, which records may be obtained from the Bureau of Navigation. The navigator's experience will often serve in making the estimate, or, if there seems to be no other means of arriving at the probable position, they may be placed at the middle position.

Compensation on two headings is also indeterminate when these headings happen to be on adjacent magnetic intercardinal points.

Example.

$Z_1 = 315° \ 00'$,	$Z_2 = 45° \ 00'$,
$Z'_1 = 316° \ 45'$,	$Z'_2 = 15° \ 30'$,
$\delta_1 = 1° \ 45'$ W.,	$\delta_2 = 29° \ 30'$ E.,
$T'_1 = 15^s.4$,	$T'_2 = 17^s.6$,
	$T = 17^s.4$.

By construction (Plate IV) it will be seen that we can proceed as usual as far as drawing the line uw which determines the point D; but the line vw will lie in the meridian, making the points D' and P indeterminate, and consequently the values of λ, λ𝔇 and λ𝔅 are unobtainable.

By drawing DB perpendicular to C_2v, however, and joining OB, we have the deviation BOC_2 due to the force ℭ and can compensate it with athwartship magnets. Further procedure would have to be as follows:

From records of a compass station similarly situated in a similar ship, which may be obtained from the Bureau of Navigation, values of λ and 𝔇 may be assumed such that $\lambda(1-\mathfrak{D}) = OD$. In the absence of data λ may be assumed as 0.8 in ordinarily well-placed compasses. Lay off OP equal to the λ found and describe a circle around P with PD as a radius cutting DB in M. Join OM. Then MOB is, approximately, the deviation due to 𝔅, and POM is, approximately, the deviation due to 𝔇, and they can be compensated as such in the usual manner.

By two-heading methods, if the magnetic headings are not on or near opposite cardinal points or adjacent intercardinal points, careful work should produce a compensation leaving less than 4° maximum error.

The values of 𝔅, ℭ, 𝔇, and λ can be obtained from the original data by computation, using the following formulæ:

$$1+a = \frac{\frac{T^2}{T'^2_1}\cos Z'_1 - \frac{T^2}{T'^2_2}\cos Z'_2}{\cos Z_1 - \cos Z_2}, \qquad (1)$$

$$1+e = \frac{\frac{T^2}{T'^2_1}\sin Z'_1 - \frac{T^2}{T'^2_2}\sin Z'_2}{\sin Z_1 - \sin Z_2}, \qquad (2)$$

$$\lambda = \frac{1}{2}\left\{(1+a)+(1+e)\right\}, \qquad (3)$$

$$\mathfrak{D} = \frac{1}{2\lambda}\left\{(1+a)-(1+e)\right\}, \qquad (4)$$

$$\mathfrak{B} = +\frac{1}{2\lambda}\left\{\left(\frac{T^2}{T'^2_1}\cos Z'_1 + \frac{T^2}{T'^2_2}\cos Z'_2\right) - (1+a)(\cos Z_1 + \cos Z_2)\right\}, \qquad (5)$$

$$\mathfrak{C} = -\frac{1}{2\lambda}\left\{\left(\frac{T^2}{T'^2_1}\sin Z'_1 + \frac{T^2}{T'^2_2}\sin Z'_2\right) - (1+e)(\sin Z_1 + \sin Z_2)\right\}. \qquad (6)$$

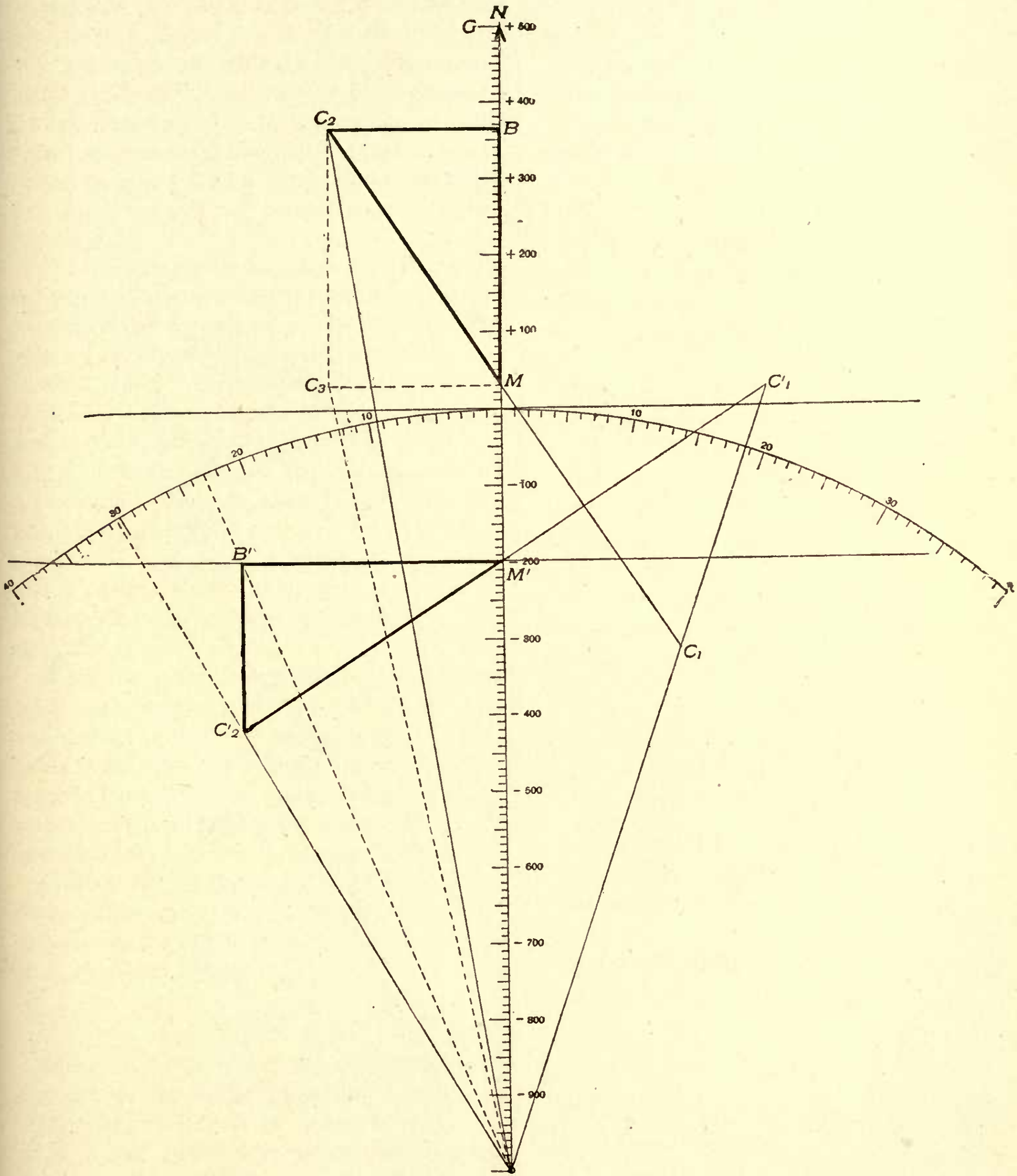
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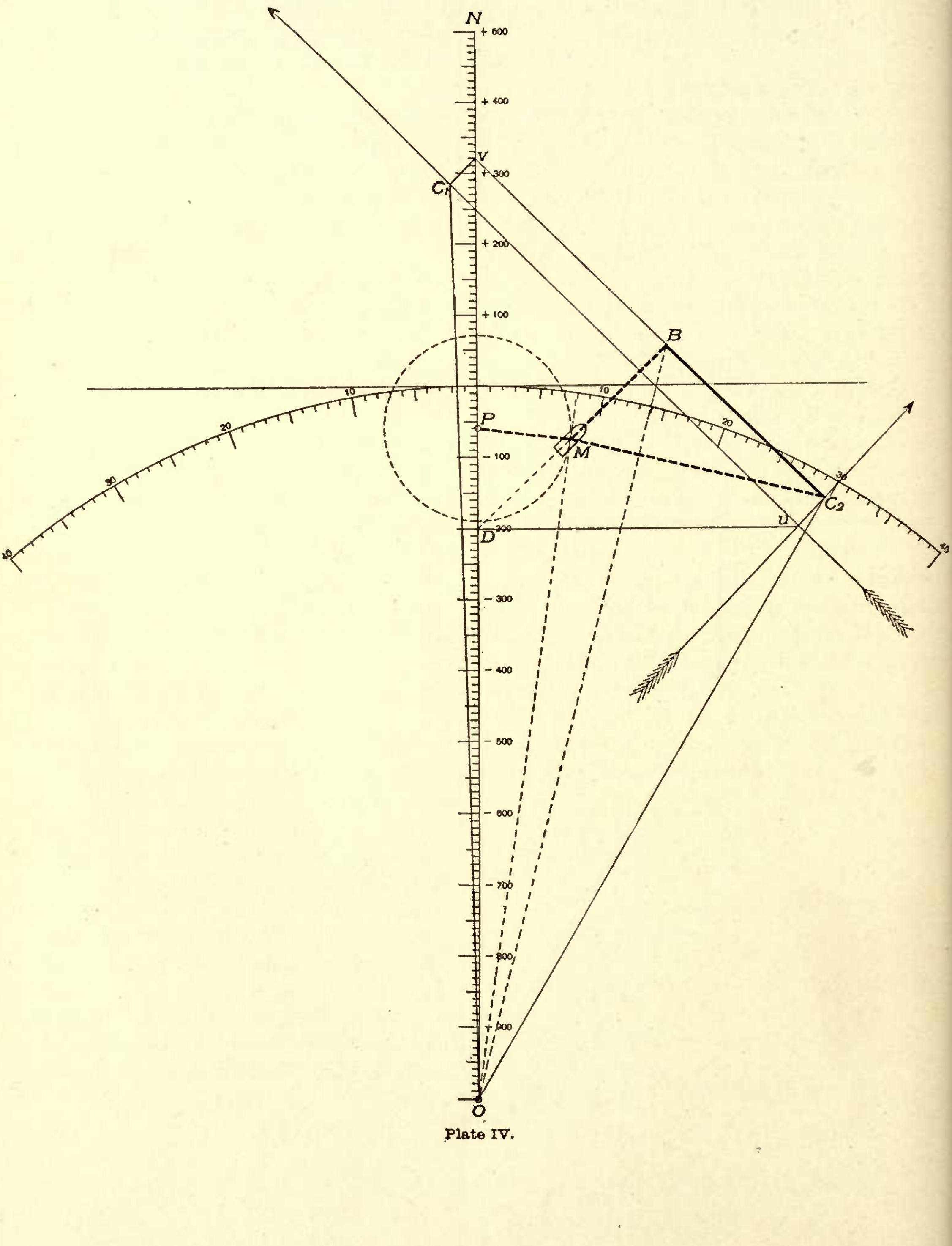
Plate III.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D
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Plate IV.

Computation should be used whenever construction gives very acute angles of intersection, rendering measurements uncertain.

129. Compensation on One Heading Alongside the Dock.—Should it not be possible to take observations for directive force on two headings, the compasses can be compensated with tolerable accuracy from observations on one heading only. In this event the quadrantal spheres must be placed by estimate and values of λ and $\mathfrak{D}$ assumed as described above for certain cases of compensation on two headings.

Center the compass accurately, place the spheres by estimate, and then compensate the heeling error regardless of the fact that the ship may not be heading near East or West.

Next, record the compass heading of the ship (Z') by the compass to be compensated, and observe and record the magnetic heading (Z) and the deviation, obtainable by means of a chart, or an azimuth of the sun, or of a distant object of known magnetic bearing, or by a single set of reciprocal bearings. Obtain T and T' with the spheres in place, by methods already described. Then, by dygogram construction (Plate V):

From the point P lay off the angle NPB equal to the magnetic heading (Z) of the ship, and draw the line PB, representing the keel line of the ship, extending it some little distance in both directions and marking it with an arrow-head and feathers, or in some other conventional way which will indicate its character.

From O lay off the angle POC equal to the observed deviation (δ), to the right of ON if easterly, to the left if westerly; draw OC and on it lay off the distance

$$OC=\frac{1}{\lambda}\frac{T^2}{T'^2}=\frac{1}{\lambda}\frac{H'}{H}.$$

OC is the force of the ship and earth in the direction of the disturbed needle, in terms of λH, or the mean force to North, as unit; that is, it is the directive force on the compass needle for the magnetic heading of the ship.

From C let fall a perpendicular CB on PB and join CP and OB. Then $PB=\mathfrak{B}$, marked + if ahead of P or − if astern of it, and $BC=\mathfrak{C}$, marked + to starboard and − to port. The angle POB is the deviation due to $\mathfrak{B}$; the angle BOC is the deviation due to $\mathfrak{C}$, and the angle POC is the deviation due to $\sqrt{\mathfrak{B}^2+\mathfrak{C}^2}$.

The numerical values of $\mathfrak{B}$ and $\mathfrak{C}$ can be obtained, if desired, by measuring PB and BC, respectively, by the vertical scale of the dygogram.

The angles POB and BOC may be measured on the graduated arc of the dygogram. Compensation can be effected with these data as already described for two-heading methods.

Example.

U. S. S. *Mayflower,* Washington, D. C. Standard compass on forward bridge. Height above main deck 20 ft. Distance from stern 180 ft. Compensate on magnetic heading 64° 30′.

From data for standard compass of U. S. S. *Scorpion,* assumed:

$$\lambda=.95,$$
$$\mathfrak{D}=.105,$$

and estimated that the 7″ spheres should be placed at 12⅞ inches.

Place and secure the spheres. Compensate the heeling error and carefully center the compass. It is then found that:

$$Z'=38^\circ\ 45',$$
$$\delta=25^\circ\ 45'\ \text{E.},$$
$$T=19^s.6,$$
$$T'=21^s.9.$$

In Plate V, draw PB making the angle $NPB=64^\circ\ 30'$ with PN, and mark it as an arrow to indicate the magnetic heading of the ship.

Draw OC making the angle $POC=\delta=+25^\circ\ 45'$, and lay off

$$OC=\frac{1}{\lambda}\frac{H'}{H}=\frac{1}{.95}\frac{\overline{19.6}^2}{\overline{21.9}^2}=.846.$$

Draw CB perpendicular to PB and join OB. Then, by measurement:

$$\mathfrak{B}=PB=.23,$$
$$\mathfrak{C}=BC=.375,$$
$$POB=\text{deviation due to }\mathfrak{B}=+11^\circ\ 00',$$
$$BOC=\text{deviation due to }\mathfrak{C}=+14^\circ\ 45'.$$

130. To Compensate.—Use C correctors, as described for two-heading compensation, to

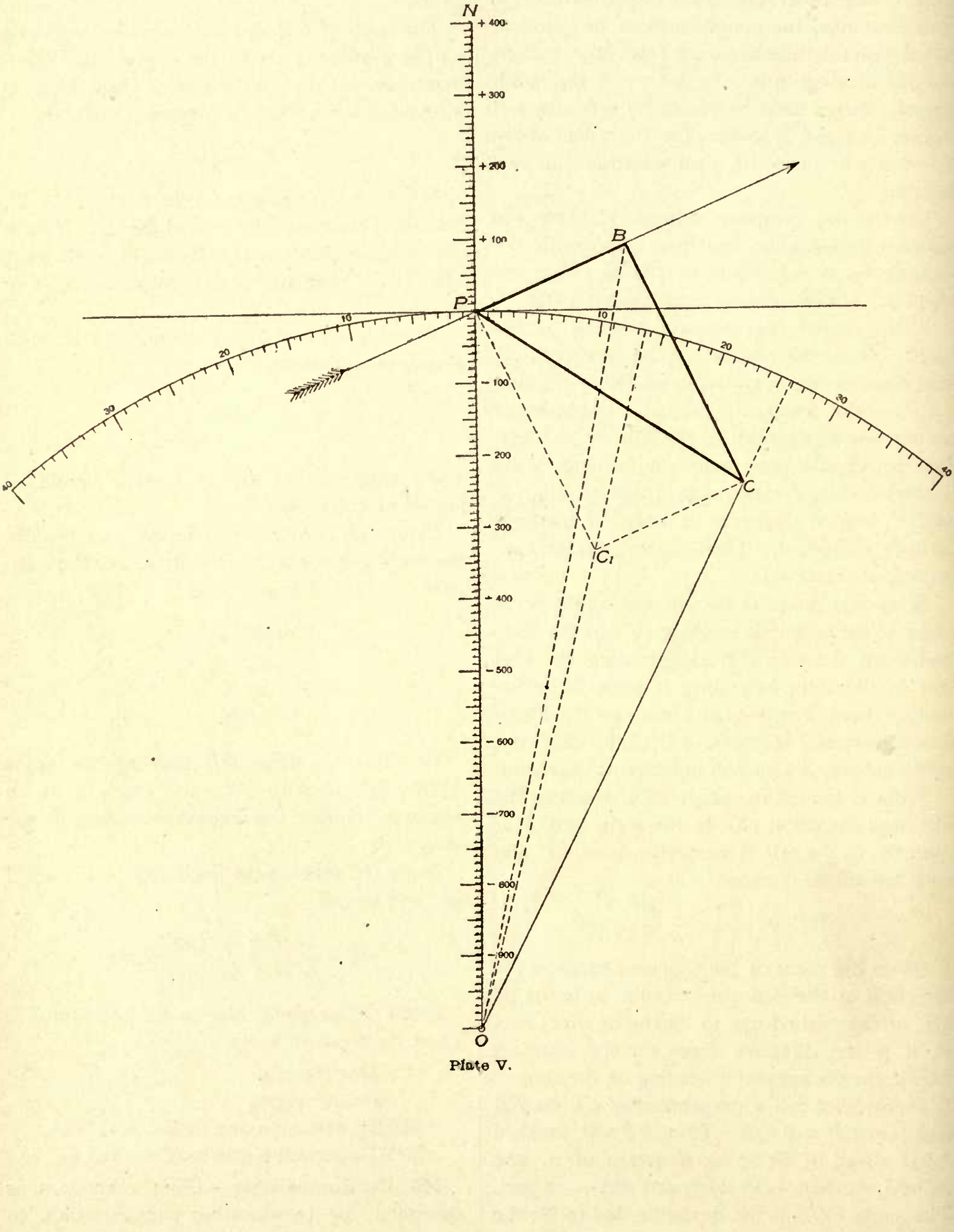
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Plate V.

make the compass card swing to the left through the angle $COB=14° \ 45'$, so that the ship's head, per compass, will be 53° 30′. Then use B correctors to make the card swing still farther to the left, through the angle $BOP=11°$, so that the ship's head, per compass, will be 64° 30′.

The directions of the 𝔅 and ℭ forces and of the compass needle, *i. e.*, of the lines PB, BC, OB, and OC, and the angles which they make with each other, should be carefully studied on the dygogram before deciding which semicircular component should be compensated first, as explained for two-heading compensation on page 66. Should this lead us to compensate 𝔅 first, we must bear in mind that the amount of ℭ deviation to be compensated *after* compensating for 𝔅 will not be the angle BOC; for, when $\mathfrak{B}=PB$ is reduced to zero, $BC=\mathfrak{C}$ takes up the position PC_1, and the deviation to be compensated by C correctors will be the angle POC_1, instead of the angle BOC. These angles will sometimes differ greatly. In the present example they differ by 1° 15′.

The preceding results may be obtained with fair approximation by computation, without the aid of a dygogram, using the following formulæ (*Admiralty Manual*, 1901, page 129):

$$\mathfrak{B}=+\frac{1}{\lambda}\cdot\frac{T^2}{T'^2}\cos Z'-(1+\mathfrak{D})\cos Z,$$

$$\mathfrak{C}=-\frac{1}{\lambda}\cdot\frac{T^2}{T'^2}\sin Z'+(1-\mathfrak{D})\sin Z.$$

To compensate from computations only, it will be necessary to know the portions of the total deviation due to 𝔅 and ℭ, respectively. Assuming that, approximately,

$$B=\mathfrak{B}\times 57.3° \text{ and } C=\mathfrak{C}\times 57.3°,$$

we can obtain values of B and C. Then we have, approximately:

$B \sin Z'$ = amount of deviation to be corrected by fore-and-aft magnets $=\mathfrak{B}\sin Z'\times 57.3°$.

$C \cos Z'$ = amount of deviation to be corrected by athwartship magnets $=\mathfrak{C}\cos Z'\times 57.3°$.

Referring to the dygogram construction, Plate V, 𝔅 and ℭ (PB and BC) are fractions of the radius OP. Since $2\pi r=360°$ and $r=\frac{360°}{2\pi}=57.3°$, the angular measure of 𝔅 and ℭ, or of PB and BC, if these were laid along the graduated circumference described by OP, would be $\mathfrak{B}\times r°$ and $\mathfrak{C}\times r°$, or $\mathfrak{B}\times 57.3°$ and $\mathfrak{C}\times 57.3°$. But 𝔅 and ℭ are chords, not arcs, and actually subtend a little more than the angles $\mathfrak{B}\times 57.3°$ and $\mathfrak{C}\times 57.3°$; hence these expressions are a little less numerically than B and C. Consequently the computed sum of the parts of the semicircular deviation, or $\mathfrak{B}\sin Z'\times 57.3°+\mathfrak{C}\cos Z'\times 57.3°$, may differ appreciably from the total deviation shown by the compass card. If this be the case, the portions of the total deviation to be compensated by B correctors and C correctors, respectively, will be proportional to, instead of equal to, the computed values of these portions.

131. Cases Apparently Indeterminate.—Compensation from observations on one heading appears to be indeterminate when, with spheres in place, that heading proves to be one on which there is no deviation (Plate VI). In such a case the two components of semicircular force, PB and BC, are neutralizing each other, and the compass needle lies in the meridian OPC.

If, however, the component ℭ were compensated, BC would shorten up to zero and the needle would take up the position OB, due to the remaining force $\mathfrak{B}=PB$. If, therefore, we place athwartship correctors at such a height as to produce a deviation POB, we have compensated ℭ; and if we then place fore-and-aft correctors so as to reduce the deviation again to zero, we will have compensated 𝔅 also, and the compensation will be complete. Compensation, in this case, is therefore simple.

Special procedures for compensation on one heading will be necessary in the following cases:

1. On magnetic North or South, where 𝔅 will lie in the plane of the magnetic meridian and will appear by the dygogram to be producing no deviation.

2. On compass East or West, where ℭ will lie in the vertical plane through the compass needle, and the corresponding correctors would have no apparent effect on the needle.

In the first case, Plate VII, if $\mathfrak{B}=PB$ were compensated, the line PB would be shortened up to zero, and the line BC would assume the

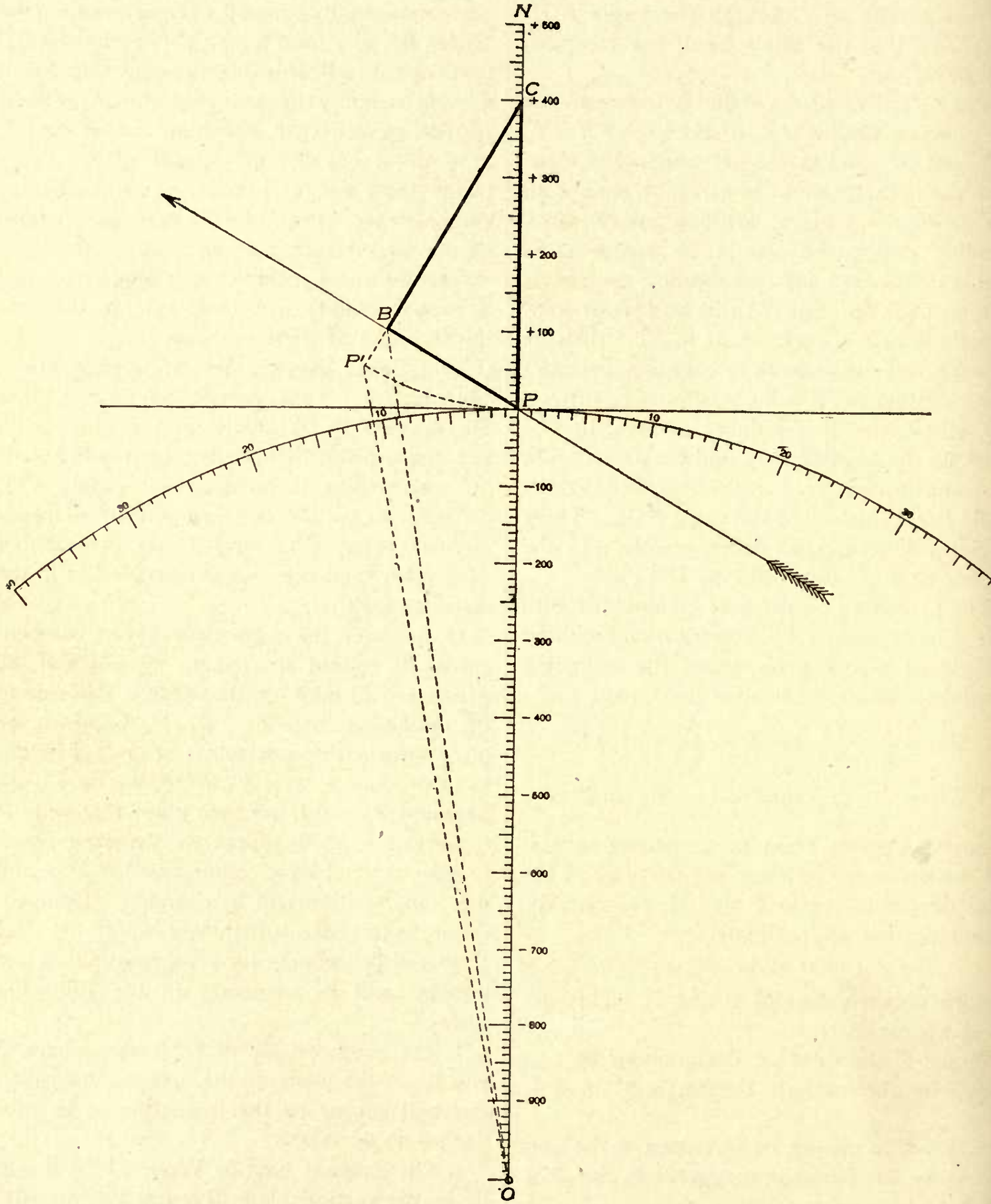
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Plate VI.

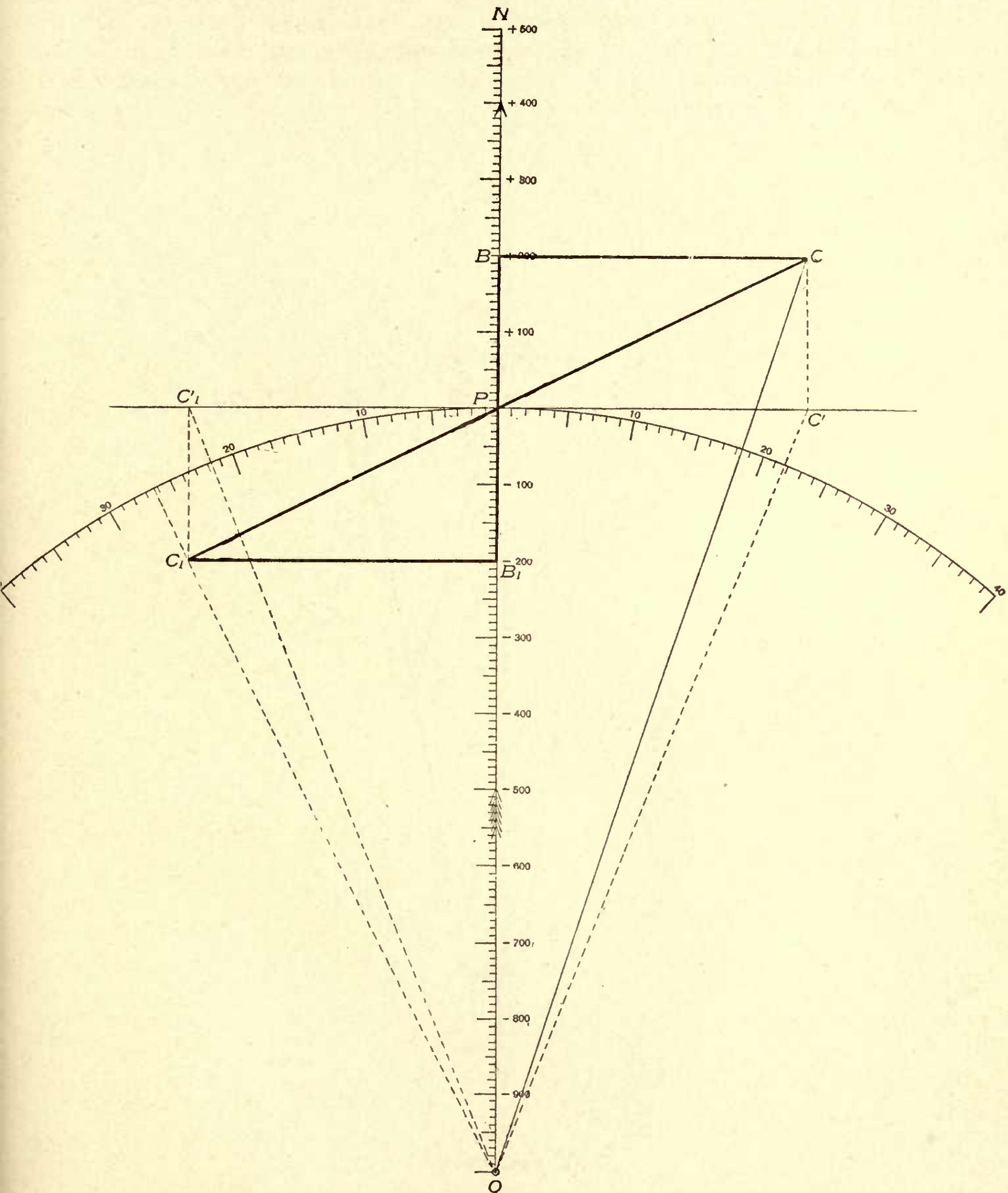
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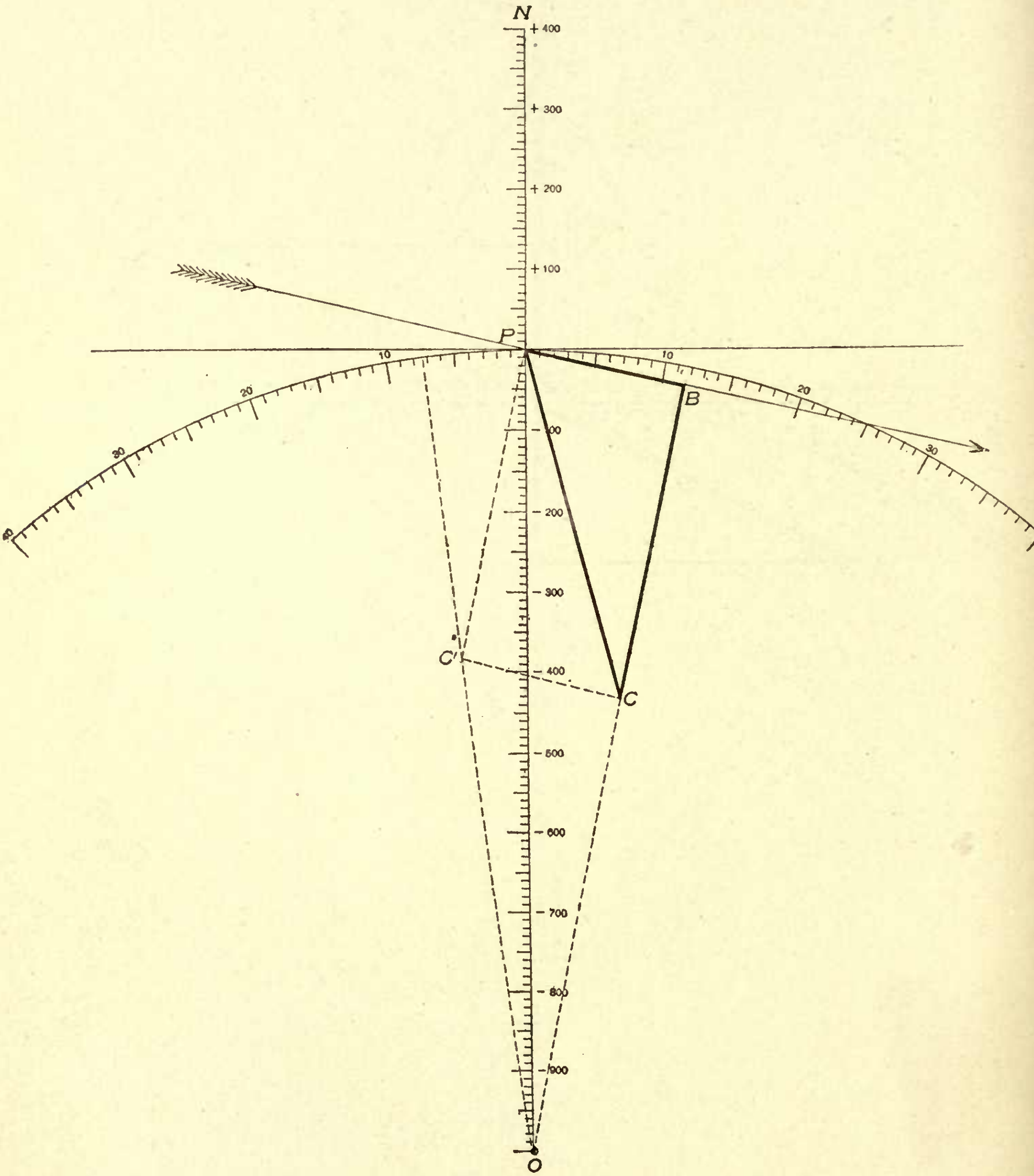
Plate VII.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O

Plate VIII.

position *PC'*, the deviation then becoming *POC'*, due to 𝕮 alone. Consequently, place the fore-and-aft magnets so as to change the deviation from *POC* to *POC'*, then place the athwartship magnets to reduce the deviation from *POC'* to zero; compensation has then been effected. The sub-lettered diagram shows the corresponding condition on the opposite magnetic heading.

In the second case, Plate VIII, if 𝔅=*PB* were compensated, the line *PB* would shorten up to zero, and the line *BC* would take up the position *PC'*, producing a deviation *POC'*, due to 𝕮 alone; consequently, place fore-and-aft magnets so as to change the deviation from *POB* to *POC'*, then place athwartship magnets so as to change the deviation from *POC'* to zero. Compensation is then effected.

CHAPTER X.

SPECIAL NOTES.

132. In the *U. S. Navy Regulations,* Chapter 14, Naval Instructions (Art. 1603), we find the following instructions, with respect to compasses, laid down for the navigating officer of a ship:

"(1) The navigating officer shall prepare the compass reports in accordance with the instructions as laid down in the prescribed forms or issued from time to time. He shall keep the Compass Record, which shall be a complete history of the compasses while on board ship and shall contain copies of all compass reports. The compass report shall be signed by him on the last day of every quarter, and shall be submitted to the commanding officer for his approval.

"(2) When the ship is under way and the weather permits, he shall each day ascertain by observation the error of the standard compass and report the result to the commanding officer in writing.

"(3) He shall prepare and keep corrected tables of deviations of the standard, battle, maneuvering, and auxiliary battle compasses, copies of which shall be kept posted near those compasses in such positions as to be accessible to the officer of the deck and other officers concerned in the navigation of the ship.

"(4) All courses and bearings that are entered in the log-book, as well as bearings for computation, shall be marked to show whether they are true, magnetic, or by the standard compass, and in the last case the ship's head 'per standard compass' must be stated.

"(5) He shall not move the standard compass, or any of its attachments or compensating magnets or appurtenances, from the position in which they were placed and secured when the ship was commissioned, unless authorized by the commanding officer.

"(6) He shall frequently examine all the compasses of the ship and see that they are in good order and ready for use, and that the spare compasses are properly stored."

In the *U. S. Navy Regulations,* Chapter 43, Naval Instructions, we find (Art. 5222):

"(2) Reports by the Navigating Officer:

"(a) At the first opportunity after commissioning; and when crossing magnetic equator; compass reports for all compasses installed, both with all correctors removed and after compensation; to Bureau of Navigation, direct; Forms 7 and 10.

"(b) When extensive alterations have taken place in the vicinity of any compass, causing a change in the magnetic surroundings; compass report for the compass affected, both with all correctors removed and after compensation; to Bureau of Navigation, direct; Forms 7 and 10.

"(c) Annually, June 30, inventory of compasses and instruments; to Bureau of Navigation, direct; Form 9.

"(d) Annually, June 30, deviation tables; to Bureau of Navigation, direct; Form 12.

"(e) Going out of commission, Compass Record Book; to Compass Office, Naval Observatory, direct; Form 14.

"(f) Quarterly, report of condition of gyrocompass set, and its action during the quarter; to the Bureau of Navigation *via* the Commander-in-Chief or Division Commander, in a letter. This report is required from all vessels equipped with gyro-compasses."

133. The Compass Record referred to above is a book made up of the blank forms issued by the Navy Department for compass work. This book contains the following instructions:

DEPARTMENT OF THE NAVY.

Bureau of Navigation.

Form No. 14.

INSTRUCTIONS.

The following instructions relative to compass observations and records under cognizance of the Bureau of Navigation are issued for the information and guidance of the commanding officers and navigators of the service.

1. Forms for compass work issued by the Bureau:

(a) Compass Record Book.

(b) Form No. 7. Record of observations and results obtained from swinging ship.

(c) Form No. 8. Napier diagram for curve of deviations.

(d) Form No. 9. Inventory of the compasses and instruments.

(e) Form No. 10. Analysis of deviations.

(f) Form No. 11. The dygogram.

(g) Form No 12. Deviation tables for all compasses.

(h) Form No. 12a. Deviation table for one compass. (This form for ship's use only.)

2. The "Compass Record" shall be a complete history of the compasses while on board ship, and shall contain copies of all compass reports. It shall be kept by the navigator, who shall sign it and submit it to the commanding officer for his approval on the last day of every quarter. It shall be sent to the Compass Office, U. S. Naval Observatory, when the vessel is put out of commission.

3. Upon receipt of the compass outfit it shall be carefully inspected. The compasses shall, at the first opportunity, be tested on shore for "sensibility" and "time of vibration" in accordance with the instructions contained on the back of Form No. 9. Compass material found defective shall be immediately surveyed. An inventory of the compasses and instruments, Form No. 9, shall be filled out and sent to the Bureau of Navigation on June 30 of each year.

4. When a vessel is newly commissioned, all the compasses shall be approximately compensated. At the first opportunity after commissioning, the ship shall be swung for deviations as follows: First, with all correctors removed; second, after compensation. A complete analysis of the deviations of all compasses installed shall be made, both before and after compensation, and a complete report forwarded, on Forms No. 7 and No. 10, to the Bureau of Navigation.

5. Similar observations and reports shall be made when on or near the magnetic equator, and data for the installation of Flinders bars obtained.

6. Similar observations and reports shall be made when extensive alterations have taken place in the vicinity of any compass, causing a change in the magnetic surroundings, such reports to cover the compass affected.

7. All compasses shall be kept as closely compensated as practicable. Every effort should be made to swing ship for residual deviations of all compasses at least once in three months. The results, properly recorded on Forms No. 7 and 8, shall be entered in the Compass Record. Deviation tables on Form No. 12a, for the standard, battle, maneuvering and auxiliary battle compasses, shall be prepared and kept posted near those compasses in such positions as to be accessible to the officer of the deck and other officers concerned in the navigation of the ship. Deviation tables on Form No. 12, for all compasses installed, shall be entered in the Compass Record at the end of every quarter.

8. Annually on June 30 all vessels shall report to the Bureau of Navigation, on Form No. 12, the deviations of all compasses installed, with the details of compensation; and on the same form a record of the various dates and places of swinging ship during the preceding year, with the variation of the compass obtained on each occasion.

9. An error in the variation affects the constant coefficient A by an amount equal to the error. Once accurately determined (preferably by the method of reciprocal bearings), the A should be used as a constant correction to the variation as obtained from the mean of the errors observed on the equidistant compass headings.

Philip Andrews,
Chief of Bureau of Navigation.

Bureau of Navigation, January, 1913.

134. Designation of Magnetic Compasses. The following instructions on the back of the "Compass Report," Form 12, names the various magnetic compasses used on board naval vessels:

"Compasses on board battleships, armored cruisers, and protected cruisers shall be designated as follows:

"*Standard Compass.*—The compass on deck, well located magnetically, and, if practicable, one that is not required for steering or maneuvering the ship.

"*Steering Compass.*—The compass used by the helmsman while cruising at sea, if it be not the same as the standard compass.

"*Maneuvering Compass.*—The compass on the upper deck used for taking bearings when maneuvering in squadron, if it be not the same as the standard or steering compass.

"*Battle Compass.*—The compass behind armor or below the protective deck that is best adapted for steering a compass course during battle.

"*Auxiliary Battle Compass.*—The compass located in or near the steering engine room, if it be not the battle compass.

"*Top Compass.*—The compass located in the top of the cage mast.

"Compasses on board torpedo-boat destroyers, torpedo-boats, and auxiliaries shall be designated as follows:

"*Standard Compass.*—The compass on deck, well located magnetically, that is used for navigating the ship.

"*Steering Compass.*—The compass used by the helmsman while cruising at sea (if not the standard compass).

"*Check Compass.*—The after-deck compass (if installed).

"If any compass is used for two or more of the above purposes, it shall be given the name, according to its use, which appears first in the above list; but all reports, etc., in regard to it shall not only refer to it by its regular name, but shall indicate by a proper note or parenthesis the other uses to which it is put."

SPECIAL INSTRUCTIONS IN THE USE OF THE COMPASS FORMS.

The instructions given in the "Compass Record" cover in general terms the use of the various forms supplied, but the following additional explanation of their use may be of service.

135. Form No. 7, Record of observations and results obtained from swinging ship (a copy of which will be found on pp. 92-93), is used by navigators in preparing the data to be entered in columns (2) and (4) of Form No. 10, "Analysis of Deviations" (a copy of which will be found on pp. 34-35). In preparing the data for an analysis, use Form No. 7 to get the compass headings, by the different compasses, corresponding to the *magnetic* headings obtained by observation with the standard compass. As the standard compass is the one usually used in steadying the ship on each fifteenth degree, the deviations of that compass for each fifteenth-degree compass heading can be at once transferred from Form No. 7 to Form No. 10 for an analysis. But for other compasses we have not the deviations on each fifteenth-degree heading by those compasses, but have the ship's head by those compasses corresponding to each fifteenth-degree heading by the standard compass. Using Form No. 7, we get in column (10) the ship's head (magnetic) for each course she was steadied on. We have the readings of the other compasses for the magnetic headings given in column (10), and can therefore at once find the deviation of those compasses for the *magnetic* headings on which the ship was steadied. But for an analysis of deviations for any compass, we require the deviations for each fifteenth-degree *compass* heading by the compass the deviations of which we are analyzing. To obtain the deviations corresponding to each fifteenth-degree *compass* heading, we construct a curve of deviations for the *magnetic* headings (using a Napier's diagram, Form No. 8), from which curve we take the deviations for each fifteenth-degree *compass* heading, which deviations are entered in columns (2) and (4) of Form No. 10, and are then used for analyzing the deviations of the compass concerned.

136. Form 8, Napier diagram for curve of deviations (a copy of which is shown in Chapter I, Art. 20, of this book), is used as explained in the preceding paragraph and as explained in Art. 20 of this book. In getting the data to be entered in the "annual compass report," Form No. 12, it is necessary to use a Napier's curve in the same manner as explained in the preceding paragraph.

137. Form No. 9, Inventory of the compasses and instruments (a copy of which will be found on pp. 94-96), is used as described in the instructions printed on the back of the form.

138. Form No. 10, Analysis of Deviations (a copy of which will be found on pp. 34-35), is self-explanatory. The products of arcs by the multipliers S_1, S_2, S_3, S_4, and S_5, to be placed in columns (7), (8), (13) and (14), may be picked out from Table IV in Muir's *Navigation and Compass Deviations* (1911), or from a similar table given in the back of this book (see Table I).

139. Form No. 11, the dygogram (copies of which are shown in Chapter IX of this book), is useful when compensating on two headings, or one heading, before leaving a navy yard. It may also be used for constructing a curve of deviations from observations on two headings (or one heading). This method of getting deviations is rarely used; but if it is, the student is referred to Muir's *Navigation and Compass Deviations,* Arts. 112 and 113, where a full explanation is given.

140. Form No. 12, Deviation tables for all compasses (a copy of which will be found on p. 97), has on the back the following instructions:

"This report, in duplicate, to be sent annually on June 30 to the Bureau of Navigation by all vessels.

"This form to be filled out on the last day of each quarter, in accordance with the latest observations, and inserted in the 'Compass Record.'

"The upper pole of heeling magnet, starboard pole of C magnets, and forward pole of B magnets, are to be entered thus: N 12″, R 16″, B 13″."

141. Form No. 12(a), Deviation table for one compass (a copy of which is shown in Chapter I, Art. 20, of this book), is filled out for each compass on board ship; and copies of it are kept near the compass concerned for use of the captain, navigator, and officer of the deck.

Form No. 7.

COMPASS REPORT No............................, of the

Date of Report...; observations for this series of deviations made on the *7th* day of *February*, 19 *08*, at *sea*, in lat. *34° 50′ S.* and long. *54° 20′ W.*; object observed, *Sun*; if terrestrial, distance and true azimuth,.............................; if celestial, altitude on beginning set of observations, *16°*; altitude on completing set of observations, *39°*; mean declination, *15° 41′ S.*; sea, *smooth*; weather, *clear*; variation by chart, *6° 40′ E.*

A

1	2	3	4	5	6	7	8	9
Ship's head by standard Compass No. *34761.*	Times of observation by watch. *h. m. s.*	Watch correction on *l. ap. t.*	Local apparent times of observation. *h. m. s.*	Azimuth of *Sun* by stand'd compass No. *34761.*	True azimuth of *Sun* by *tables.*	Errors of compass No. *34761.*	Variation.	Deviations of compass No. *34761.*
0	*7 58 00*		*7 46 51*	*84° 30′*	*88° 25′*	*3° 55′ E*		*3° 05′ W*
15	*7 53 20*		*7 42 11*	*84 50*	*88 57*	*4 07 E*		*2 53 W*
30	*7 48 40*		*7 37 31*	*86 10*	*89 38*	*3 28 E*		*3 32 W*
45	*7 44 00*		*7 32 51*	*87 30*	*90 25*	*2 55 E*		*4 05 W*
60	*7 39 20*		*7 28 11*	*88 50*	*91 01*	*2 11 E*		*4 49 W*
75	*7 34 40*		*7 23 31*	*91 20*	*91 45*	*0 25 E*		*6 35 W*
90	*7 30 00*		*7 18 51*	*93 00*	*92 16*	*0 44 W*		*7 44 W*
105	*7 25 20*		*7 14 11*	*94 00*	*93 00*	*1 00 W*		*8 00 W*
120	*7 20 40*		*7 09 31*	*94 45*	*93 38*	*1 07 W*		*8 07 W*
135	*7 16 00*		*7 04 51*	*94 30*	*94 10*	*0 20 W*		*7 20 W*
150	*7 11 20*		*7 00 11*	*92 20*	*94 57*	*2 37 E*		*4 23 W*
165	*7 06 40*		*6 55 31*	*89 10*	*95 33*	*6 23 E*		*0 37 W*
180	*7 02 00*		*6 50 51*	*85 30*	*96 05*	*10 35 E*		*3 35 E*
195	*6 57 20*		*6 46 11*	*81 30*	*96 53*	*15 23 E*		*8 23 E*
210	*6 52 40*		*6 41 31*	*80 00*	*97 27*	*17 27 E*		*10 27 E*
225	*6 48 00*		*6 36 51*	*78 00*	*97 59*	*19 59 E*		*12 59 E*
240	*8 35 20*		*8 24 11*	*63 30*	*81 53*	*18 23 E*		*11 23 E*
255	*8 30 40*		*8 19 31*	*66 35*	*83 22*	*16 47 E*		*9 47 E*
270	*8 26 00*		*8 14 51*	*69 15*	*84 01*	*14 46 E*		*7 46 E*
285	*8 21 20*		*8 10 11*	*73 35*	*84 51*	*11 16 E*		*4 16 E*
300	*8 16 40*		*8 05 31*	*77 50*	*85 31*	*7 41 E*		*0 41 E*
315	*8 12 00*		*8 00 51*	*80 30*	*86 11*	*5 41 E*		*1 19 W*
330	*8 07 20*		*7 56 11*	*83 10*	*86 58*	*3 48 E*		*3 12 W*
345	*8 02 40*		*7 51 31*	*84 10*	*87 36*	*3 26 E*		*3 34 W*

Column 3: Error of watch on local apparent time: .... To be added to watch time of observation. *11m 09s* To be subtracted from watch time of observation.

Column 8: (To be applied to Col. 7.)
Mean of *24* equidistant azimuths, Col. 5, = *83° 31′*
Mean of the corresponding azimuths of Col. 6, = *90 31*
Variation by observation + Constant A, = *7° 00′ E.*
Constant A (apply when found accurately), = ...
Variation by observation, = ...

Local apparent time by chron.	*h. m. s.*
Chron. No.............	*12 17 30*
C. C..................	+ *7 32*
G. m. t................	*12 25 02*
Eq. t..................	— *14 16*
G. ap. t. ⊙............	*12 10 46*
Long W................	*3 37 20*
Local ap. t............	*8 33 26*
Watch..................	*8 44 35*
Error of watch on l.a.t.	*11 09*

C

Location of compasses and—

Designation of compass.	Feet from bow.	Feet from keel.	Number and type of binnacle.	Flinders correctors. Description and location.
Standard No. *34761.*	*193*	*89*	*✕543 VI*	
Steering No. *34759.*	*193*	*80*	*✕551 VI*	
Battle No. *34765.*	*175*	*25*	*✕547 VI*	
Aux. Battle No. *34781.*	*459*	*24*	*✕530 VI*	

Approved:

....

U. S. Navy, Commanding.

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U. S. S.. Date of Commission,......................................

COMPARISON OF THE STEERING AND OTHER COMPASSES ON BOARD WITH THE STANDARD COMPASS.

B

10	11	12	13	14	15	16
Ship's head, magnetic.	Ship's head by steering compass No. *34759*.	Deviations of compass No. *34579*.	Ship's head By *Battle* Compass No. *34765*.	Deviations of compass No. *34765*.	Ship's head By *Aux. Battle* Compass No. *34781*.	Deviations of compass No. *34781*.
356° 55′	*3° 04′*	*6° 09′ W*	*9° 04′*	*12° 09′ W*	*354° 55′*	*2° 00′ E*
12 07	*11 04*	*1 03 E*	*23 44*	*11 37 W*	*358 37*	*13 30 E*
26 28	*22 14*	*4 14 E*	*41 14*	*14 46 W*	*2 28*	*24 00 E*
40 55	*32 04*	*8 51 E*	*58 34*	*17 39 W*	*7 55*	*33 00 E*
55 11	*42 44*	*12 27 E*	*72 34*	*17 23 W*	*15 11*	*40 00 E*
68 25	*57 14*	*11 11 E*	*88 04*	*19 39 W*	*25 15*	*43 10 E*
82 16	*74 34*	*7 42 E*	*102 04*	*19 48 W*	*40 56*	*41 20 E*
97 00	*91 54*	*5 06 E*	*115 10*	*18 10 W*	*70 10*	*26 50 E*
111 53	*113 49*	*1 56 W*	*128 46*	*16 53 W*	*127 53*	*16 00 W*
127 40	*131 04*	*3 24 W*	*140 34*	*12 54 W*	*148 30*	*20 50 W*
145 37	*146 54*	*1 17 W*	*151 58*	*6 21 W*	*164 57*	*19 20 W*
164 23	*164 24*	*0 01 W*	*164 47*	*0 24 W*	*173 33*	*9 10 W*
183 35	*177 04*	*6 31 E*	*176 04*	*7 31 E*	*179 35*	*4 00 E*
203 23	*192 24*	*10 59 E*	*188 58*	*14 25 E*	*192 58*	*10 25 E*
220 27	*207 41*	*12 46 E*	*200 06*	*20 21 E*	*208 27*	*12 00 E*
237 59	*227 04*	*10 55 E*	*213 04*	*24 55 E*	*232 03*	*5 56 E*
251 23	*246 55*	*4 28 E*	*224 43*	*26 40 E*	*259 14*	*7 51 W*
264 47	*270 04*	*5 17 W*	*239 12*	*25 35 E*	*292 17*	*27 30 W*
277 46	*290 04*	*12 18 W*	*254 04*	*23 42 E*	*311 34*	*33 48 W*
289 16	*308 43*	*19 27 W*	*270 34*	*18 42 E*	*322 28*	*33 12 W*
300 41	*321 49*	*21 08 W*	*289 57*	*10 44 E*	*331 49*	*31 08 W*
313 41	*333 04*	*19 23 W*	*310 34*	*3 07 E*	*339 56*	*26 15 W*
326 48	*345 44*	*18 56 W*	*329 57*	*2 09 W*	*345 48*	*19 00 W*
341 26	*352 24*	*10 58 W*	*348 24*	*6 58 W*	*350 13*	*8 47 W*

PARTICULARS OF COMPENSATION WHILE SWINGING FOR ABOVE DATA.

Horizontal Magnets.				Heeling Magnet.		*D* Correctors.	
Direction of Red Ends.		Number.	Distance Below Plane of Needles.	Name of Upper Pole.	Distance Below Plane of Needles.	Type and Size.	Distance from Compass Pivot.
B Correctors.	*C* Correctors.						
		All cor	*rectors remo*	*ved.*			

Respectfully,

....

U. S. Navy, Navigator.

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N. Nav. 9.

INVENTORY

of the U. S. S.. ....made

[or Navy Yard.]

(1) Number of Compass.	(2) Diameter of Card, Inches.	(3) Particular use: Standard; Steering; Tell-tale; Boat; Monitor; etc.	(4) Date on Card.	(5) Name of maker and place of manufacture	(6) How long has it been on board (or at the Navy Yard)?	(7) Where is it stored (or used) at present?	Sensibilit
							Read'g before After, when at Difference..
							Read'g before After, when at Difference..
							Read'g before After, when at Difference..
							Read'g before After, when at Difference..
							Read'g before After, when at Difference..
							Read'g before After, when at Difference..
							Read'g before After, when at Difference..
							Read'g before After, when at Difference..
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							Read'g before After, when at Difference..
							Read'g before After, when at Difference..
							Read'g before After, when at Difference..
							Read'g before After, when at Difference..
							Read'g before After, when at Difference..
							Read'g before After, when at Difference..

Forwarded:

....Com

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Place of observation, ...

THE COMPASSES

Longitude, ...

Latitude, ...

the..................................day of.., 191.....

		(9)			(10)	(11)	(12)
Right.	Left.	Time of Vibration.	Right.	Left.	Temp. of open air during test.	Earth's Hor. Mag. Force.	GENERAL CONDITION.
° ′	° ′		° ′	° ′	m. s.	m. s.	
....	....	Time of 0° first passing keel line	....	....			
....	....	Time of 0° sec'd pass'g keel line	....	....			
....	....	Difference=Time of vibration..	....	....			
....	....	Time of 0° first passing keel line	....	....			
....	....	Time of 0° sec'd pass'g keel line	....	....			
....	....	Difference=Time of vibration..	....	....			
....	....	Time of 0° first passing keel line	....	....			
....	....	Time of 0° sec'd pass'g keel line	....	....			
....	....	Difference=Time of vibration..	....	....			
....	....	Time of 0° first passing keel line	....	....			
....	....	Time of 0° sec'd pass'g keel line	....	....			
....	....	Difference=Time of vibration..	....	....			
....	....	Time of 0° first passing keel line	....	....			
....	....	Time of 0° sec'd pass'g keel line	....	....			
....	....	Difference=Time of vibration..	....	....			
....	....	Time of 0° first passing keel line	....	....			
....	....	Time of 0° sec'd pass'g keel line	....	....			
....	....	Difference=Time of vibration..	....	....			
....	....	Time of 0° first passing keel line	....	....			
....	....	Time of 0° sec'd pass'g keel line	....	....			
....	....	Difference=Time of vibration..	....	....			
....	....	Time of 0° first passing keel line	....	....			
....	....	Time of 0° sec'd pass'g keel line	....	....			
....	....	Difference=Time of vibration..	....	....			
....	....	Time of 0° first passing keel line	....	....			
....	....	Time of 0° sec'd pass'g keel line	....	....			
....	....	Difference=Time of vibration..	....	....			
....	....	Time of 0° first passing keel line	....	....			
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....	....	Time of 0° sec'd pass'g keel line	....	....			
....	....	Difference=Time of vibration..	....	....			
....	....	Time of 0° first passing keel line	....	....			
....	....	Time of 0° sec'd pass'g keel line	....	....			
....	....	Difference=Time of vibration..	....	....			
....	....	Time of 0° first passing keel line	....	....			
....	....	Time of 0° sec'd pass'g keel line	....	....			
....	....	Difference=Time of vibration..	....	....			
....	....	Time of 0° first passing keel line	....	....			
....	....	Time of 0° sec'd pass'g keel line	....	....			
....	....	Difference=Time of vibration..	....	....			
....	....	Time of 0° first passing keel line	....	....			
....	....	Time of 0° sec'd pass'g keel line	....	....			
....	....	Difference=Time of vibration..	....	....			
....	....	Time of 0° first passing keel line	....	....			
....	....	Time of 0° sec'd pass'g keel line	....	....			
....	....	Difference=Time of vibration..	....	....			

Respectfully,

...7.

...., *Navigator.*

INVENTORY OF INSTRUMENTS.

ARTICLE.	MAKER.	SERIAL NOS.	CONDITION.
Azimuth circles:			
Type III			
Other types for 7½-in. compasses			
Spare mirrors for azimuth circles			
Azimuth instrument for 6¾-in. compass			
Bars and pintles for 7½-in. compasses			
Tripods for 7½-in. compasses			
Binnacles, compensating:			
Type VII			
Type VI			
Older types for 7½-in. compasses			
Torpedo-boat standard			
Conning-tower with 5-in. compass			
Centering battens			
Compass readers			
Flinders bars			
Magnetic instruments:			
H. F. instrument, Heeling adjuster } In one case			
Magnetic instruments, old types			
Supporting tables for magnetic inst.			
Peloruses:			
Illuminated dial			
Old type			
Spare dials for ill. dial peloruses			

BUREAU OF NAVIGATION, NAVY DEPARTMENT, WASHINGTON.

This Inventory will be sent to the Bureau on June 30 of each year. In it is to be entered information relative to every compass and every instrument belonging to compass outfit, whether fit or unfit for use, and whether complete in all its parts or deficient in any of them; compasses of same size and type to be grouped together in the Inventory.

To obtain the data for columns (8) and (9) the compasses are to be moved out of the influence of magnetic masses, and each compass (while under trial) separated from all the others; compasses aboard ship must be taken ashore for these observations. The observations may be made in the following manner: To determine a suitable location, set up a compass and its azimuth circle on a tripod, and a staff about fifty yards distant from it; observe the bearing of the staff; interchange the positions of staff and compass, and observe again; repeat these observations on a line nearly transverse to the first one; then the direct and reverse bearings on each line should differ 180°; if not, select a place where such difference will be found.

For Sensibility: Set the keel line of the bowl at the 0° mark of the compass card, and, by means of a magnet or piece of iron, *gently* draw the card about 2° to the right, and observe with a magnifying glass the reading of the card when it returns to rest; then draw it to the left about 2° and observe as before. Set down all the readings, estimating them as closely as possible.

For Time of Vibration: Set the keel line at the 0° mark of the card; draw the card to the right *one* point; as it swings back, note the instant of 0° *first* passing the keel line, and again its *second* passage of that line (in the opposite direction). Repeat this observation, drawing the card *one* point to the left. Should the 0° mark of card stop short of the keel line when approaching the second transit, note the arc it is short of it.

It is essential that both needle and liquid be at absolute rest before each series of observations are begun.

For column (12) information is required as to air bubbles in the compass; liquid turbid; card tilted (dipping to one side); discoloration; keel lines indistinct; bowl leaky; balance of bowl on gimbals imperfect; motion not free—sticking when the ship rolls, a difficulty in fitting the binnacle, etc. Only *defects* need be noted, otherwise it will be taken for granted that the compass is in good condition.

The date on the card is the time that the compass was made, or (in case of repairs) when the essential parts—magnets, card, cap, pivot, liquid, etc.—were made entirely new. The following is the approximate time of one vibration of the compass card at the corresponding temperature (earth's horizontal magnetic force=4 f.g.s. units=.185 c.g.s. units; see H. O. Chart No. 1701, Horizontal Intensity of Earth's Magnetic Force):

Temperature	10°	20°	30°	40°	50°	60	70°	80°	90°	100°
7½-in. compass, time (seconds)	26	24	22	20	18	17	16	15	14	13
6¾-in. " " "	24	22	20	18	16	15	14	14	13	12
5-in. } 4-in. } " " "	17	16	15	13	12	11	10.5	10	9	8.5

VICTOR BLUE,
Chief of Bureau.

4—584

DEVIATION TABLES.

Form 12.

...., *191*

U. S. S..., *Attached to*..

Date of swinging ship for deviations given in following tables..

DEVIATIONS OBTAINED FROM NAPIER'S CURVES.

SHIP'S HEAD BY COMPASS.		STANDARD.	STEERING.	MANEUVER-ING.	BATTLE.	AUX. BATTLE.	TOP.	CHECK.	
NORTH.	0								
	15								
	30								
N. E.	45								
	60								
	75								
EAST.	90								
	105								
	120								
S. E.	135								
	150								
	165								
SOUTH.	180								
	195								
	210								
S. W.	225								
	240								
	255								
WEST.	270								
	285								
	300								
N. W.	315								
	330								
	345								

LOCATION OF COMPASSES AND PARTICULARS OF COMPENSATION WHILE SWINGING FOR ABOVE DATA.

Feet from bow								
Feet from keel								
Heeling magnet, Dist.								
Flinders bar No. or length								
B Magnets No.								
Distance								
C Magnets No.								
Distance								
D Balls, Dist.								
No. on card.								

ENTER BELOW THE REQUIRED INFORMATION FOR EACH DATE FOR SWINGING SHIP SINCE LAST REPORT, INCLUDING THAT ON WHICH THE ABOVE DEVIATION TABLES WERE OBTAINED.

DATE OF SWINGING SHIP.	LATITUDE.	LONGITUDE.	VARIATION OBTAINED.	VARIATION BY CHART.

.... *Captain.*

.... *Navigator.*

CHAPTER XI.

DESCRIPTION OF SERVICE INSTRUMENTS.

142. The instruments supplied to the modern vessels of the United States Navy in connection with compass work are as follows:

Binnacles:
- Type VI.
- Type VII.
- Torpedo-boat standard.
- Conning-tower.
- Boat.

Magnetic compasses:
- 7½-inch navy standard.
- 7½-inch illuminated card.
- 6¾-inch torpedo-boat.
- 5-inch conning-tower.
- 4-inch boat.

Azimuth circle, Type III.
Azimuth instrument.
Supporting table.
Centering batten.
Perolus, illuminated dial.
Horizontal force instrument.
Heeling adjuster.
Tripod.
Bar and pintle.
Compass reader.
Gyro-compass set, including master-compass, repeaters and accessories. (Chapter XII.)

COMPENSATING BINNACLE, TYPE VI.

143. The binnacle of this type (Fig. 49) is arranged for the compensation of the deviations of the compass by the use of fore-and-aft and athwartship magnets for the correction of the semicircular deviation, soft iron spheres for the correction of the quadrantal deviation, and a magnet placed vertically under the compass for the compensation of the heeling error. Binnacles of this type may also be fitted with a Flinders bar for correction of that part of the semicircular deviation due to vertical induction in vertical soft iron. This binnacle carries the U. S. Navy standard 7½-inch compass.

144. General Description.—The complete binnacle includes the stand; the hood; the central tube for heeling magnet; the fore-and-aft and athwartship magnet trays and the mechanism for operating them; the Flinders bar holder, if fitted; and the correctors, including 9-inch and 7-inch soft-iron spheres, semicircular corrector magnets, heeling magnet, and the Flinders bar.

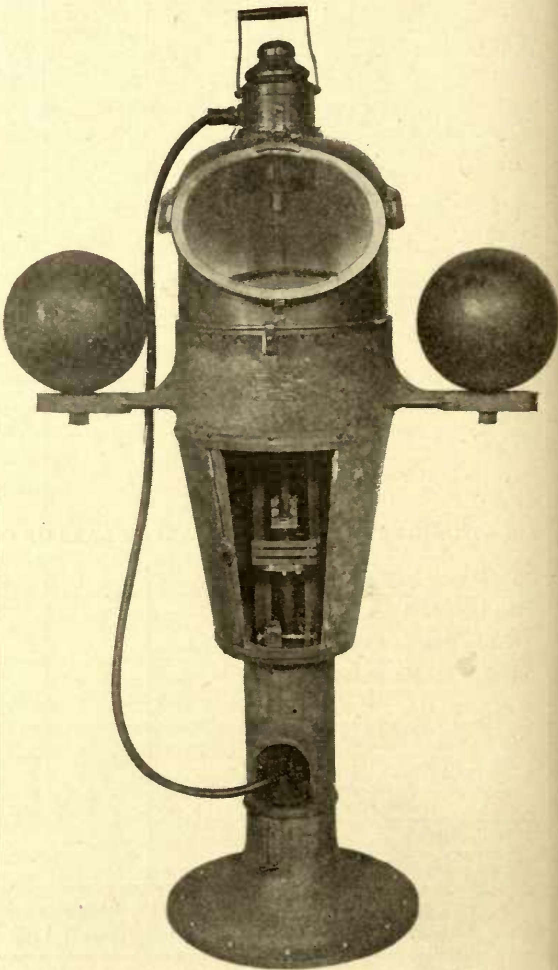

Fig. 49.

145. Binnacle Stand.—This is a single casting of composition, including the base, the ped-

estal, magnet chamber, compass chamber, and the graduated arms for the quadrantal correctors.

146. Magnet Chamber.—This is a conical-shaped receptacle between the compass chamber and the top of the cylindrical column which forms the pedestal. It is provided with a door to give access to the mechanism within, the door sliding laterally around the chamber.

147. Hood.—The hood is of brass and has a hinged glass window in front and a sliding door in the back. In those of recent design, the glass window is given a wide flare laterally, to provide as large an opening as possible for the convenience of the helmsman. The latest hoods are fitted with sight vanes for taking approximate compass bearings. Handles designed to lower when not in use are fitted for lifting the hood on and off. Either kerosene-oil or electric illumination may be used, the lamp fitting in a holder in the top of the hood, and the light being reflected onto the compass card by the prism which illuminates 15° on each side of the lubber's line.

148. Compass Chamber.—This is a cylindrical chamber in the top of the binnacle stand in which the compass is suspended in its gimbal ring. The knife-edges of the latter rest in wyes secured to the inner walls of the chamber, and are set at right angles to the fore-and-aft line of the binnacle. Conical-shaped screws for adjusting the compass accurately in the center of the binnacle pass through the walls of the chamber and take against the faces of the knife-edges of the gimbal ring. Fore-and-aft and athwartship lines are traced on the upper edge of the compass chamber to facilitate placing the binnacle on board ship, in an exact fore-and-aft line.

149. Semicircular Corrector Magnets, Carriers and Mechanism.—The correcting magnets are cylindrical in shape, and consist of bundles of steel wires, magnetized and enclosed in brass cases, open at each end. They are held in horizontal tubes mounted on two carrier trays which can be raised or lowered independently of each other. Each tray has a group of three tubes on each side of the vertical axis making six in all. The magnets are held in their tubes by a spring closing device.

The carrier trays, raised and lowered by means of a screw moved by beveled gears, may be set at any desired distance below the plane of the compass needles, from 7 inches to 21 inches. Vertical scales graduated to tenths of an inch indicate the distance of each tray below the plane of the compass needles.

The athwartship magnet carrier tray, which is fitted to turn in azimuth, is graduated in degrees towards the right on the outside vertical circumference, from 0° to 360°, every fifth degree being accentuated, and every tenth degree marked by figures. The 90° mark and the 270° mark are on the diameter at right angles to the magnet tubes, and the index for this tray is in the fore-and-aft line. The locking screw underneath the tray should be securely set up when the tray has been set at the desired angle.

150. Tube for Heeling Corrector.—Centrally in the vertical axis of the binnacle there is a hollow brass tube occupying the entire depth of the binnacle from the bottom of the compass chamber to the bottom of the binnacle. By removing the compass, the heeling corrector, a cylindrical magnet with a hook in each end, may be lowered by means of a chain attached to one end, and held at the proper height in the tube by the chain which passes over a roller at the top of the tube and secures to a cleat or a drum in the magnet chamber. In binnacles of recent design the central tube is slotted, so that the heeling magnet is visible through the magnet chamber and the distance of the top of the magnet below the compass needles may be read off from the scale on the outside of the tube. When the top of the magnet goes out of sight below the bottom of the magnet chamber, a silver link in the chain will be visible near the top of the chamber and may be used for recording any lower positions of the magnet.

151. Quadrantal Correctors—These are spheres made of pure soft cast iron free from retained magnetism, secured by screw bolts to slotted supporting arms at each side of the binnacle. The centers of the spheres are in the same horizontal plane as the compass needles, and in the athwartship line passing through the center of the compass. The length of the slots in the supporting arms is such as to allow the

spheres to travel from 11 inches to 15 inches from the axis of the binnacle, a scale graduated to inches and quarter-inches being cut on the arms. The latest binnacles of this type are fitted with screw mechanism for operating the quadrantal spheres, by means of a sliding block which is a snug fit in the slot and is slightly less in depth than the arm, to permit the securing nut to clamp the sphere. This block is moved by a long threaded bolt with bearings in the arm, and is secured by means of a set-screw.

152. Flinders Bar and Holder.—The holder consists of a water-tight inner and outer cylindrical brass casing with screw tops, the outer casing supported by strong brackets securely fastened to the forward side of the binnacle in the exact fore-and-aft line. The inner case is removable and is fitted with a rubber pad in the bottom. The top of the holder is about two inches above the plane of the compass needles, and the distance from the center of the compass to the center of the holder is nine inches.

The Flinders bars are made of pure soft iron carefully annealed. The diameter of the bar is 2 inches. The total length of the bar, 24 inches, is cut into the following lengths, viz.: one length of 12 inches, one length of 6 inches, one length of 3 inches, one length of 1½ inches, and two lengths of ¾ inch each. Hardwood blocks of the same dimensions as the lengths of soft iron are supplied with each Flinders bar, both the soft-iron rods and the wooden blocks fitting in a transporting case with felt bearings.

153. Binnacle Base.—There are twelve equally spaced holes in the base, two of which are in the fore-and-aft line. Accurate fore-and-aft marks are scored on the forward and after edge of the base, in addition to those on the rim of the bowl.

COMPENSATING BINNACLE, TYPE VII.

154. The binnacle of this type is designed for use with the U. S. Navy 7½-inch illuminated card compass, and differs from the Type VI binnacle only in so far as is necessary to provide for the illumination of the compass card from below. The hood is exactly the same as in the Type VI binnacle; so that, if necessary, the same method of illumination may be used. The U. S. Navy standard 7½-inch compass may be used in this binnacle, if desired.

The illumination of the compass card from below is provided by an incandescent lamp carried in a small chamber in the center of the binnacle which projects into the upper part of the magnet chamber and into the lower part of the compass chamber, and is entered from the magnet chamber. The illumination is regulated by means of a shutter above the light, which is operated from the outside of the binnacle by a lever. This shutter permits of the illumination of the compass card only in the vicinity of the lubber's line, for steering, or a general uniform illumination of the whole card for taking bearings.

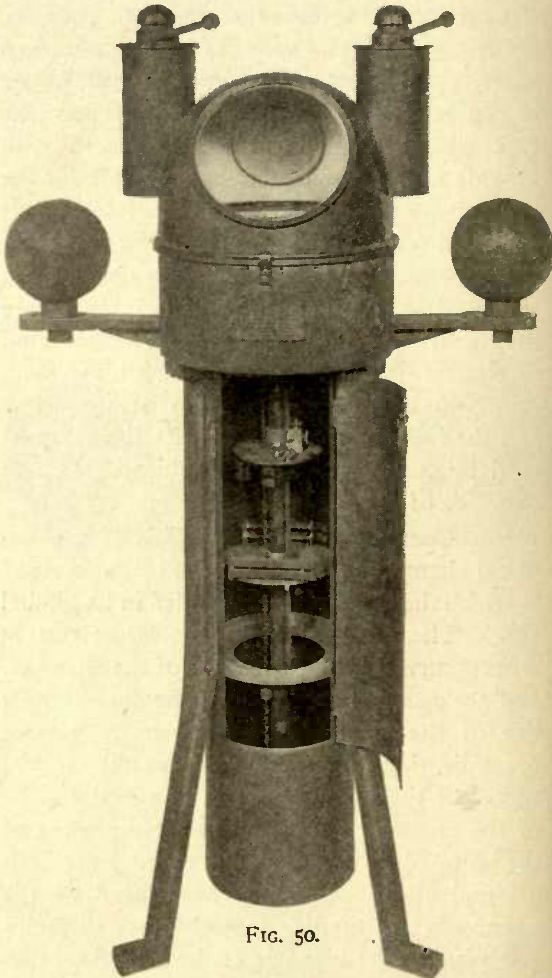

Fig. 50.

COMPENSATING BINNACLE, TORPEDO-BOAT STANDARD.

155. The binnacle of this type (Fig. 50) carries the U. S. Navy 6¾-inch compass, and is supplied to torpedo-boats and submarines. The method of compensation is the same as in the

Type VI binnacle, except that no Flinders bar is provided.

156. General Description.—The complete binnacle includes the compass chamber, the magnet chamber, the legs, the hood, the central tube for heeling magnet, the fore-and-aft and athwartship magnet trays and the mechanism for operating them, and the correctors, including 5-inch or 6-inch soft cast-iron spheres, semicircular corrector magnets, and heeling magnet.

The compass chamber is supported on three gun-metal legs, and is in one casting with the athwartship arms for the quadrantal correctors. Within the three supporting legs is a cylindrical brass tube which forms the magnet chamber. The mechanism for the semicircular corrector magnets consists of two magnet carriers sliding upon a central tube. In this tube hangs the heeling magnet, which is raised or lowered by a chain clamped inside the magnet chamber. The two carriers hold four magnets each, and may be fastened at any height by racks and side clamps. The upper tray is generally used for the fore-and-aft magnets, and the lower for the athwartship magnets. Each tray is so arranged that it may be rotated horizontally about the central tube, and may be secured with the tubes either fore-and-aft or athwartship as desired. The magnet chamber is closed by a long door with locks at top and bottom. The hood has a glass window in the after side, and a hinged door in the forward side. Two oil lamps fitting in holders, one on each side of the hood, provide illumination for the compass card.

CONNING-TOWER BINNACLE.

157. The conning-tower binnacle (Fig. 51) is a compensating binnacle of small dimensions, and is used in the conning-towers of torpedo-boats, where only a small space is available.

The compensation of the semicircular deviation is effected by the use of rectangular magnets inserted in small tubes on the sides of the binnacle. To effect the correction of small deviations and make the final adjustment, it is necessary to break the bundle of wires of which the semicircular magnets are composed, and use a few wires in place of the brass-encased tube.

The quadrantal correctors consist of soft cast-iron spheres, threaded to screw on a projection from the side of the binnacle, and are fitted with lock-nuts to prevent disarrangement. A 5-inch compass graduated to quarter-points is used. This compass and binnacle were originally designed for use in the conning-towers of large vessels, but experience demonstrated that the directive force was too small for the satisfactory working of the compass.

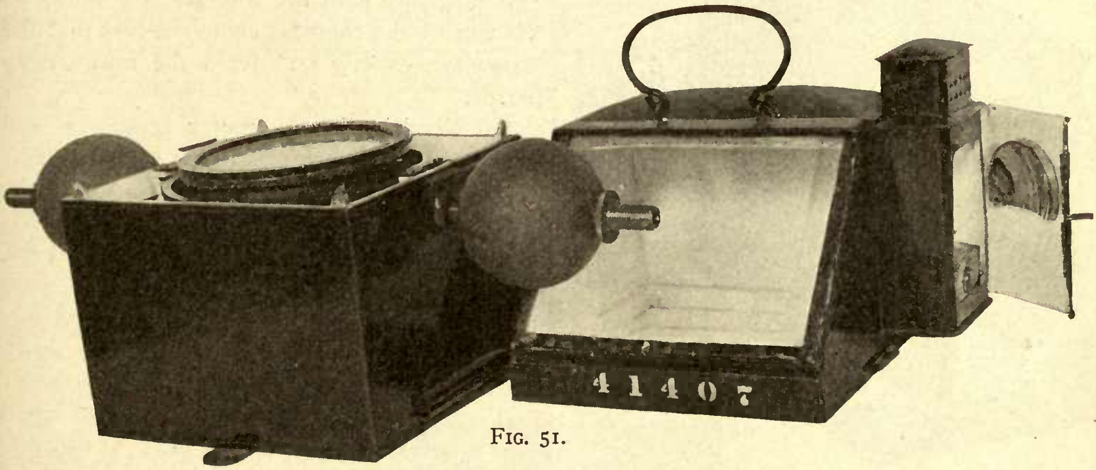

FIG. 51.

BOAT BINNACLE.

158. The navy standard boat binnacle (Fig. 52) is fitted for the use of the 4-inch boat compass, and is of the general form of the conning-tower binnacle, except that it is smaller and not fitted for compensation.

TESTS FOR BINNACLES.

159. Before acceptance, U. S. Navy compensating binnacles are tested as follows:

(a) The binnacle having been leveled by means of a spirit level, and the heeling magnet

inserted and lowered to the bottom of the tube, either pole up, put the compass in place and center it accurately by means of the side screws. Turn the binnacle until it heads North by compass. Raise the heeling magnet slowly until it reaches its upper limit; no deflection of the compass card should occur. If deflection is shown, the compass may not be exactly centered, which may be corrected by the side screws. If deflection continues to be shown, the heeling tube is either not central or not vertical.

(b) With the binnacle heading North by compass, move the fore-and-aft magnet tray to its upper limit. Enter four magnets in the

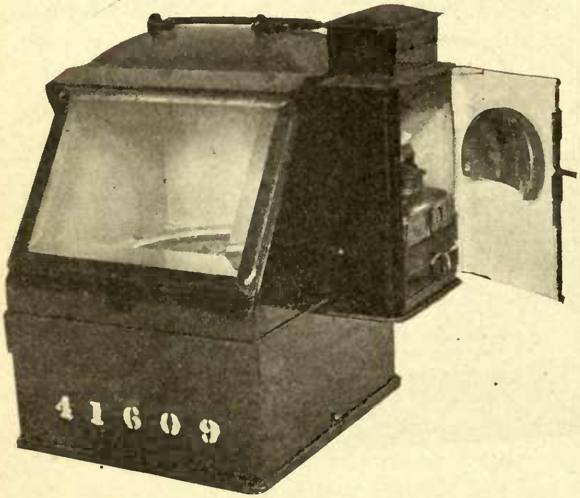

FIG. 52.

tubes, blue ends forward. Move the tray to its lower limit. No deflection of the compass card should occur, otherwise the magnet tray is not accurately placed in the fore-and-aft plane.

(c) With the binnacle heading East by compass, move the athwartship magnet tray to its upper limit. Enter four magnets in this tray, blue ends to port. Clamp tray at 90° mark of scale and move to its lower limit. No deflection should be produced; otherwise the athwartship tray is inaccurately placed. Repeat this test with the tray clamped at the 270° mark of scale, reversing the correctors in the carriers.

(d) With the binnacle heading North by compass and all correctors removed, put the spheres on the arms and move them as close in towards the compass pivot as possible. Next turn one sphere at a time successively through 90° on its own axis until it has been completely rotated, noting after each turn of 90° if any deflection of the compass from the lubber's line has been produced. Should a deflection of more than 0° 30′ for 9-inch spheres, or more than 0° 15′ for 7-inch spheres, be apparent during the rotation of any sphere, that sphere is polarized beyond the acceptance limit and must be re-annealed. Within the limits mentioned, the spheres are accepted.

(e) By means of straight-edge and plumb-bob, see that the center lines of the slots for quadrantal spheres line up with the athwartship marks traced on the upper edge of the compass chamber; also that the fore-and-aft lines on the base of the binnacle are in the same vertical plane with the fore-and-aft marks on the rim of the compass chamber, and that the latter are exactly 90° from the athwartship marks.

(f) Semicircular corrector magnets and heeling magnets are tested for strength individually by observing the deflection produced on the needle of a horizontal-force instrument at a standard distance for each class of magnet.

(g) With binnacle heading East by compass and all correctors removed, put the Flinders bar in the holder and note the deflection produced. Reverse the Flinders bar in the holder and note the difference between the deflection now produced and the former one. If this difference is greater than 2°, the bar should be re-annealed.

The tests described above for polarity of spheres and Flinders bars should be made from time to time on board ship, as opportunity offers, preferably when the vessel is alongside a dock.

To re-anneal a quadrantal sphere or a Flinders bar, heat to a dark heat only; then cover with ashes and allow to cool slowly. Magnetism picked up by a Flinders bar may be removed or much reduced by holding the bar in a direction at right angles to the magnetic lines of force—East and West magnetic—and hammering it with a piece of wood.

MAGNETIC COMPASSES.

160. All magnetic compasses used in the navy are of the liquid type. Liquid compasses were first developed in this country, and came

into general use many years before they were adopted abroad. After many years of trial, liquid compasses have been found to be better adapted for naval use than the dry card compass, and are now generally used throughout the world on naval vessels and are being gradually adopted by the merchant marine.

The great advantage of their use is the greater steadiness of the card when subjected to the shock of gun-fire, and the greater steadiness in a sea-way. The liquid compass allows the use of more powerful magnets, and therefore greater directive force and sensibility.

The disadvantages claimed are, that with the more powerful magnets required for liquid compasses, compensation is more difficult, due to the induction caused by the magnets in the soft-iron correctors. The principal effect of this induction is, to cause the compensation for quadrantal deviation to change with change of the earth's horizontal force. This condition is found to exist with the navy standard 7½-inch compass, with its long needles.

The navy standard compasses for ship's use are graduated from 0° to 360°, but the quarter-point and cardinal-point graduations are retained for use in piloting, where it is convenient to keep the sense of direction easily.

161. 7½-inch Navy Standard Compass.—The 7½-inch compass with card of tinned brass is the one in general use; it is a liquid 4-needle compass with card 7½ inches in diameter.

The card is of the curved annular type and is made of tinned brass, convex on the upper and inner side, and graduated to read to quarter-points and half-degrees from 0° to 360°, with degree figures every five degrees.

In the center of the card is a spheroidal air-vessel to buoy the weight of the card and magnets, allowing a pressure of between 60 and 90 grains on the pivot at a temperature of 60° F. The air-vessel is provided with a conical opening on the under side, in which is a pivoted cap containing a sapphire, to form the bearing of the card on the pivot.

The magnets consist of four cylindrical bundles of highly magnetized steel wires contained in sealed cylindrical cases, the magnets placed parallel to the North and South line of the card Two magnets are 5¼ inches long, the ends on the chords (30° apart) of a circle passing through their extremities; two magnets are 4⅝ inches long, the ends on the chords (about 90° apart) of a circle passing through their extremities. The weight of the card complete is about 3060 grains. The plane of the needles is ¾ inch below top of pivot.

The card is mounted in a cast-bronze bowl weighted with lead at the bottom. A pivot is fastened to the bottom of the chamber, made of bell-metal and moderately sharp. This pivot is fitted with adjusting screws, so that the card can be accurately centered.

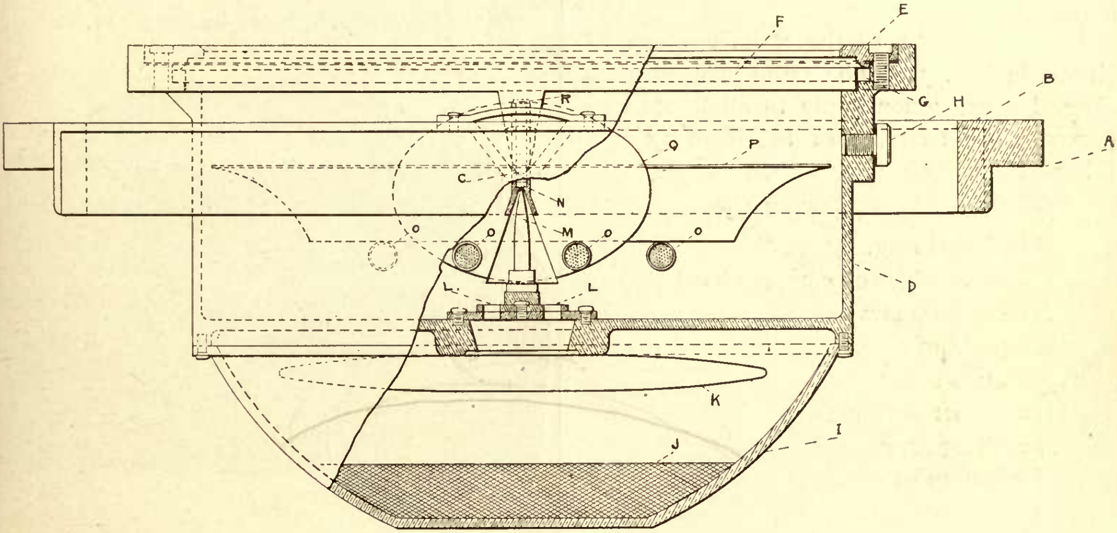

FIG. 53.

The bowl is entirely filled with liquid, 45 per cent alcohol and 55 per cent distilled water.

Beneath the bowl is a self-adjusting expansion chamber of elastic metal, arranged with two small holes to permit circulation of the liquid between the bowl and expansion chamber. This expansion chamber is so designed that upon change of temperature the expansion of the bowl is counteracted by the expansion of the chamber, thus keeping the bowl free from bubbles. The inner surface of the bowl is painted white with a paint insoluble in the liquid. Two lubber's lines are drawn on enameled plates inside the bowl.

The bowl and compass card are accurately balanced with lead weights.

The construction of the 7½-inch compass is shown in Fig. 53. The same principles and general construction apply to all liquid compasses. The lettering of the drawing is as follows:

A = knife-edges on gimbal ring.
B = gimbal ring.
C = knife-edges on compass bowl.
D = compass bowl.
E = packing ring.
F = glass cover.
G = rubber packing.
H = filling screw.
I = bottom of compass bowl.
J = lead weight.
K = expansion chamber.
L = communicating holes between bowl and expansion chamber.
M = pivot.
N = sapphire cap.
O = magnets or compass needles.
P = tinned brass card.
Q = air-vessel.
R = centering screw.

The marking of the 7½-inch navy standard compass card may be seen in Fig. 54, which shows the compass, with gimbal ring, in its transporting box. Compasses of this type manufactured hereafter will have a card marked as shown in Fig. 55. The card is here marked to degrees instead of to half-degrees; the degree figures are larger and are marked at every ten degrees instead of every five degrees, and only the eight principal points are lettered.

162. 7½-inch Illuminated Card Compass.—This compass is adapted for use in the Type VII binnacle, being constructed with a glass bottom and a flat card made of mica, in order to permit of illumination from below. It differs from the 7½-inch navy standard compass in the following particulars, the general characteristics being the same as for that compass:

(1) The expansion chamber is of the annular type, attached to the bowl.

(2) The pivot is fastened to a narrow crossbar placed 90° from the lubber's line and as close to the bottom glass as possible.

(3) The compass bowl has a glass bottom and is therefore balanced with lead weights at the sides of the bowl instead of at the bottom.

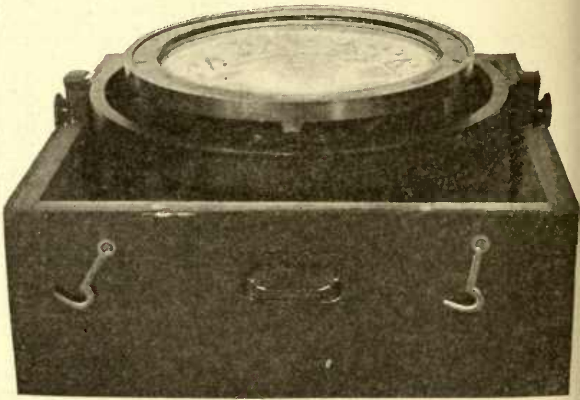

FIG. 54.

(4) The compass card is flat and is made of the best grade of mica.

The card for this compass is marked as is shown in Fig. 55.

163. 6¾-inch Torpedo-boat Compass.—The navy standard 6¾-inch compass is of the same general characteristics as the 7½-inch compass. The bowl is of the same construction, but smaller. The card is 6¾ inches in diameter, is made of mica, and is of the flat type as distinguished from the curved annular type of the larger compass. The card is mounted on a very light skeleton frame attached to the magnets, which in turn are attached to the air-vessel. The sapphire and pivot are of the same general construction as in the 7½-inch compass.

The magnets are four in number and comprise two of $4\frac{3}{4}$ inches in length and two of 4 inches in length. These magnets are made up of small wires enclosed in tinned air-tight chambers.

These compasses are graduated in degrees from 0° to 360°, and are also marked with quarter-points. This compass is adapted for use on torpedo-vessels and submarines using the torpedo-boat standard binnacle.

Owing to the increased size of the later torpedo-vessels, they are provided with Type VI or Type VII binnacles and $7\frac{1}{2}$-inch compasses.

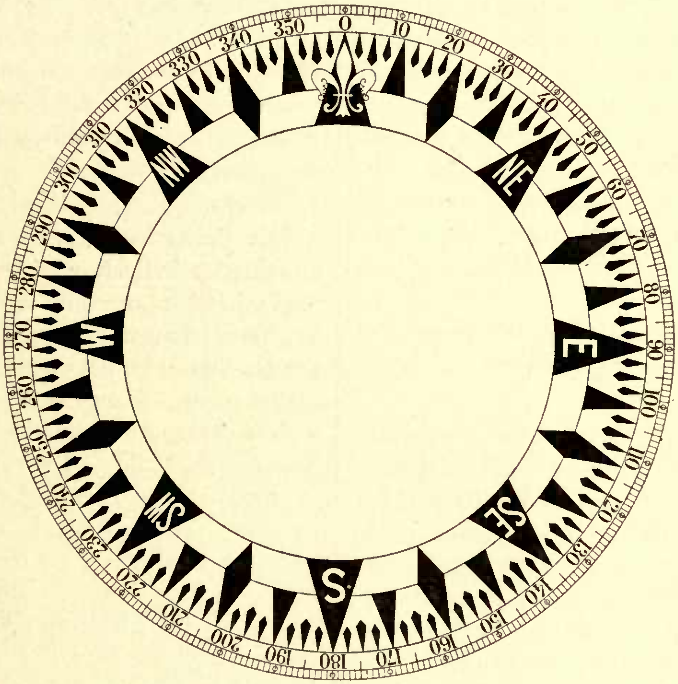

FIG. 55.

164. 5-inch Conning-tower Compass.—The navy standard 5-inch conning-tower compass (Fig. 51) is adapted for use in the conning-tower binnacle.

It possesses the same general characteristics, in regard to bowl, pivot, sapphire, air-vessel, and expansion chamber, as the $7\frac{1}{2}$-inch compass.

The card is of mica, 5 inches in diameter, graduated to quarter-points, and is of the flat type.

The magnets are six in number, two of $3\frac{13}{16}$ inches, two of $3\frac{1}{4}$ inches, and two of $2\frac{3}{16}$ inches.

This compass is adapted for use in the conning-towers of torpedo-vessels. On board larger vessels the conning-tower compass is being replaced by compasses below decks, or by the gyro-compass.

165. 4-inch Boat Compass.—This compass is adapted for use in the boat binnacle. It is of the curved annular type, with the card of tinned brass, 4 inches in diameter. (Fig. 52.)

It possesses the same general characteristics, in regard to bowl, pivot, sapphire, air-vessel, and expansion chamber, as the $7\frac{1}{2}$-inch compass.

The magnets are two in number, $3\frac{1}{16}$ inches in length.

166. Submarine Compasses.—The submarine compasses are generally of special design. furnished under contract by the builders of the vessels. The compasses are required to conform to Navy Department standards where applicable, and are subjected to the same tests before acceptance as are other compasses for naval use.

Submarines are also supplied with a torpedo-boat standard binnacle carrying a $6\frac{3}{4}$-inch compass for surface work. This is readily unshipped when preparing to submerge.

167. Testing Compasses.—The strength of the individual magnets is tested by observing

the deviation produced on a horizontal force instrument at a standard distance for each length of needle.

The card is weighed before assembly, and afterward the pressure of the card on the pivot in the standard liquid is determined.

After assembly the compass is tested for magnetic moment, sensibility, steadiness, centering, balance, and accuracy of zero point.

168. Accuracy of Zero Point.—In a magnetic system composed of four magnets the individual magnets must be so assembled that the resultant of their directive force causes the North point of the card to point to magnetic North. If the magnets are not parallel or the strength of the magnetism is not balanced, the card will not point to magnetic North.

To test this indication all compasses are compared to a standard consisting of a single powerful magnet accurately centered and balanced, the zero marks of this magnet having been established by long continued and accurate magnetic observations.

Any $7\frac{1}{2}$-inch compass that shows an error of over 10′ in its indication of magnetic North is rejected.

169. Magnetic Moment.—This test, which must be made in a place free from local magnetic influence, consists in drawing the card 11° to one side by means of a magnet and noting with a stop watch the time of the North point first passing the lubber's line, and then the second time, which will be in the opposite direction The time of vibration thus obtained should agree approximately with the following table arranged for temperatures:

Temperature (Fahr.)	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°
$7\frac{1}{2}$-inch, time (sec.)	26	24	22	20	18	17	16	15	14	13
$6\frac{3}{4}$-inch, time (sec.)	24	22	20	18	16	15	14	14	13	12
5-inch, time (sec.) / 4-inch, time (sec.)	17	16	15	13	12	11	10	10	9	8

If the compass does not complete the second passage of the lubber's line, it should be rejected or surveyed; for the indications are that the jewel is cracked, the pivot blunted, or the magnets weak. In making this test, the compass should be kept in a temperature corresponding to the temperature at the time of test; for it takes an hour or more for the liquid to take up the temperature of the air or of a room.

This is an important test to make and should be made by the navigator annually, as required by general orders, and oftener if he has reason to suspect his compass of being sluggish.

In the above table the earth's horizontal magnetic force is assumed to be .185 c. g. s. units (see Hydrographic Office chart, No. 1701, giving horizontal intensity of earth's magnetic force). If observations are made where the earth's horizontal magnetic force is less than above, as in high magnetic latitudes, the time of vibration should be greater; and if made where it is greater, as in low magnetic latitudes, the time of vibration should be less.

170. Sensibility.—The inspection test for sensibility consists in drawing the compass card 1° aside by means of a magnet and then observing, through a telescope with cross-wires, whether the card returns to the same point. An error of over 10′ is sufficient to cause rejection.

171. Centering.—For the compass to give an accurate indication of the movement of the ship's head as the ship turns in azimuth, the graduations must be accurate and the center of the graduations must correspond with the center of the pivot. The graduations are made from a plate carefully tested before manufacture, so that the possibility of error in this respect is very small; but an error of centering may readily exist. This is tested by adjusting the cross-wires of a telescope on the North and South points of the compass; then, with a magnet resting on the glass top or attached to an azimuth circle, the card is turned through 180°. If the centering is out on the North and South line, the North and South marks will not be both on the cross-wires; but with one on, the other will be off a distance twice as great as the error of centering. Similarly, the East and West points are tested.

As North and South lubber's points are marked on all navy compass bowls, this test may be made by setting up the bowl with the North and South points on the lubber's points; then with magnets swing the card through 180°, bringing the South point to the North lubber's point. Any error in centering will appear by the North point not being on the South lubber's point. Similarly, the test may be made for East and West.

172. Balance.—The compass is balanced at the point of manufacture by a small piece of lead soldered to the card to counteract the dip. With a change of dip this balance becomes inaccurate, the error so produced depending on the distance the center of gravity of the card is below the point of suspension. In ordinary cruising latitudes the error produced is negligible, because with the navy compasses the center of buoyancy is slightly below the center of suspension, and the center of gravity is far below both—about three-quarters of an inch. This means that there is a great tendency (a mechanical moment) of the card itself to keep level.

The compass bowl is tested for balance after the compass is assembled, using a spirit level. The position of the center of gravity of the bowl is made to be far below the gimbals by the addition of the lead weight in the false bottom. To allow the compass bowl to move freely in its gimbals, it is necessary that the knife-edges be kept clean and that the centering screws used to center the compass in the binnacle be not set up too tight. If the compass fails to maintain its level position, the indications of the compass become unreliable.

173. Steadiness.—The test for steadiness consists in subjecting the compass to an exaggerated motion and noting the oscillation of the card. A liquid compass is greatly superior to a dry compass in this respect, and a small card to a large one. No trouble has been experienced in this regard with the standard 7½-inch compass.

174. To Expel an Air-bubble from Liquid Compass.—Remove the false bottom of the compass bowl, exposing to view the expansion chamber. Place the bowl on its edge with the filling hole up. Bring the bubble immediately underneath the filling hole. Press the expansion chamber, keeping up a slight pressure; gradually loosen the filling screw, letting the air escape around the threads of the screw, also a little of the liquid. Set up the screw tight and remove the pressure from the expansion chamber. If the bubble has not entirely disappeared, remove the filling screw and pour in a mixture of 45 per cent pure alcohol and 55 per cent distilled water. Then put in the filling screw and set up gradually to a full due.

If a large amount of the liquid is allowed to escape and is then replaced with water instead of the standard mixture, the specific gravity of the liquid may be raised to such an extent that the compass card will float instead of maintaining a slight pressure on the pivot. Instances have been reported where the loss of liquid has been made up with water to such an extent that the liquid froze during cold weather and burst the glass of the bowl. If distilled water is not used, the impure water will discolor the paint on the inside. The standard mixture of alcohol and water will withstand all temperatures exceeding −10° F. As the temperature decreases, the density of the liquid increases, presenting greater resistance to the movement of the compass card in the liquid and causing the compass to become sluggish, and finally inactive if the temperature decreases sufficiently.

Should the compass become inactive during cold weather, the only recourse is to remove it from the binnacle and warm it up in a hot room or over a steam-pipe.

AZIMUTH CIRCLE, TYPE III.

175. This instrument (Fig. 56) consists of a composition ring turned true to fit over the compass bowl. The inside of the ring is fitted with three raised points, 120° apart. One is in the form of a compression spring. They are intended to reduce friction when the ring is revolved. It is provided with two sets of prisms, vanes, and mirrors for taking observations, fixed at the extremities of two diameters at right angles to each other. The first set, intended for observations of the sun alone, is composed of a curved mirror hinged to move around a horizontal axis and facing a prism, the latter completely inclosed in a brass case. A narrow slit is in the casing opposite the mirror.

The sun's rays reflected by the mirror upon the slit in the casing of the prism appear as a thin pencil of light on the card circle of the compass. A level on the rim assists in adjusting the circle into position.

The second set is intended for direct bearings of distant objects, or of a reflected bearing of the sun when partially obscured, and con-

sists of a plain black mirror, sight vanes, and prism.

The vanes sight directly upon the object, the mirror reflects the image of the sun directly to the eye, and the prism reflects the card circle and vane thread to the eye.

176. Tests for Azimuth Circle.—Before acceptance the azimuth circles are carefully tested at the manufacturer's works, but it has been found, in service, that through accident the vanes or mirrors are liable to be bent and the indication incorrect, the error in some cases amounting to as much as 4°.

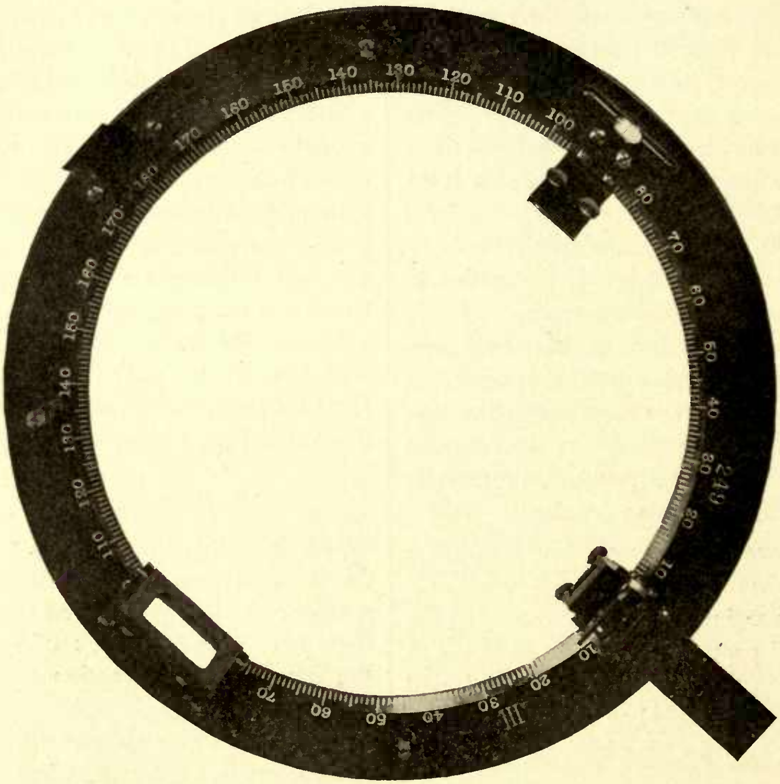

FIG. 56.

With the facilities at hand on board ship, it is very difficult to determine the exact cause of error.

It is recommended that when the ship is at the navy yard or when facilities for shore observations are available, the azimuth circles and the spare compass be taken ashore, the compass carefully leveled and observations of the sun taken as follows: When the sun is low, take the direct bearing of the sun with the direct vanes, protecting the eye with a piece of colored glass; then, using the curved mirror, take the bearing of the sun. If the two bearings agree, it may safely be assumed that the instrument is in adjustment. When the sun is higher, the bearings of the sun, using the black mirror and the curved mirror, should again be compared, protecting the eye as before with a piece of colored glass. If the observations taken do not agree, the instrument should be surveyed and replaced at the first opportunity, as without a special outfit it is very difficult to locate the error and correct it.

AZIMUTH INSTRUMENT.

177. The azimuth instrument (Fig. 57) is used with the $6\frac{3}{4}$-inch torpedo-boat compass. It contains the same features as the Type III azimuth circle, with the exception that the eye-vanes are combined with the curved mirror arrangement and mounted on a bar centering in a hole in the glass top of the compass instead of on a ring.

SUPPORTING TABLE FOR TYPE VI BINNACLE.

178. To facilitate the taking of magnetic observations in the compass chamber of the binnacle, a supporting table is supplied which is adapted for holding either the horizontal force instrument or the heeling adjuster. It consists of a circular brass table attached to a column fitting in the heeling magnet tube of the binnacle. A clamp is fitted to the column, that prevents the column from projecting into the tube too great a distance. In the later models the table is fitted with a screw travelling in a thread in the column, thus allowing the top of the table to be adjusted to the correct height.

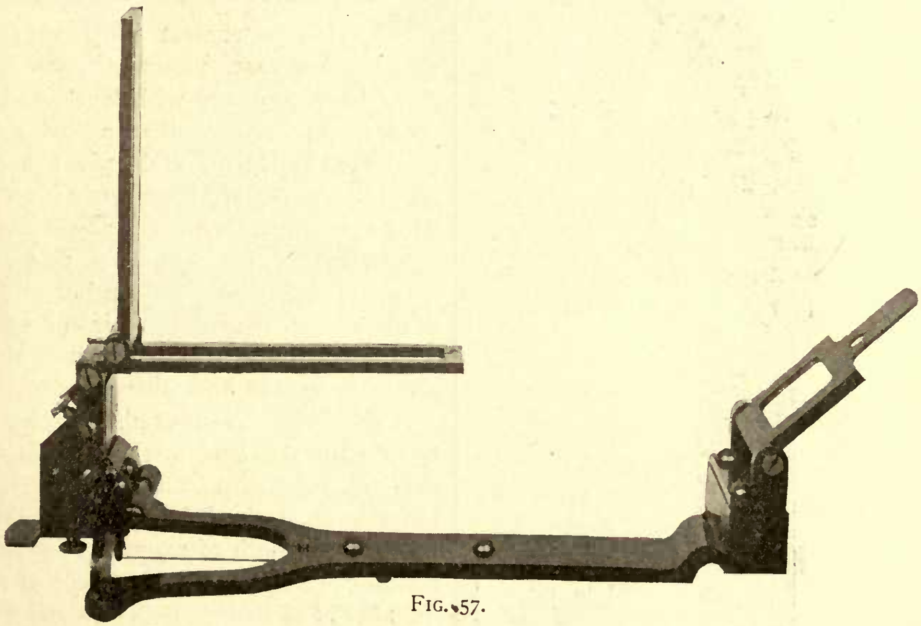

FIG. 57.

SUPPORTING TABLE FOR TYPE VII BINNACLE.

179. A special supporting table is needed for this type of binnacle owing to the fact that the heeling magnet tube does not extend up to the bottom of the compass chamber as it does in the Type VI binnacle. The supporting table is therefore made with three legs, which rest on the bottom of the compass chamber and hold the circular brass plate at the proper height. It is suitable for use with the Type VI binnacle also.

CENTERING BATTEN.

180. For use in centering and adjusting the height of the horizontal force instrument in the binnacle, a centering batten of hard wood is provided. This batten rests in the Y's of the binnacle and has a projection in its center extending $\frac{3}{4}$ inch below the bottom of the Y's. The bottom of this projection indicates the position of the center of the needles of the $7\frac{1}{2}$-inch compass.

ILLUMINATED DIAL PELORUS.

181. For taking bearings when the line of sight from the compass is cut out by the smoke-stacks, stanchions, and other obstructions, the illuminated dial pelorus (Fig. 58) is provided—usually one on each end of the bridge.

The pelorus standard is composed of the pelorus bowl, supporting column, and base. In the pelorus bowl is mounted the pelorus card of clear plate glass, 9 inches in diameter, graduated in degrees and quarter-points, the degree graduation conforming to the compass card, running from 0° to 360°.

The pelorus card is so fitted that it may be revolved and clamped in position, so that the reading corresponds to the ship's head by compass; or it may be set to the true or magnetic heading of the ship. In the supporting column is placed an electric light, which illuminates the dial at night. To provide access to the light, the column is fitted with a door, which is also convenient to use at night as a lantern for writing down the observed bearings.

For taking bearings, the pelorus is provided with an alidade mounting two vanes, which is capable of revolution about the center of the card; for taking bow and beam bearings and similar observations, the alidade may be clamped independently of the clamping of the card. For taking bearings of the sun, the alidade is provided with a black reflecting mirror attached to the far vane; the near or eye vane

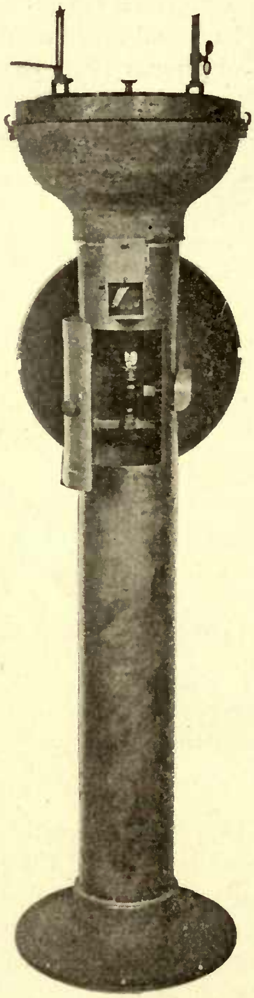

FIG. 58.

is provided with a slide of adjustable colored shades, to protect the eyes of the observer.

182. Telescopic Attachment.—The latest illuminated dial peloruses are provided with a telescopic alidade which is made interchangeable with the ordinary vanes. This telescope is fitted with cross-lines which may be illuminated for night work. This attachment is useful in taking bearings of distant objects which cannot be distinguished with the naked eye, and for taking bearings of dim lights. It may also be used for taking azimuths of stars.

The illumination of the telescope cross-wires is provided by dry cells supported on a brass plate located in the column underneath the lamp basket.

MAGNETIC SETS.

183. The magnetic set (Fig. 59) consists of the horizontal force instrument and heeling adjuster put up in the same transporting case.

HORIZONTAL FORCE INSTRUMENT.

184. This instrument consists of a cylindrical brass case, mounted upon a rectangular base, provided with levels and leveling screws. The case contains a horizontal circle graduated to degrees, and a pivot supporting a small lozenge-shaped magnetic needle. The needle is fitted with an adjustable sliding weight to counteract the dip, and admits of a free vibrating motion in a horizontal plane. A glass cover excludes all air currents during observations. When not in use, the needle should be kept in its leather case.

It should be remembered, in taking observations with the horizontal force instruments, that the time of vibration depends not only upon the strength of the magnetic field but also upon the strength of magnetism in the needle, the temperature, and the moment of inertia of the needle, so that, in using the needle for obtaining the directive force on board ship, the same instrument should invariably be used or the observations will be worthless. Using two standard sets, the time of ten vibrations at the same place and the same time has been known to vary as much as two seconds. The temperature at the places of observations should be approximately the same.

HEELING ADJUSTER.

185. This instrument consists of a brass box with a removable glass top mounted upon a rectangular base provided with levels and leveling screws. Within the box a small magnetic needle is suspended on its horizontal axis, and is free to vibrate in the vertical plane. The ten-

dency of the needle to dip is counteracted by a small platinum sliding weight, whose distance from the axis of suspension is measured on a scale on the glass cover of the box. A second scale on the bottom prevents any error due to parallax in reading the scale. A small glass opening in each end contains an index line marking the horizontal plane, and on the latest instruments an index arm attached to the needle points to the 0° mark of the glass cover when the needle is horizontal. A lifting device, operated from the side, raises the needle from its bearings when not in use.

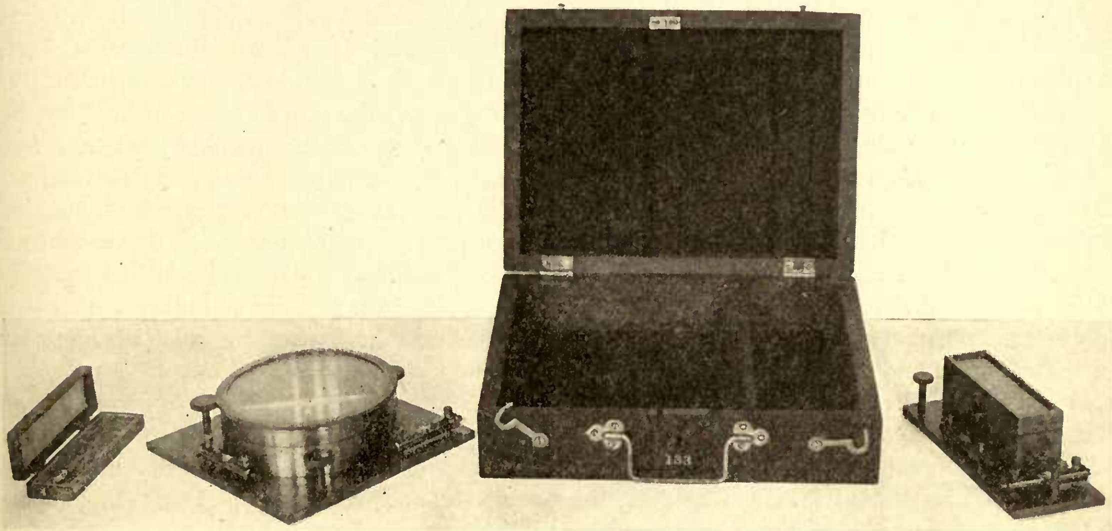

FIG. 59.

BAR AND PINTLE, WITH TRIPOD.

186. The bar and pintle with tripod are furnished for work on shore where observations are taken with the 7½-inch navy standard compass. The bar and pintle are made of brass or composition, and the tripod of hard wood with fittings of brass or composition. The bar is U-shaped, and is fitted to carry the 7½-inch navy compass mounted in its gimbal ring. The pintle secures to the top of the tripod and fits into a hollow conical receptacle in the center and underneath the bar. A clamping attachment is provided for clamping the bar to the pintle. The gimbal supports on the bar have movable lugs and thumb-screws for securing them, to prevent a sliding lost motion and to hold the gimbals in place.

COMPASS READER.

187. The compass reader is a magnifying-glass mounted on spider legs that rest on the glass top of the compass. It is especially used for steering compasses, enabling the helmsman to steer to degrees.

CHAPTER XII.

THE GYRO-COMPASS.

188. The Necessity for a Gyro-compass and Points of Superiority over the Magnetic Compass.—Reports from battleships and armored cruisers in recent years have repeatedly emphasized the urgent necessity for an efficient compass for use under battle conditions. The difficulty in properly compensating magnetic compasses on such vessels, for various magnetic latitudes, has increased greatly with the increase in size of the vessels and with the use of great masses of moving steel in the turrets and guns. Conditions for magnetic compasses are especially bad at steering stations below the protective deck and in conning-towers, owing to the lack of directive force; and in many cases a magnetic compass at such a station is practically useless. The gyro-compass, being subject to no magnetic influence whatever, has solved the problem of obtaining an efficient battle compass; and experience has demonstrated that it is also to be used for navigation purposes practically at all times. The magnetic compass will, however, always be retained for a check on the gyro-compass and for use in case of casualty to the latter.

The following points of superiority of the gyro-compass over the magnetic compass may be cited:

It is not subject to magnetic influence or to sudden changes in magnetic condition that result from the training of turrets and boat-cranes, alternate heating and cooling of the funnels, operation of electric generators or motors, or alteration in the ship's structure. It always points true North, thereby eliminating magnetic variation. The "master compass" can be mounted below the protective deck, where it cannot be damaged by the enemy's shells. There is no heeling error, and the gyro-compass maintains a steady heading while rolling, and is sensitive only to actual changes in course. The "repeaters" are not affected by their position, motion or surroundings; one can be placed or moved anywhere, as long as it has its cable connected. When steering by gyro-compass, much less helm is required owing to its inertia and large directive force, with consequent lack of lag, as the helmsman can instantly detect the ship's change of head by the compass alone. In maintaining position in formation, the number of orders to the engine-room for changes in revolutions is reduced when steering by gyro-compass, due to the fact that the headway is not deadened so frequently by the use of the rudder; and it is probable that a considerable saving in coal consumption results.

The magnetic surroundings of compasses on submarines have always been bad, especially for those inside the vessels, which must be used when running submerged. The gyro-compass will therefore be a valuable aid to vessels of this class.

The Navy Department is now installing gyro-compasses on all new battleships and submarines; and they will be supplied eventually to all battleships, armored cruisers, and submarines in the service. The compass now in use is described in the following section, and is the invention of an American engineer, Mr. Elmer A. Sperry.

THE SPERRY GYRO-COMPASS.

By LIEUTENANT J. A. MONROE, U. S. N.

189. In this discussion, "gyro" will be used to denote a spinning or rapidly rotating wheel suspended so as to have freedom of movement about three rectangular axes, one of which is the axis of spin of the wheel. Fig. 60 represents a gyro suspended with three degrees of freedom, the axes being xx', yy' and zz'. Only such properties of the gyro as are utilized in the Sperry Gyro-compass will be considered.

190. A gyro tends to maintain its axle pointing in the same direction, unless it is acted on

by an impressed *angular* force. When acted on by such a force, a gyro will resist that force, and in so doing will move so as to place its axle parallel to the axis of the impressed force, and in such a relation that the direction of its rotation is the same as that of the impressed force. This motion is called *precession*. In Fig. 60, S indicates the direction of rotation of the gyro; FF' is the externally impressed *angular* force, acting about a fixed axis initially coincident with xx'; PP' indicates the resultant pre-

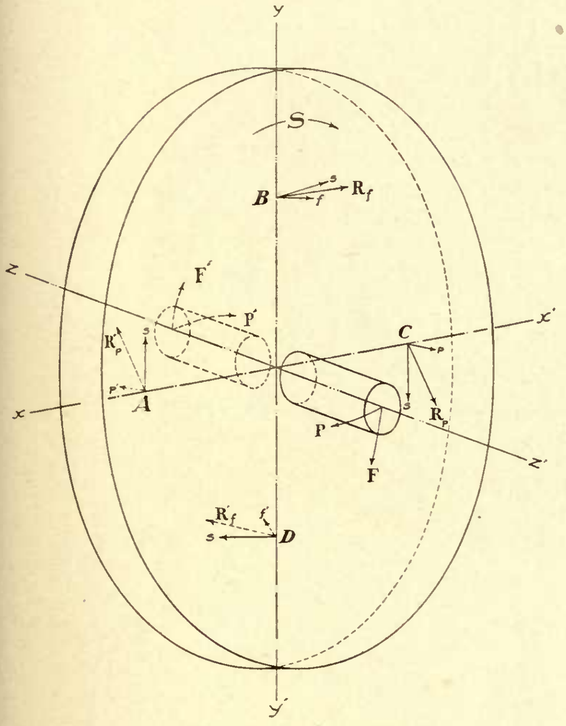

Fig. 60.

cession about axis yy'. This action is a result of the operation of Newton's laws of motion and can be analyzed as follows: For this purpose, consider that the mass of the gyro, in Fig. 60, is concentrated in the four particles A, B, C, D. Then the forces and resultant accelerations of these particles are the averages of all the forces and accelerations of the wheel. Force FF' has no action on A and C, for they lie in the axis about which it acts. However, it causes B and D to move in plane $yy'zz'$, as indicated by ff', and, since they already are moving in plane $xx'yy'$, as indicated by ss, their resultant path lies in a plane between those two planes, as indicated by R_fR_f'. Since the wheel is free to turn about yy', it will do so, as indicated by PP', and will include the paths R_fR_f'. Now, PP' also has a similar action on the wheel, but its tendency to cause the wheel to rotate about xx', as indicated at A and C by $R_p'R_p$, exactly balances FF', and there is therefore no motion about xx'. Precession will continue as long as the force acts, until zz' coincides with the axis of force F.

191. Suppose that such a gyro be mounted on land at a place, A (Fig. 61), whose latitude is L. At this place the earth's velocity of rotation, v, about its axis, PC, can be resolved into two components: one, $v \cos L$, about the projection of the meridian on the horizontal plane, z_nz_s; and another, $v \sin L$, about the vertical axis of A, AY; *i. e.*, the horizontal plane rotates about the meridian and the meridian rotates about the vertical. The gyro, spinning as indicated by S, has three degrees of freedom, except as limited by weight G, which is attached at a point below and eastward (considering the end of axle marked n as being the gyro's North) of the axle. Whenever the axle of the gyro is not horizontal, G will exert an angular force, whose components about axes x_ex_w and yy' will cause precession about axes yy' and x_ex_w, respectively. The former will be called *azimuthal force*, and the latter *damping force*. Suppose that the gyro starts with its axle (North end) pointing West and horizontal. After a time, the earth will have rotated so that it will be at A'. The horizontal plane has tilted, and the meridian has rotated about the vertical axis. Due to the tilting of the horizontal plane, the axle of the gyro is pointing downward, for the gyro tends to maintain its axle parallel to itself. But G is acting as indicated by a and d, causing precessions P_a and P_d, respectively. If d were not acting to bring the axle horizontal, the axle would precess toward the meridian, the horizontal plane tilting more and more toward it until it had crossed the meridian, when the horizontal plane would tilt away from it until the axle was pointing East. The axle would then be horizontal and a would cease to act. But the horizontal plane continues to tilt away from the axle; the precession commences in the reverse direction, and the axle precesses

toward the meridian, crosses it, and again reverses when it is pointing West. This oscillation would continue indefinitely, with undiminished amplitude, were it not for force *d*. But *d* tends to bring the axle horizontal; so at each swing the amplitude of the oscillation is diminished, until the axle comes to rest with such angular displacements from the meridian and the horizontal as to cause P_a and P_d to just equal the components of the earth's velocity. We therefore have a gyro-compass which employs a gyro with three degrees of freedom, two of which are partially destroyed by a pendulous weight, and which will seek the meridian by a series of damped oscillations. It will have an error on true North which varies with the latitude.

192. In order that this compass may be used aboard ship, the following additional forces must be considered: (1) Changes of torque of gyro; (2) meridianal component of ship's speed; (3) acceleration forces incident to changes of course and speed and to rolling, pitching and vibration of ship.

Changes of torque of gyro occur only when gyro wheel is accelerated or decelerated. When the axle of the gyro is horizontal, these torques have no component tending to cause precession. However, the normal position of the axle is inclined slightly to the horizontal, except at the equator; hence there is a component of torque tending to cause precession about axis $x_e x_w$ and, through action of the weight, about yy'. By making the center of gravity of

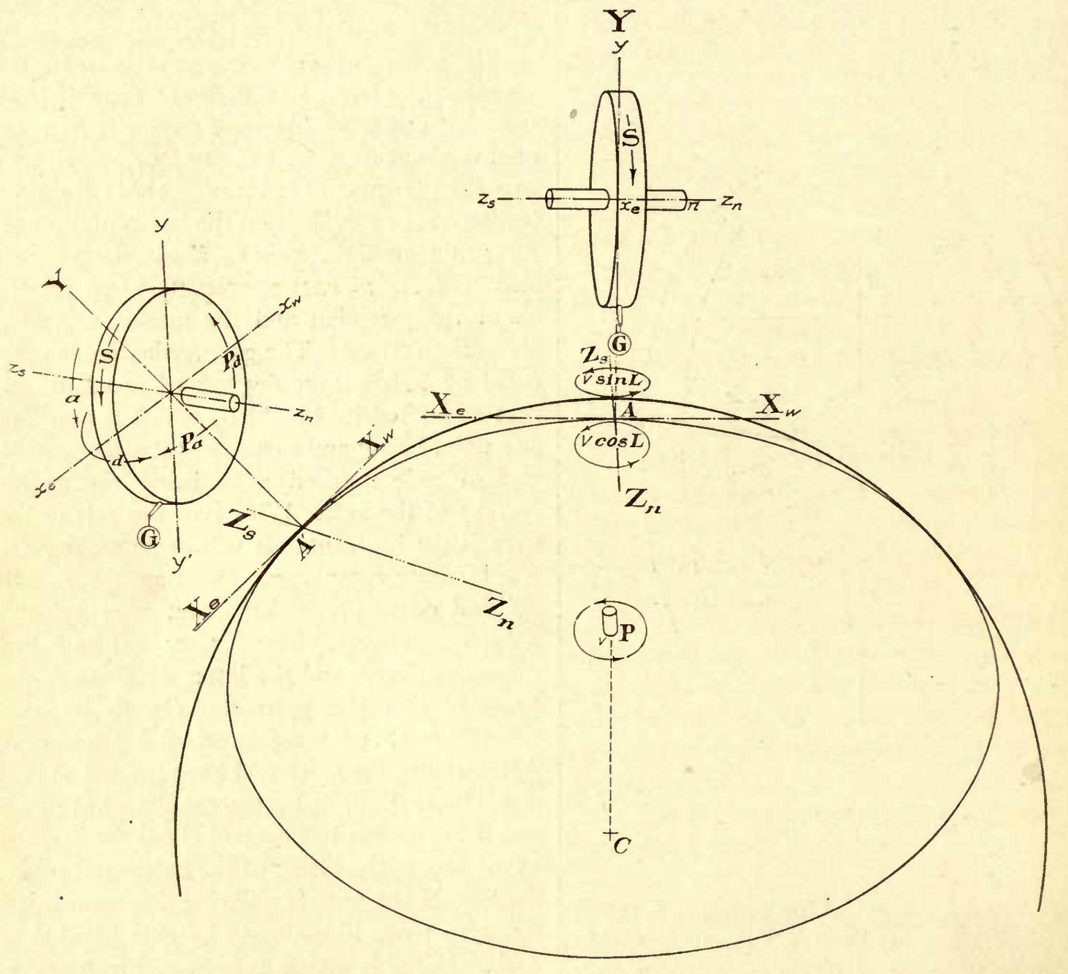

FIG. 61.

the weight adjustable, however, relative to the point of attachment to the gyro, the axle can be made to assume a horizontal resting position and at the same time have the same angular displacement from the meridian that it would have if it were inclined to the horizontal. This adjustment varies with the latitude.

Easterly and westerly components of the ship's speed average with the component of the earth's rotation, and are so small in proportion that their effect on the directive force of the gyro can be neglected. However, the meridianal component combines with the earth's velocity component to give a resultant at an angle to the earth's component. The gyro assumes a new resting position to accommodate itself to this new velocity. The error on true North due to this cause varies with the latitude, speed and course.

Acceleration pressures due to changes of course and speed, and to rolling, pitching and vibration, can effect the gyro only through the weight, since the suspension with three degrees of freedom prevents any angular forces from being transmitted to the gyro. The angular forces that would be transmitted to the weight are reduced to negligible amounts by mounting the whole compass in gimbal rings hung from a spring-supported ring. There only remain the straight acceleration pressures due to inertia of the weight; and, by choosing a proper period of oscillation for the gyro, the compass is made dead-beat for a mean latitude, and the oscillations at other latitudes are small enough to be neglected.

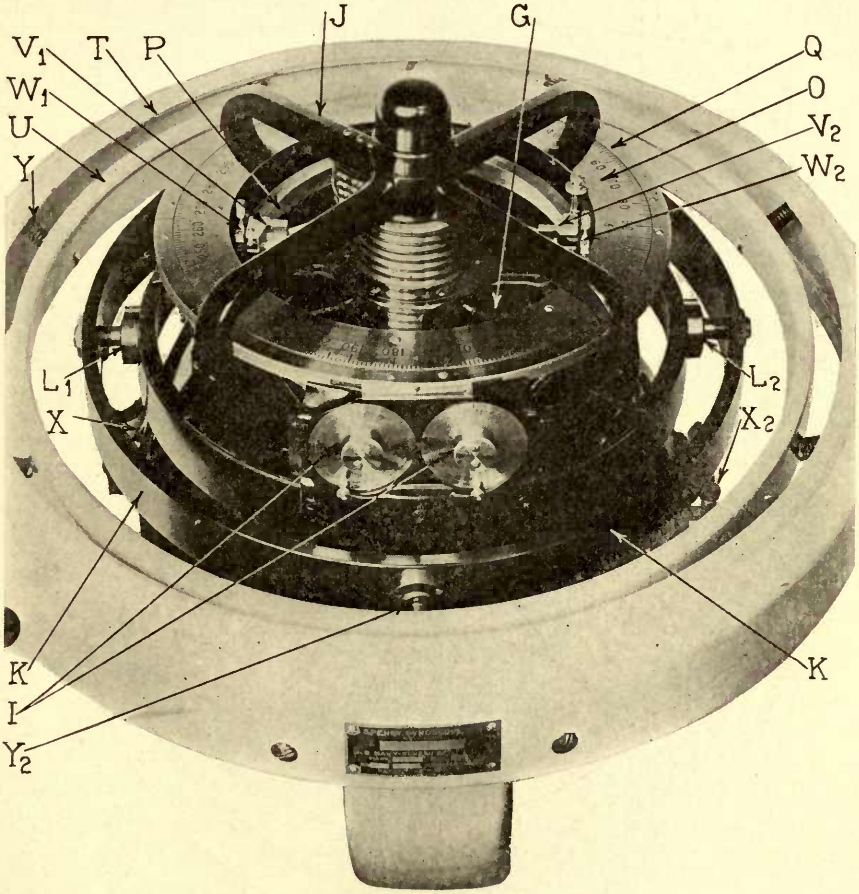

Fig. 62.

193. Having considered the theory of the gyro-compass using a gyro suspended with three degrees of freedom, let us see how this is

applied practically in the gyro-compass as supplied to the United States Navy by the Sperry Gyroscope Company. Fig. 62 is a plan view of the master-compass; Fig. 63 is a part section, part elevation view as seen from the South side; and Fig. 64 is an elevation of the West side as seen from a point a little to Northward of West.

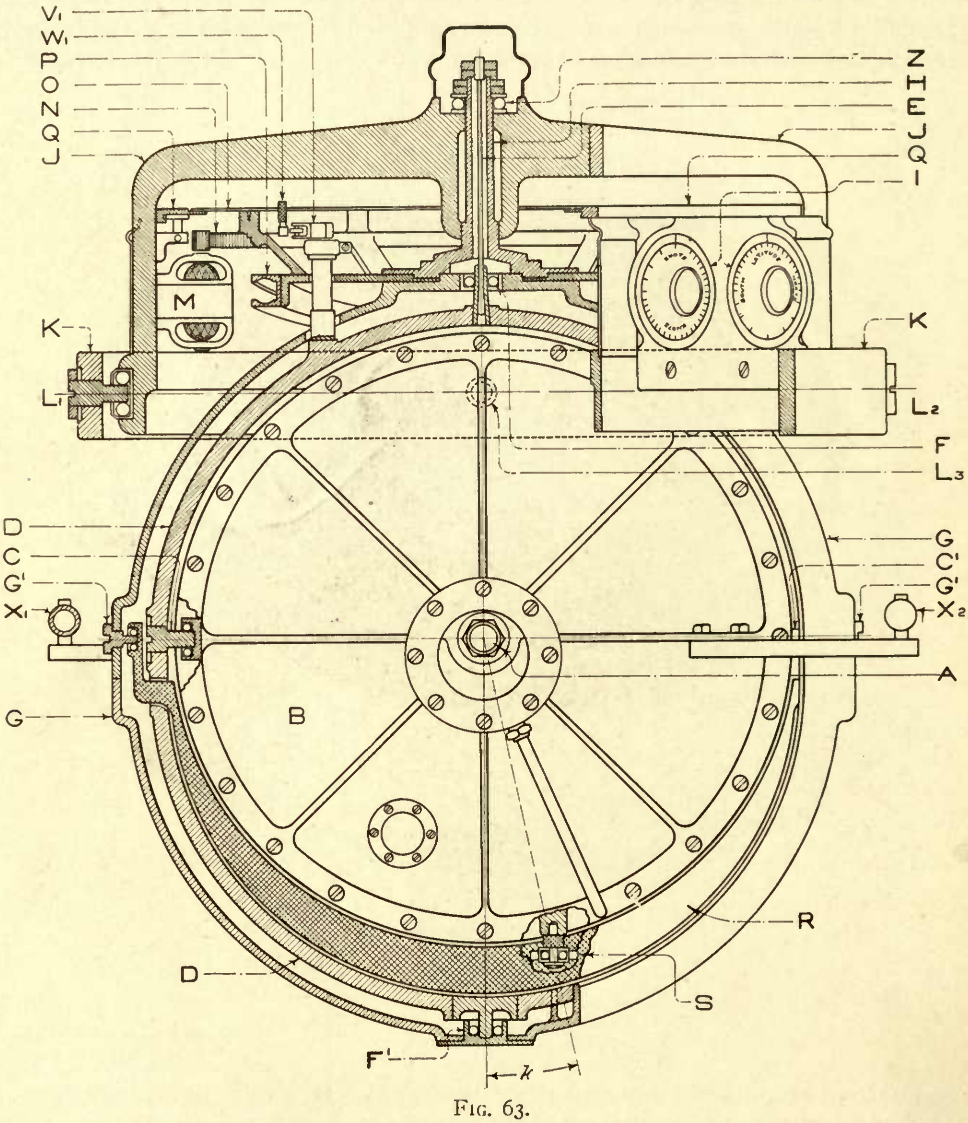

Fig. 63.

The master-compass is mounted in a binnacle having two covers. The upper one is transparent and is provided with a door permitting all necessary adjustments to be made without removing it. The lower cover or bowl can be lowered if desired. Thus, when running, the compass is shielded from air currents. Hung from the binnacle ring *T*, by spiral tension springs *Y*, is the suspension ring *U*, which carries the ball-bearings Y_1, Y_2 of the gimbal ring *K*, which carries the ball-bearings L_1, L_2 of the main frame *J*, from which the gyro is hung. By means of this suspension, angular forces due to vibration, rolling and pitching are reduced to such small proportions that no appreciable deviation is produced.

Supported in the main frame by a ball-bearing *Z* at the top of the stem *H*, is the electrically-driven azimuth element consisting of the phantom-ring *G*, stem *H*, azimuth gear wheel *N*, compass card *O*, cosine-cam *P*, and slip rings *a*. The azimuth element is driven through

gear N, by azimuth motor M, controlled by the follow-up system in such a manner that the 0° mark on card O always indicates the position of the North end of the gyro axle. Vertical cardan-ring D is suspended within phantom G by suspension wire E, and is guided by ball-bearings F, F'. Mounted on horizontal ball-bearings C, C' is the vacuum case B, which contains the gyro wheel, mounted on ball-bearings at A, A' and the 3-phase, A. C. induction motor that drives it. The rotor of the induction motor is a part of the wheel. Ring D, together with case B and its contents, is called the *sensitive element*. The azimuth motor, and consequently the azimuth element, are controlled through a relay r, by duplicate trolleys V_1, V_2 carried on posts attached to vertical ring D and resting on duplicate contactors W_1, W_2. Each contactor is composed of two tungsten-faced silver segments, insulated from each other by mica. One segment is in circuit with the ahead-motion field coils of the azimuth motor, and the other is in circuit with the reverse-motion field coils. By this means the proper motion (depending on the segment on which the trolley is resting) is given to the azimuth element to keep it in a constant relation in azimuth, to the sensitive element; and since ring D is suspended from the azimuth element by wire E, which is virtually torsionless on account of the constant relation of the two elements, the gyro is almost perfectly free about its vertical axis. Current is carried from the main frame to the azimuth element, through slip rings a, and from the azimuth element to the ring D by means of very flexible wires running parallel to wire E. From D it reaches the case B by means of spirally-coiled flexible wires near C. Bail R, which corresponds to weight G (Fig. 60), is suspended from phantom G by ball-bearings G', G'. It is attached to the case B at a point S, a little to Northeastward of the vertical axis of the gyro. It will therefore have an orienting and damping effect on the gyro, varying with the axle's angle of inclination whenever the gyro's axle is inclined to the position in which the point of attachment is in the same vertical plane with bearings G', G'. That this is not when the gyro axle is horizontal, is due to the necessity of having a relative tilt to keep the gyro pre-

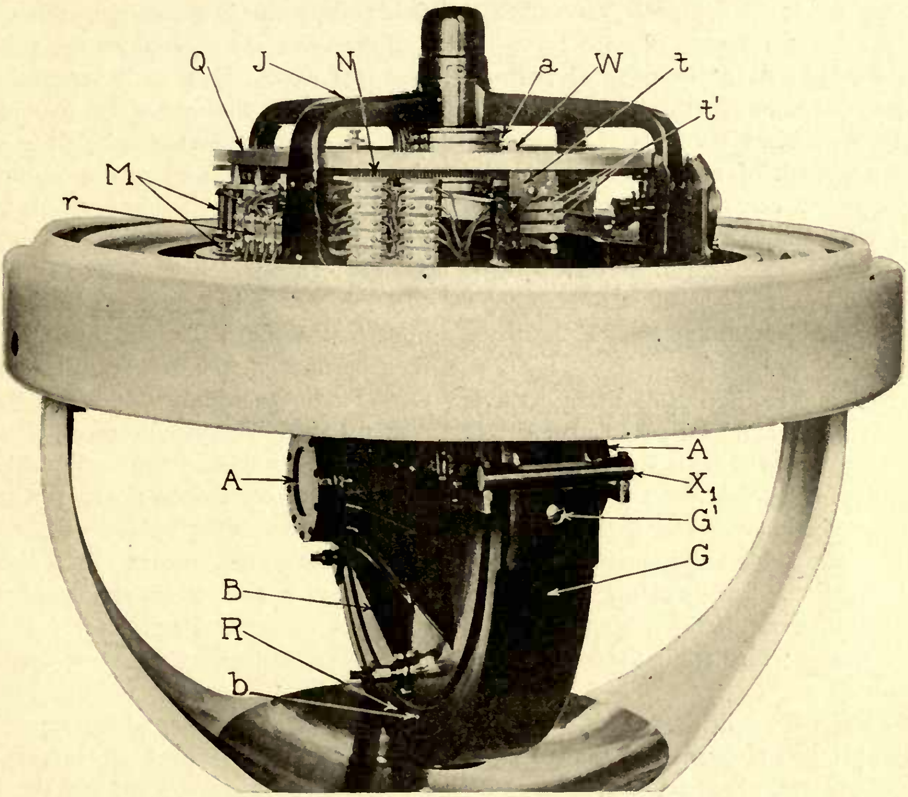

FIG. 64.

cessing and at the same time having the axle horizontal in order to eliminate the effects of change of gyro speed. In addition to the Northerly offset, a weight *b*, whose position can be shifted to keep the axle horizontal at any latitude, is attached to the bail. Thus we have a gyro suspended with three degrees of freedom (about axes *FF'*, *CC'* and its axle *AA'*), two of which are limited by a pendulous weight or bail. In addition, its axle will be horizontal at all latitudes, when the compass card indicates true North; for the center of gravity of the bail can be adjusted for changes of latitude, and the bail, due to its Northerly offset, retains a working arm when the axle is horizontal. Due to the method of suspension, practically no angular forces can reach the element, and the effects of accelerations that reach it through the bail are negligible, due to its offset to the Eastward and the relation between gyroscopic resistance of the element and the inertia of the bail.

The errors due to the lag of the gyro axle from the meridian, and to the ship's speed, are corrected by a system of cams and levers, which automatically add or subtract the various factors and move the lubber's ring *Q* the necessary amount to make the card indicate true geographical direction. Cosine-cam *P* applies the meridianal component of the course, and dials *I* control the cams which apply the latitude and speed factors.

Case *B* carries two spirit levels, X_1, X_2, supported parallel to the gyro axle by arms extending outside the phantom, near *C* and *C'*. These levels indicate the angle that the axle is making with the horizontal, and therefore one can see at a glance whether or not the compass is indicating true North. Also, by observing the rate of travel of the bubble, one can ascertain the approximate error of the compass. This latter is valuable when the position of the meridian is unknown and it is desired to set the gyro to the meridian by hand, in order to avoid the delay of waiting for it to settle of itself.

194. Besides the master gyro-compass, there are repeater compasses located at the various steering stations about the ship. These are controlled electrically by the master-compass through the secondary transmission system. Each repeater consists of a case having a glass cover and containing: a six-pole step-by-step motor geared to a translucent compass card; a lamp for illuminating the card; a hand-crank for setting the card; and a magnetic stop, which, when energized, will lock the card at 0°. Secured to the lubber's ring *Q* of the master-compass, and geared to azimuth gear *N*, is a transmitter *t*, which, by means of a cam and contact finger *t'* for each pair of repeater motor field coils, controls the energization of the coils and therefore the position of the armature and compass card. Due to its mounting, it can transmit only the corrected readings of the master. The repeaters can be set to agree with the master-compass by means of the synchronizer, which is a hand-operated transmitter geared to a dial, indicating degrees. The repeaters can be connected to this and turned through 360°, when they will have been locked at 0° by the stops. The circuit to the stops can then be opened, the repeaters brought to the same reading as the master-compass, and connected to it. The synchronizer, double-throw repeater switches, stop and synchronizer switches are carried on a panel called the *repeater panel.*

195. The gyro-compass outfit also includes the following accessories and spare parts:

(1) A dynamotor-generator for converting 100 to 125-volt D. C. current into 130-volt, 3-phase, A. C. current, for operating the 3-phase induction motor, which drives the gyro wheel; and into 22-volt D. C. current for operating the follow-up system and the secondary transmission system.

(2) A main supply panel on which are mounted measuring, controlling and protective devices for the master-compass circuits.

(3) A 20-volt storage battery, used as an auxiliary to the 20-volt generator.

(4) A 6-volt primary battery for supplying current to the alarm system, which indicates failure of the various current supplies.

(5) A box of spare parts and tools for the master-compass and repeater compasses.

(6) A box of spare parts for the dynamotor-generator and switchboards.

(7) A box containing spare sensitive element and casing.

CHAPTER XIII.

SOME NOTES ON THE PRINCIPLES OF THE GYROSCOPIC COMPASS, PARTICULARLY THE SPERRY GYROSCOPIC COMPASS.

By COMMANDER LOUIS M. NULTON, U. S. N.

196. While in command of the U. S. S. *Montana,* a Sperry gyroscopic compass was installed on board. Being unfamiliar with the underlying principles of operation of the gyroscopic compass, these notes represent information which I, as the captain of the ship, desired to have, and which I could not find in print in the form I desired. They are merely my own personal notes in explanation of one point or another as each point arose. They are qualitative, not quantitative, in character, and are designed to create a conception of principles.

197. In its ordinary definition, a gyroscope is an instrument for illustrating the laws of rotation, and consists essentially of a heavy rotating wheel, the axis of which is free to turn in any direction, and may be acted upon by external couples or forces.

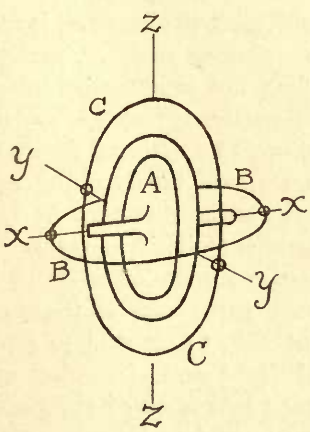

Fig. 65

Such an instrument is shown in Fig. 65.

The gyro wheel *A* is capable of spinning on its axis, *xx,* which axis is supported by the frame *BB*. Frame *BB* is at the same time capable of rotating around the axis, *yy,* which axis is supported by the frame *CC*. Frame *CC* is at the same time capable of being rotated around the axis *ZZ*. The above construction permits the axis of spin *xx* of the gyro wheel to turn, or point, in any direction in space.

The gyro wheel *A* has some peculiar characteristics. For example, suppose we start it spinning around its axis, *xx,* and then, while it

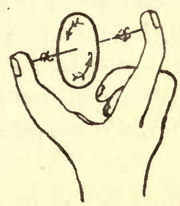

Fig. 66

spins, lift it out of its mounting, holding it between the thumb and first finger, thus: Fig. 66.

We may move the wheel in space in any direction, *and so long as the axis, xx, remains parallel to its original position and the wheel*

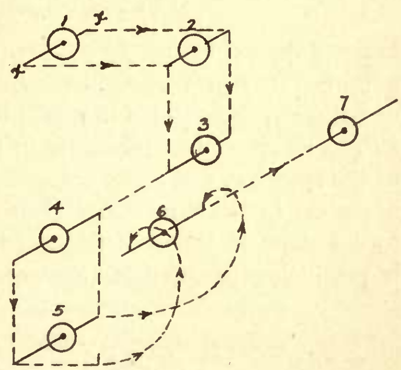

Fig. 67

is spinning no special results of any kind will be noted.

For example, the axis of the wheel while spinning may be moved to the successive positions 1, 2, 3, 4, 5, 6, 7 as in Fig. 67, and so long as each movement carries the spinning axis

through space parallel to itself no special phenomena present themselves. If, however, the spinning wheel be moved in such a way as to produce rotation of the spinning axis as in Figs. 68 and 69, instead of mere translation, most curious and striking results occur.

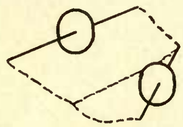

FIG. 68

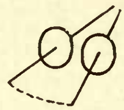

FIG. 69

There is felt first a definite, positive *resistance* to this rotating movement of the axis accompanied, at the same time, by a curious wriggle and tilting of the wheel and its axis *xx*. This resistance, and its accompanying wriggle, follow definite laws and possess the secret of the gyroscope and the gyroscopic compass. Unless this cause and effect is remembered in its physical sense, it is useless to attempt to understand the principles of the gyro compass.

198. The "Wriggle"-Precession.—Suppose (in Fig. 70) while the wheel is spinning

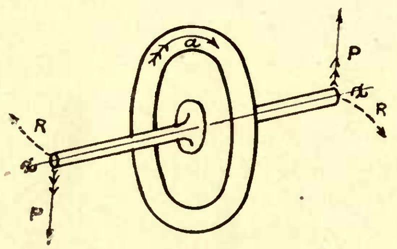

FIG. 70

in the direction shown by the arrow, *a,* we put a light, steady pressure on each end of the axle of spin, *xx,* so as to tilt this axis by the couple *PP*. The result is astonishing in that the axis of the spin, *xx,* will resist being tilted, and will move off in the direction *RR at right angles* to the plane of action of the couple *PP,* which is producing the tilting. Suppose in Fig. 71

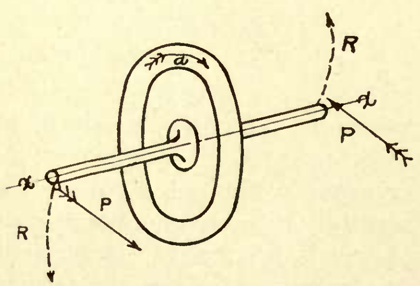

FIG. 71

we apply a couple tending to rotate *xx* as shown by the arrows *PP*. What is the result? It is equally astonishing—*xx* will resist rotation by the couple *PP,* and will at once tilt in the vertical plane in the direction *RR at right angles* to the plane of the couple *PP*. This effect in in the spinning gyroscope always follows this cause, or this cause always produces the above-noted effect, and *it is the application of this principle which permits the gyroscopic compass.*

It is not necessary for the dabbler in applied science to be able to understand the mathematics of the gyroscope, but he must be able to remember the physical phenomena here presented as "cause and effect," if he desires to understand the principle of the gyroscopic compass.

Referring to the conditions represented in Figs. 70 and 71, the movement of the axis of spin, *xx,* in a plane perpendicular to that of the couple applied to it is called a "precessional motion" or "precession." The application of the couple is said to cause the spinning wheel to "precess."

It doesn't matter whether the initial position of the spinning axis in space is horizontal, vertical or tilted, the *relations of the directions* of the precession and its producing couple are the same.

Again, referring to Fig. 67, it is recalled that moving the spinning axis, *xx,* parallel to itself in space does not produce precession. Conversely, unless the gyroscopic system of Fig. 65 is acted upon by external forces tending to produce precession the spinning axis always points in the same direction in *space, i. e.,* remains parallel to itself *in space.*

A gyroscope suspended so as to be able to rotate around three axes as those of *xx, YY* and *ZZ,* of Fig. 65, is said to possess three degrees of freedom. If motion around one axis is denied by reason of rigid construction, that motion is said to be suppressed and the gyroscope is said to possess but two degrees of freedom.

199. Effect of Earth's Rotation and of Gravity on a Gyro Located at the Equator.—In Fig. 72, let *AB* represent the earth as seen from above the North Pole. Let *G* be a gyroscope spinning at the celestial equator, at the

end of the radius, NG, with its axis, xx, horizontal and standing east and west, the gyro being so far away, in space, from the earth that it is *not* affected by gravity.

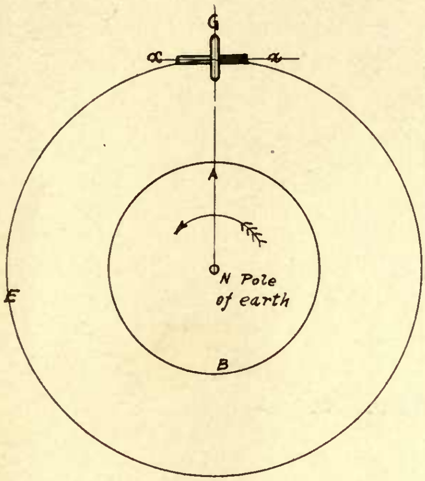

FIG. 72

After a certain length of time, the earth will have rotated until the gyro is at the position G_1, Fig. 73, then in the case of the gyro with three degrees of freedom, *i. e.*, uniformly suspended and free to turn in all directions in space, the axis of spin, xx, would no longer be horizontal as regards the surface of the earth, but the condition would be as shown at G_1, Fig. 73, the gyro having kept its spinning axis parallel in space to the original position which it occupied when at G in Fig. 72. Under this assumption there would be no precession.

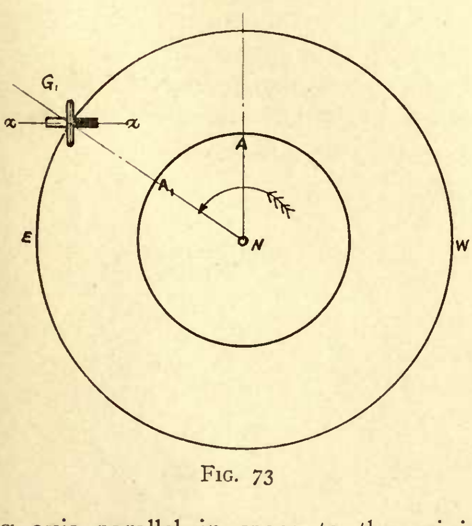

FIG. 73

Suppose now Fig. 74, the gyro be moved in towards the earth's center, along the radius. As it approaches the earth's surface, the force of gravity is caused to act in the gyro compass to make the axis of spin, xx, take a horizontal position $x'x'$, relative to the earth's surface, and in so doing will cause this axle to tilt through the angle θ. Recalling the discussion of Figs. 70 and 71, we see that the rotation of xx to $x'x'$, will cause precession of this axis so that the gyro finally occupies the position of G_3 in which the plane of the spinning wheel coincides with the plane of the equator, while the axis of spin lies in the vertical plane through the earth's axis, *i. e., the axis of the spinning wheel* lies in a meridian plane and thus points true north and south.

So long as the force of gravity acts in this manner to tilt and keep the gyro's spinning axis horizontal to the earth's surface, just so long will the precession caused by the resultant of this and the earth's rotation cause the gyro's spinning axis to point true north and south, unless acted upon by some force tending to throw it away from the meridian. A compass card may be so mounted on this axis as to show true compass readings.

Oscillation—Damping.—But the mass of the gyro wheel possesses inertia, and as the wheel passes from the position G_2 to G_3 its inertia will carry the axis, xx, past the horizontal and meridian planes. When this occurs, a reverse process will take place and in time the axis, xx, be brought back to the meridian plane, only to again swing past it. This process, unless retained, will continue for a very long time before the oscillations finally disappear as the forces come into final equilibrium.

Practically, in order to use a compass card on a gyro, mechanical processes are used to check this oscillation and produce equilibrium sooner than would otherwise occur. This is called damping.

In all of the foregoing, the gyro has been considered as stationary on shore at the equator.

200. The Action of the Gyroscope at Another Place than the Equator.—If the gyro be at some parallel of latitude other than the equator, the force of gravity is caused to keep the axis of rotation of the gyro horizontal to

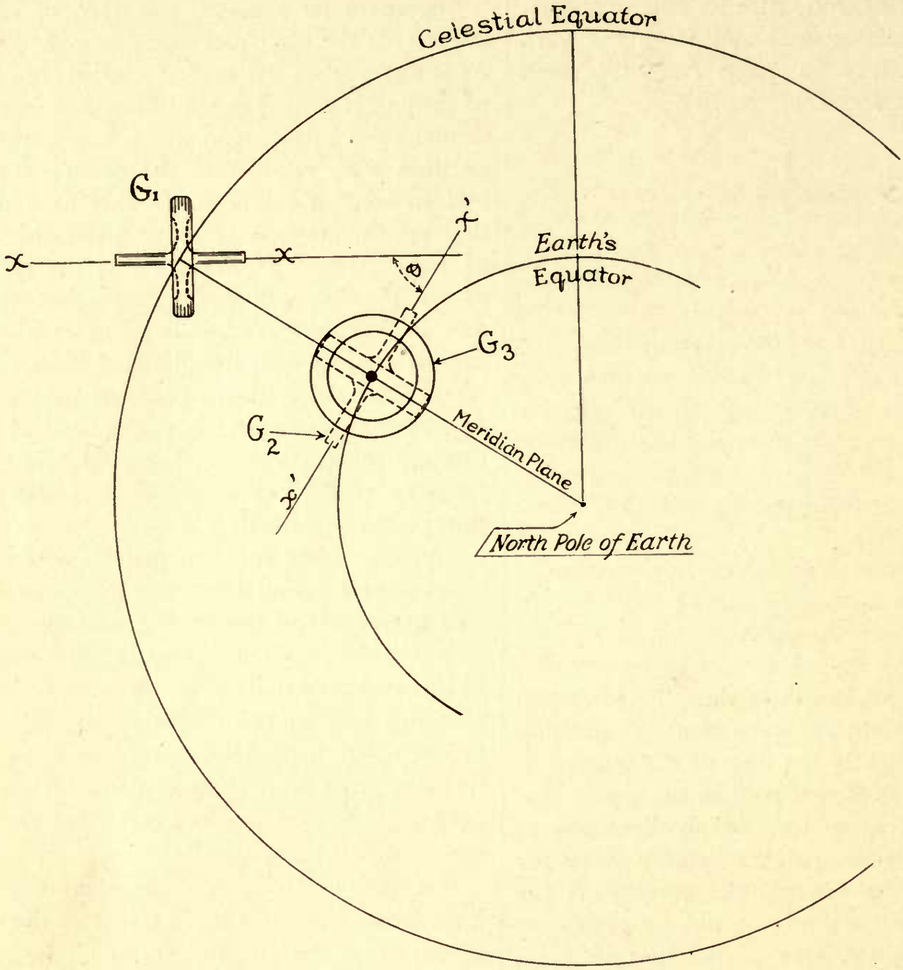

FIG. 74

the earth's surface and turned into the meridian line, *i. e.*, pointing to the earth's poles, in a manner similar to that discussed in Figs. 72, 73, and 74. For illustration: Assume the gyro of three degrees of freedom at *A*, Fig. 77, to be *not* acted upon by gravity. Then as the earth

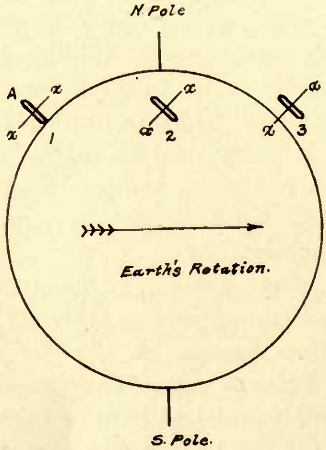

FIG. 77

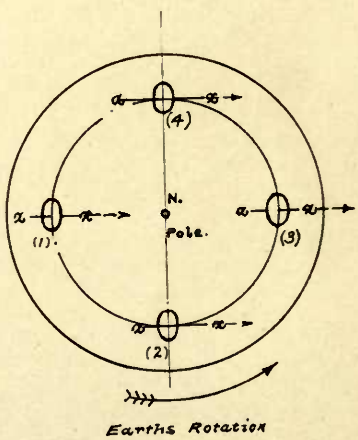

FIG. 78

NOTE.—Figures 75 and 76 of the original manuscript are combined in figure 88a.

rotates, the spinning axis, xx, under this assumption would move through space parallel to itself as indicated in the successive positions 1, 2, 3, 4 of Figs. 77 and 78.

However, as a matter of fact, with gravity acting, the gyro would not arrive at 3 in the position shown in Fig. 77 for its spinning axis, xx, would be held, by gravity, horizontal to

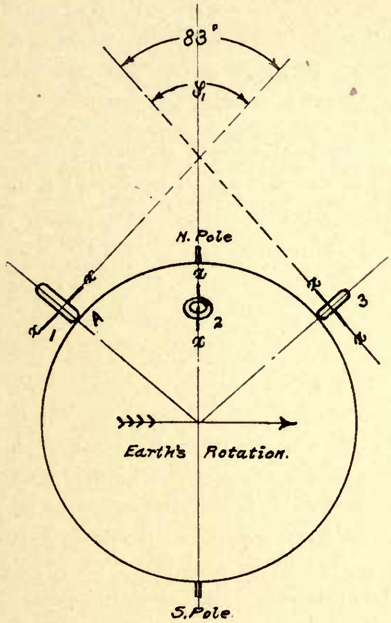

Fig. 79

the earth's surface so that it would arrive at position 3 as shown in Fig. 79. In reaching position 3 from position 1 (see Fig. 79) the spinning axis, xx, will have been tilted through an angle of 83°. This tilting will have been gradual and continuous during the movement from (1) to (3) and such a tilt would produce

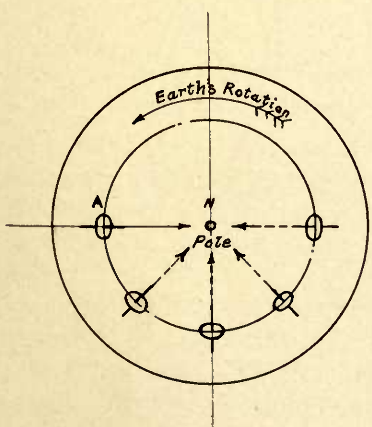

Fig. 80

continuous "precession" tending to keep the spinning axis in the meridian plane, *i. e.*, pointing true north, as shown in Fig. 80.

201. Further Latitude Considerations.—Suppose the gyro instead of being located at a place whose latitude was *A*, as in Fig. 79, was located at latitude *B* or *C* as shown in Figs. 81 and 82, respectively. A study of the

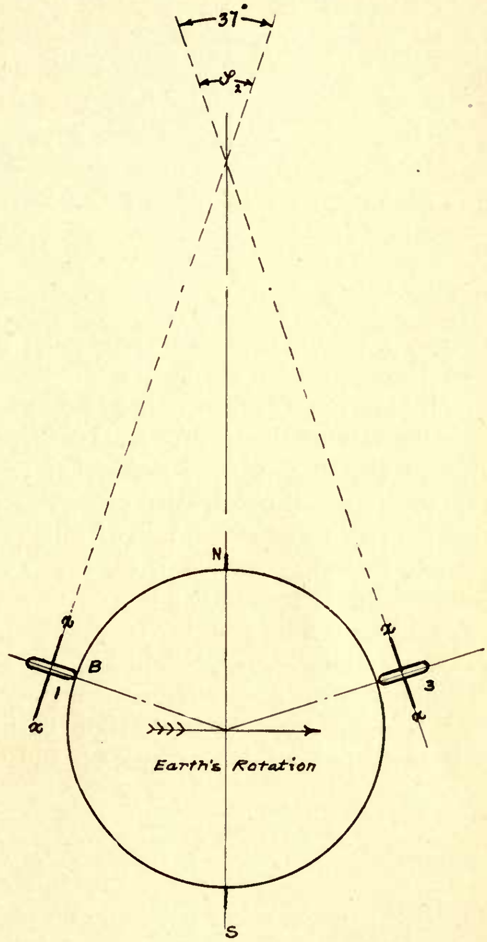

Fig. 81

figures will show that the angle ϕ, through which the spinning axis, xx, must tilt in order to remain horizontal to the earth's surface, is less for latitude *B*, and greater for latitude *C*, than it was for the place whose latitude was *A*. Furthermore, as the earth rotates around its own axis once in 24 hours, each gyro has required the same absolute amount of time, *i. e.*, 12 hours, to move from position (1) to position (3) regardless of whether its latitude is that of *A, B* or *C*. But in this same length of time, one spinning axis has tilted through an

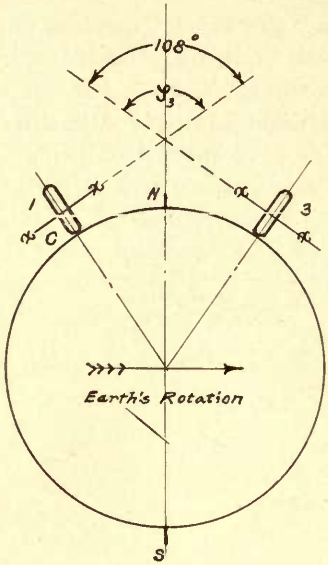

FIG. 82

angle $\phi_1°$, the other through angle of $\phi_2°$, the third through an angle $\phi_3°$, each differing from the other and dependent upon the latitude. Thus the rate of tilting of *xx* must vary for different latitudes, and as precession results from this tilting, it follows that each particular latitude must have its own rate of tilting, and resulting rate of precession, if the gyro's spinning axis is to be kept turned into the meridian, *i. e.*, kept constantly pointing true north.

202. Damping.—Suppose, in Fig. 83, *G* be a weight hanging quietly at rest suspended by the spring *S*. Suppose this weight be lifted by hand to the position 1, Fig. 84, and then suddenly released. Under the influence of gravity the weight will fall from (1) towards its previous position of rest, but upon arrival there will not stop but will be carried to position 2. At this point the weight will stop and begin to travel upwards towards *O* but again by

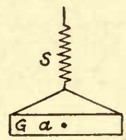

FIG. 83

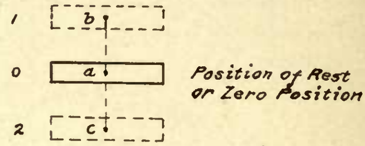

FIG. 84

virtue of its inertia will pass *O* and continue to travel towards (1). There will thus be set up a series of oscillations of *G*, and, if it so happens that the mass of *G* and the length and character of the spring *S* are just right for it, the oscillation of *G* will continue for a very long time unless they are checked or " damped " by the application of some outside force.

Under the conditions of Fig. 84, the path followed by any point *a*, of *G*, would be the vertical straight line of *bc*. Now, in Fig. 85, let a slot be cut in *G* and in this slot one end of the axis of spin, *xx*, of a spinning gyro wheel be inserted as at *a*, position *O*, Fig. 85. Let *G* now be started oscillating in the same manner as described for Fig. 84. As *G* rises and falls in the vertical plane, it will cause *xx* to rise and fall (tilt) with it, but recalling the principle of precession explained by Fig. 70, we see that *xx* will not only rise and fall with *G* but

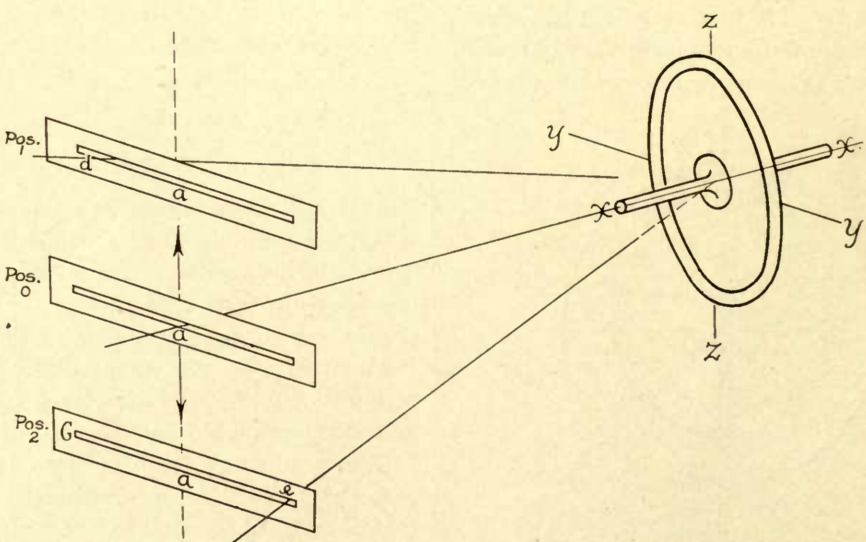

FIG. 85

will precess right and left as illustrated at positions (1) and (2), Fig. 71, so that while the end of *xx* travels in a vertical oscillation equal to *bc* of Fig. 84 it has also a horizontal oscillation equal to *de* of Fig. 85. The result is that any point on the end of the axis of spin, *xx,* is oscillating both vertically and horizontally at the same time and, in consequence, describes a path which is an ellipse.

Now a careful study of Figs. 79 to 82, inclusive, with the text relating thereto shows that the gravity couple (force of gravity) is constantly tilting the axis of spin, *xx,* of the gyros therein shown, to keep them in the horizontal plane. Also there exists the fact that the inertia of the mass of the gyro tends to force *xx* on past the horizontal plane, just as *G* of Fig. 84 was forced past its middle, *O,* position, and that when forced past gravity tends to return it. So, in reality, in a spinning gyroscope there may be the same kind of vertical oscillations and corresponding precessions as indicated in Fig. 85 and these will continue unless checked or " damped."

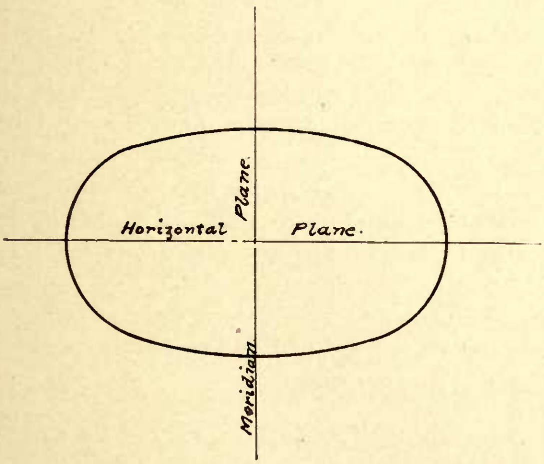

FIG. 86

In a gyroscope in which the oscillations just referred to are allowed to take place unchecked or undamped, the end of the axis of spin is constantly describing a curve similar to that of Fig. 86.*

In a gyroscope in which such oscillations are unchecked or undamped, the oscillations continue for a very long time and render such a gyro useless for carrying a compass card, since such a card would be constantly oscillating (precessing) through a wide range on each side of the meridian thus producing a compass whose error was constantly changing from one instant to the next.

Hence, before a gyroscope can be used for mounting upon it a compass card that will be of any practical value whatsoever, *mechanical arrangements, of one kind or another, for damping oscillations must be incorporated in the design of such a compass.*

An undamped gyro's axis when acted upon by gravity and the earth's rotation will constantly travel around the path of Fig. 86, but when this compass has a damping force applied to it, its oscillations get less and less and the axis finally settles down at some point *S* (settling point) at which it remains practically constant for the place (the latitude). See Fig. 87.

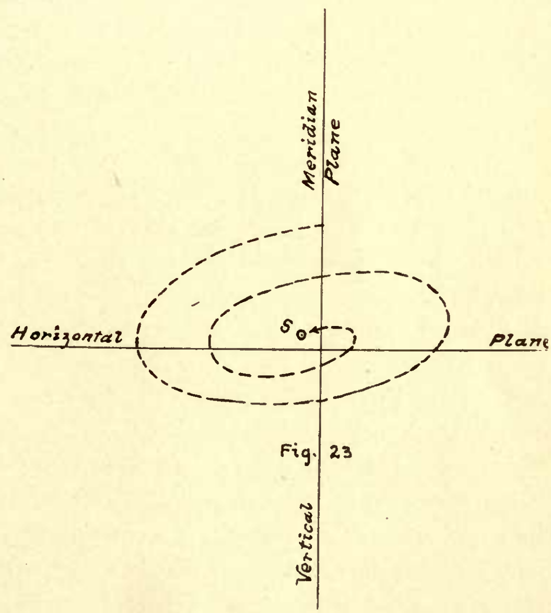

FIG. 87

203. Explanation of the Principle of the Application of the Damping Force of Couple. In Fig. 88 let *A* be a gyroscopic wheel with the usual axes *YY, ZZ,* and axis of spin *xx.* Let the horizontal and vertical planes through the meridian be as indicated. Let *xx* be tilting downward under the influence of gravity *g.* Let *gi* represent the continuation of the downward tilt past the horizontal because of the wheel *A*'s inertia. The resulting precession

* Try this with a torpedo gyro.

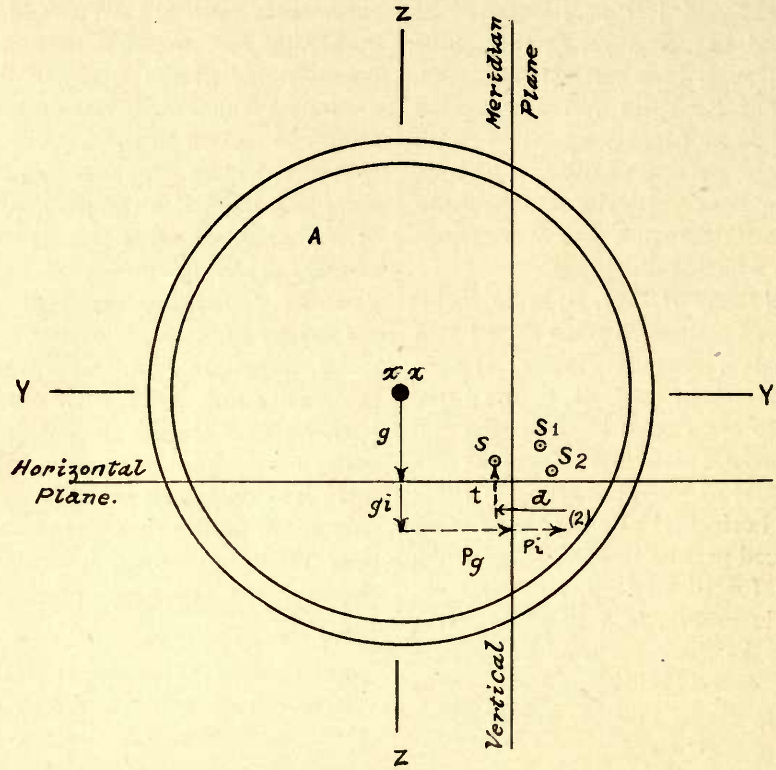

FIG. 88

around axis ZZ due to the tilt $g+gi$ would be $pg+pi$ as shown in the figure and the end of xx would tend to take the position (2). Suppose, however, as xx approaches the meridian and tends to pass it to go on to (2) we forcibly turn it back around the axis ZZ by applying to it an external couple or force d. This rotation of A by d around the axis ZZ will cause tilting of xx around YY (the amount of tilt t being indicated in the figure), with the result that under the combined action of the gravity and damping forces the axis of the wheel will settle at some point S (called the settling point), very close to the meridian and horizontal planes and, in a properly designed, constructed and operated machine, will, for all practical purposes, remain at S. Any condition and direction of forces might have been taken for illustration and S might be either above or below the horizontal, or east or west of the meridian, but in any case very small and practically constant so long as the gravity and damping couples (forces) act as just described.

In the earlier German compass the damping force or couple consisted in the action of an air blast tending to turn the wheel A around the axis ZZ; in the Sperry compass a connection or bearing eccentric to the axis, ZZ, produces a similar effect. *But in each compass damping must be produced if the compass is to be of any use to the mariner.**

The diagrams below show the character of the curves of damped and undamped oscillations in a gyro compass.

* The following explanation of damping is by Mr. H. L. Tanner, of the Sperry Company:

"As the connection between the bail and wheel case is eccentric (see *e* Fig. 90), the torque applied to the wheel case is about a line inclined to the horizontal by an angle equal to the angle of eccentricity of the above connection. This causes precession about a line inclined the same amount to the vertical, *i. e.*, a line passing through the eccentric connection and the center of the wheel. This precession may be resolved into two components, one in a horizontal plane and one in a vertical, and it will always be found that the component in the vertical plane is in such direction as to decrease the angle of tilt of the wheel's axis, thus de-energizing it and reducing the amplitude of its oscillations about the meridian."

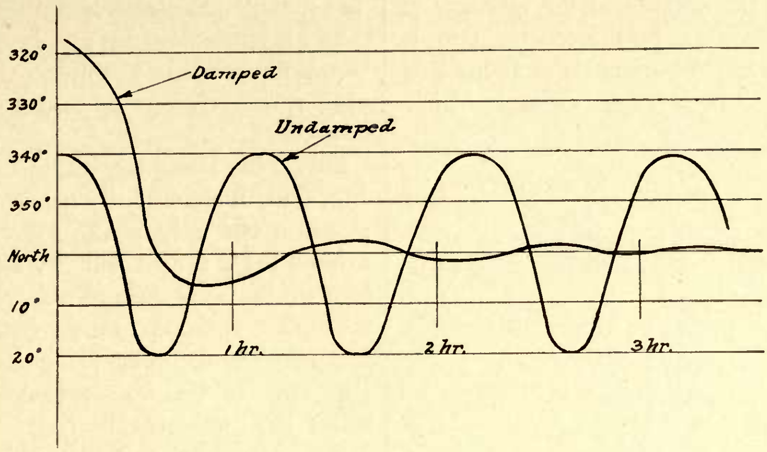

FIG. 88a

In Figs. 79, 81 and 82 it is shown that the spinning axis has tilted through 37°, 83° and 108°, respectively and that in each case it required the same amount of time, 12 hours, to do it.

The rate of tilting in each case is 3.0°, 6.9° and 9.0° per hour, respectively, and this rate is different for each and every position in latitude. Or, to put it in another way, each and every latitude requires its own particular rate of tilting, *and resulting precession,* in order to turn the axis, *xx,* into the meridian and to keep the compass pointing true north.

Bearing this in mind, and referring to the damping force *d* of Fig. 88, we see that *d* has to balance a rate of precession that varies with every change in latitude, and that unless this balance is absolutely exact for each latitude the compass will change the position of its settling point, *S,* upon a change of latitude so that while in one latitude it might settle at *S,* in other latitudes it might settle at S_1, or S_2 relative to the meridian plane. This balance is very difficult to accomplish in the actual building of a compass.

In practice, it is customary to mechanically construct a material compass which is exactly balanced or adjusted for one latitude, then calculate the error of the settling points (relative to the meridian) for other latitudes and correct for them by moving the lubber's line. In the German compass, this is done by loosening a couple of set screws and shifting the plate which has the lubber's line marked on it. In the Sperry compass a similar result is obtained by different mechanism described later.

The German compasses of 1910 were all adjusted for a mean latitude of 50° north. In going to other latitudes the errors due to change in latitude, which error is corrected in each case by shifting the lubber's line, are given in the following table:

FOR A COMPASS ADJUSTED TO BE CORRECT IN LATITUDE 50° N.

Latitude of Place	Error required to be corrected by shifting lubber's line (German Compass)
60° N	0° 36′ easterly.
50° N	None, compass designed for this latitude.
40° N	0° 30′ westerly.
20° N	1° 06′ westerly.
0°	1° 36′ westerly.
20° S	2° 06′ westerly.
40° S	2° 42′ westerly.
60° S	3° 48′ westerly.

204. How the Gravity Couple or Force of Gravity is Applied in the Gyroscopic Compass to Keep Tilting the Spinning Axis, *xx*, into the Horizontal Plane.—Throughout this paper the expression "gravity keeps the spinning axis turned into the horizontal plane" has been repeatedly used. (Study Figs. 76, 79, 81, 82 and 88.) Gravity is utilized to accomplish this as follows:

In the German compass of 1910 the casing carrying the gyro wheel is suspended from a hollow circular ring, *rr,* floating in a bowl of mercury, *mm.* The gyro wheel casing is rigidly connected to *rr* by *H* and *Z,* and as *rr* floats

horizontally on the surface of the mercury at every latitude, then *xx*, by the construction, is constrained to remain horizontal at every latitude.

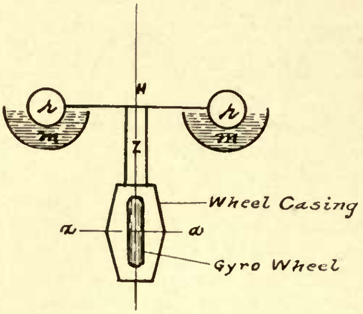

FIG. 89

In the Sperry compass, a similar result is obtained by a different construction.

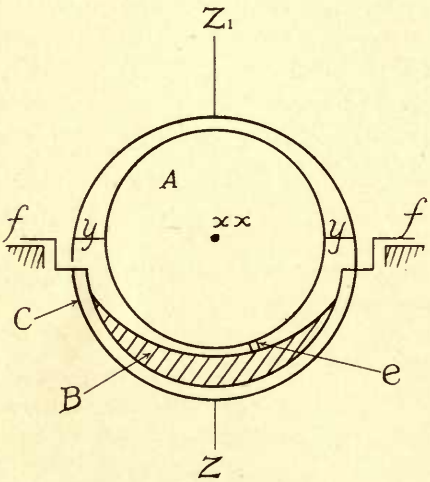

FIG. 90

In Fig. 90, *A* is the casing carrying the gyro wheel, *xx* its spinning axis; the horizontal and vertical axes, *YY* and *ZZ* being shown also. Between the ring *C* and the wheel casing *A* is a weight *B* (called the "bail") supported at points *ff* outside of the gyroscope proper. Under the influence of gravity, this weight hangs in the vertical plane through *ff* whatever may be the latitude of the place. There are slots in *C* which allow *B* to do this. Between the wheel casing *A* and the weight or bail *B* there is at *e* a pin connection or bearing.

Now the bail *B* constantly hangs in the vertical plane, but the plane of the gyro wheel *A* tending to keep its position in space as the earth revolves will tend to separate from *B*. The flexible pin connection *e* prevents this and thus gravity acting by means of *B* through *e* constantly tends to keep the plane of the spinning wheel, *A*, vertical and its spinning axis horizontal.

205. The Damping Couple.—A study of Fig. 90 will show that when *A* and *B* tend to separate not only is the gyro wheel rotated around the *YY* axis, but if *e* be set off to one side of the axis *ZZ*, *A* will receive from *B* through *e* rotation around *ZZ*. This brings into play the damping force *d* as explained in Fig. 88. In this compass, *e*, of Fig. 90, is called the "eccentric bearing."

206. Summary of Preceding Notes.—So far, all that has been written refers entirely to a compass mounted on a stationary base on shore. The notes have indicated the following points:

1. The axis of the gyroscope, with three degrees of freedom, tends to remain pointed in one and the same direction *in space* unless acted upon by an external force.

2. That in the gyroscopic compass the tendency of paragraph 1 is constantly overcome by a mechanical application of the force of gravity, which constantly tends to pull the axis of the spinning wheel into a horizontal position relative to the earth's surface.

3. That the pull of paragraph 2 causes the axis to tilt and this tilt results in precession which tends to make the spinning axis of the gyro always lie in a meridian plane (tends to set itself parallel to the earth's axis), *i. e.*, always point towards the earth's true poles, *i. e.*, true north.

4. That because of the material gyroscopic wheel possessing mass and inertia, the foregoing combined causes produce oscillations in the spinning wheel, rendering it useless for carrying a compass card unless these oscillations are checked or damped.

5. That damping is an essential feature of every practical gyroscopic compass.

6. That a compass may be built to read correctly for one latitude but will be in error in another latitude.

7. That the error in any latitude, other than that for which the compass was designed, is allowed for by moving the zero point (lubber's line) to compensate for the error due to differ-

ence in latitude. This correction which is dependent upon the latitude alone is known as the "latitude correction."

207. The Compass Mounted on a Moving Ship.*—The gyroscopic compass on a moving

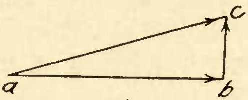

Fig. 1

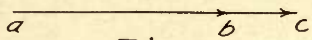

Fig. 2

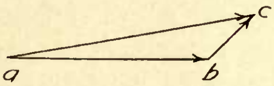

Fig. 3

ship does not point exactly to the true north but constantly requires the introduction of some three positive, or negative, correction factors before one can ascertain the true location of the meridian.

Referring to Figs. 81 and 82, suppose we take the compass at latitude $B°$ of Fig. 81, mount it on board ship and steam true north at a speed of 10 knots per hour to the place whose latitude is $C°$ of Fig. 82.

By so doing we have steamed directly from a place at which the rate of tilting of xx was 37° in 12 hours to a point at which the rate is 108° in 12 hours. Suppose in starting from *B,* we had steamed 20 knots per hour instead of 10 knots. We would thus arrive at *C* in one-half the time it would have taken us at 10 knots and the rate at which this change in the tilt of xx takes place, as due to differences in speed, would be twice as great in the second case as in the first case. Thus speed is introduced as a factor.

Suppose, starting from any point, we steam true east at either 10 or 20 knots. As we do not change our latitude, the *rate* of tilting of xx is the same at every point at which we arrive as it was at any point we left. There is no appreciable disturbance of the compass from this case because the ships speed is merely additive to that of the surface of the earth, as the earth revolves on its axis, and is negligible.

Suppose we steam NE. true. Then the true *northerly component* of the ship's speed will have an effect, because it changes the rate of tilting of xx and as this northerly component depends upon the ship's course, the course is thus introduced as a factor.

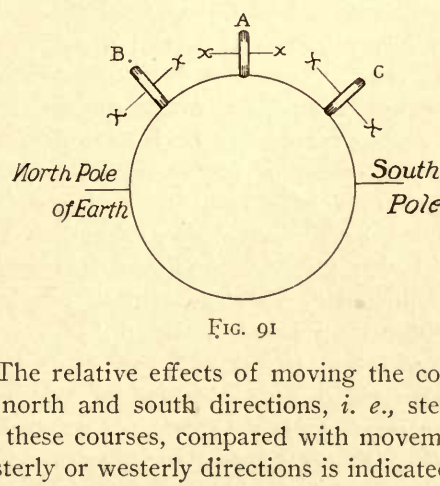

Fig. 91

The relative effects of moving the compass in north and south directions, *i. e.,* steaming on these courses, compared with movement in easterly or westerly directions is indicated very simply in Figs. 91 and 92.

* The following explanation of the deflection due to the actual movement of the ship north, or south, is due to the courtesy of Mr. Harry L. Tanner, Engineer of the Sperry Gyroscope Co.:

"If we assume the ship to be at rest and the earth rotating, the compass will assume a position with its axis in the plane of the earth's axis; then if we assume the earth to be standing and the ship to be moving north over the earth's surface, it will be moving in a great circle, the axis of which lies in the plane of the equator and the end of the compass wheel which is normally the north end will point west. It is evident that if we combine the movement of the ship and the rotation of the earth the compass will assume an intermediate position, and as the velocity due to the rotation of the earth is many times that due to the movement of the ship, this position will deviate but slightly from the plane of the earth's axis. The amount of this deviation may be computed as follows:

In Fig. 1 let ab represent the linear velocity of the compass due to the rotation of the earth (this velocity of course will vary with the latitude, being proportional to the cosine of the latitude) and bc the velocity of the ship with respect to the earth the resultant velocity will then be ac and the deviation of the compass will be equal to the angle cab.

In Fig. 2 the ship is shown with an easterly velocity bc and as ac coincides with bc, no deviation of the compass will be produced.

Fig. 3 shows the ship moving northeast and the angle cab is intermediate between that of Figs. 1 and 2. In practice, line ab is so long with respect to line bc that the easterly component of bc may be neglected and only the northerly component, which is equal to bc cosine ship's heading, need be considered.

In Fig. 91 let *A* be a gyro at the equator, the projection in Fig. 92 being on a meridian plane. If we steam true north or south from *A* to *B*, or to *C*, we do not transport *xx* parallel to itself in space but by introducing gravity cause it to tilt as shown, and this tilting of *xx* causes precession, the rate of which is affected, not only by the latitude we happen to be in, but by the speed with which we steam from *A* to *B*, or to *C*.

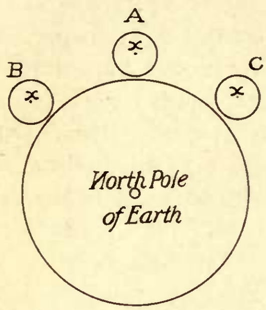

FIG. 92

In Fig. 92 we have a projection on the plane of the equator. From *A* let us steam true east, or west, to *B* or to *C*. In so doing we have transported the spinning axis *xx* of the gyroscopic wheel *parallel to itself in space*, in consequence of which there is no resulting precession. See Figs. 66 to 69 and the text thereon. If we steam east or west from any other latitude we do not change the *rate* of tilting of *xx*, *hence* there is no change in precession due to an east or west course alone.

208. The Sperry Compass.—Fig. 93 is a diagrammatic sketch of the Sperry compass. It is only intended to illustrate certain principles of construction and operation.

The gyroscope wheel *A* is mounted to spin on a horizontal axis, *xx*, within the casing *B*, which is pivoted on the horizontal axis *YY* through its center of gravity and carried by the frame or vertical ring *D*. The ring *D* is suspended by the tortionless strand *E* and guided by bearings *ZZ'* to allow a free oscillation of limited amount about its vertical axis *ZZ'* within the frame or phantom *G*.

The phantom *G* has a hollow stem *H* to which the strand *E* is attached at its upper end, and the stem forms a journal for rotation in azimuth with respect to the supporting base frame *J*. The frame *J* is mounted in gimbal rings *K'K'* on the binnacle in the same or similar manner as the ordinary magnetic compass is mounted in its binnacle stand.

Secured rigidly to the stem *H* of the phantom is a large gear wheel, *NN*, having 360 teeth, one tooth for each degree of azimuth. This gear wheel can only move with the phantom and conversely when the gear wheel, *NN*, is moved the phantom must move.

Rigidly secured to the frame *J*, and thus fixed relatively to the ship is a motor, *M*, whose small spur wheel *w* engages with the teeth of *NN*. Mounted rigidly on *NN* is the compass card *CC* graduated to 360°. Flush with the surface of the compass card is a flat ring, *FF*, on which is engaved the lubber's line. *FF* is supported by brackets, *QQ*, on the frame *J*. Rigidly secured to the lubber's ring, *FF*, is a transmitter *P* whose function is to transmit electrically to the repeater compass at the helmsman, or to the pelorus repeaters, any movement made by the compass card *CC*.

The wheel *A* together with the wheel casing *B* and the ring *D* is called the *sensitive element*. As a matter of fact, and most important, the sensitive element is the real gyroscopic compass, and all the other mechanism is installed simply to reproduce the exact movement, headings, or readings of the sensitive element in azimuth without interfering with it. Attached to the sensitive element, on the vertical posts, *a*, *a*, as shown, are two electrical trolley contacts, *a*, *a*, which make a light electrical contact with double stationary contacts *bb'*, *bb'* carried by the phantom. The object of this mechanism is to make the phantom carrying the compass card follow *exactly* every movement in azimuth of the axis of the gyro wheel and thus register in degrees either the heading (course) of the ship or the direction in which the gyro axis, *xx*, is pointing relative to the meridian. Furthermore, this movement, by means of the repeating transmitter, *P*, is sent to every steering compass, bridge pelorus, and repeater compass in the ship. This work is performed without any interference with the freedom of action of the sensitive element except that of the very light touch of the electrical contacts *aa* and *bb' bb'*.

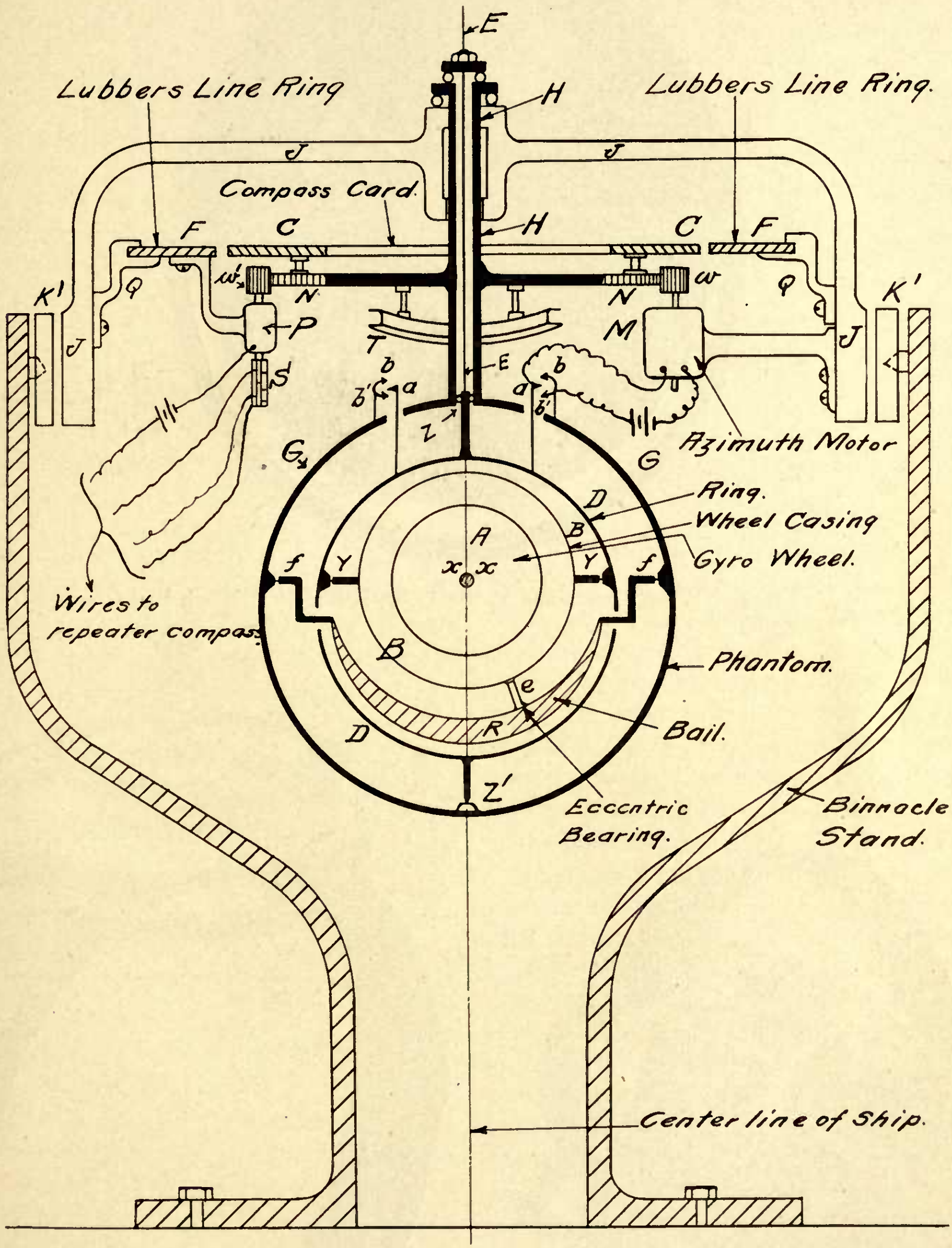

FIG. 93.—Partial diagram of section in an east and west line illustrating mounting and the follow up system.

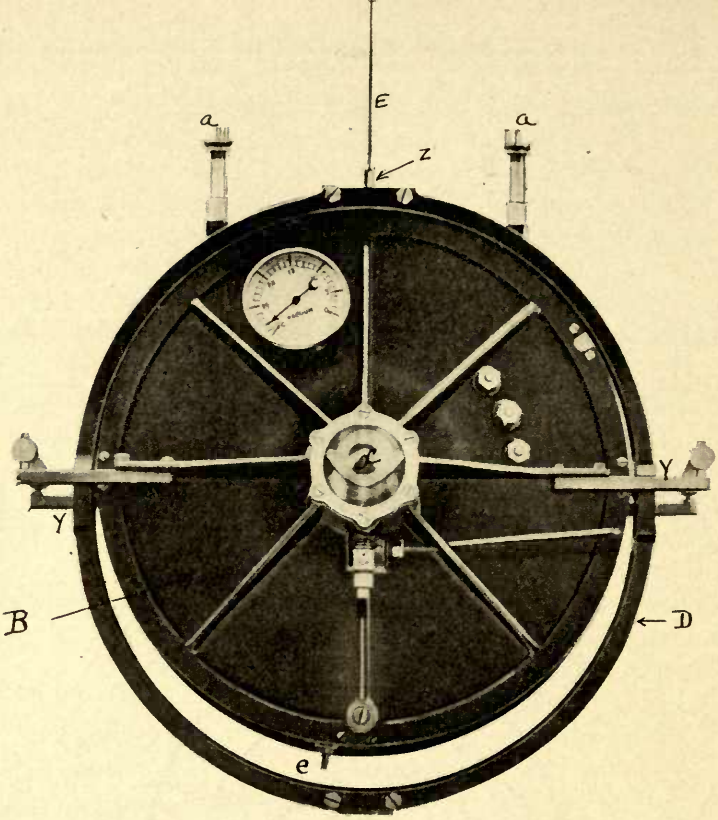

Fig. 94.—Wheel Casing and Vertical Supporting Ring, North End.

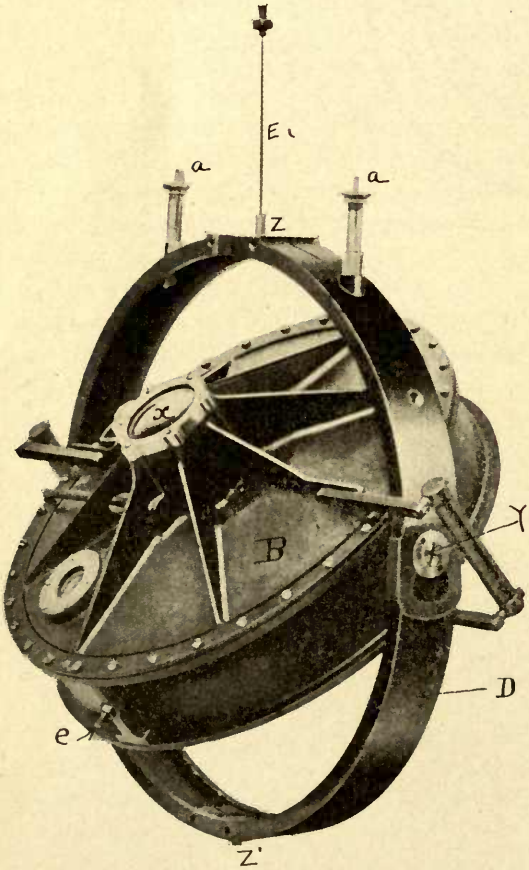

Fig. 95.—Wheel Casing and Vertical Supporting Ring, East Side.

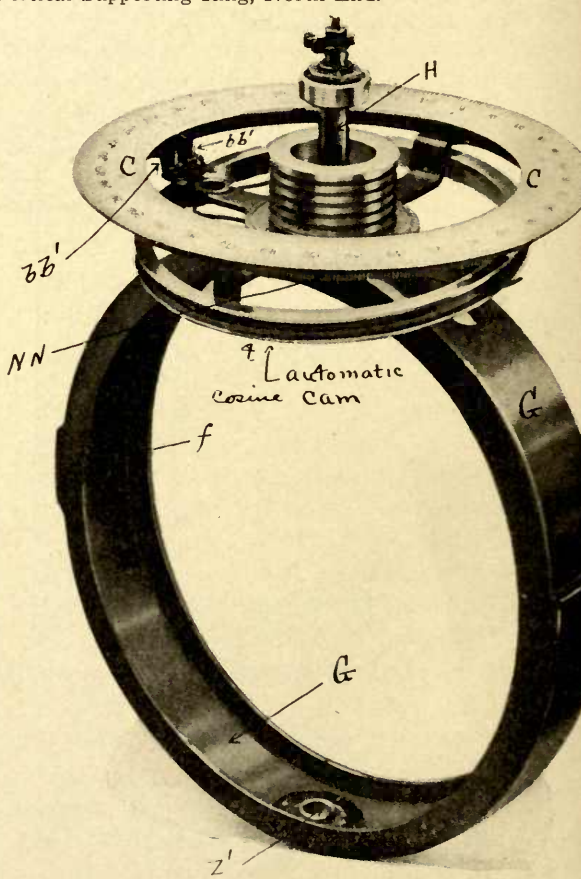

Fig. 96.—Phantom Card, Azimuth Gear and Cam for automatic Correction Mechanism.

Illustrations of the sensitive element and phantom are shown in Figs. 94, 95 and 96. Compare them with Fig. 93.

The method of operation follows:

Referring to Fig. 93, let us assume that the compass has been shut down and stopped for several days, that the ship is tied up to the dock and is stationary, heading say SE. and that the sensitive element has stopped so that its axis happens to be pointing in the direction of the keel line, SE. and NW., which is perpendicular to the plane of the paper upon which Fig. 93 is drawn. Now start the up compass. As the wheel A gathers speed, it will tend to move out of the plane of the paper upon which Fig. 93 is drawn and the axis, xx, will tend to turn into the meridian to point north and south, carrying with it the sensitive element. As the sensitive element moves in azimuth to seek the meridian the contacts aa come in touch with the contacts bb' bb' and send current through the azimuth motor M which in turn rotates NN (and the phantom and compass card) through exactly the same number of degrees in azimuth through which xx has turned. In other words the compass card is forced to register exactly the movement in azimuth of the gyroscopic wheel.

As NN is revolved by M it turns the spur wheel w' of the repeater transmitter P. This wheel carries a commutator or contact maker S which energizes the motors of the compass cards of each and every repeater compass in the ship and makes them, too, register exactly as the compass card, CC, of the master compass shown in Fig. 93.

The conception and construction of this "follow up" and repeating system is very pretty.

209. The Automatic Correction System.—Fig. 97 is a diagrammatic sketch of this mechanism. In studying this figure it must be borne in mind that it is a sketch made solely for the purpose of illustrating principles and is not a mechanical drawing of a machine. It merely illustrates how the operations may be carried on but does not show the exact mechanical details of the construction. In Fig. 97 and in Fig. 93 the same parts have the same letters.

As stated previously in these notes, the gyroscopic compass on moving ships does not point north as has been supposed, but constantly requires the introduction of some three positive, or negative, correction factors before one can ascertain the true location of the meridian. While on land a gyro compass will point to the absolute north, yet when mounted upon a moving body, as a ship, which has a northerly or southerly course, or component of course, the gyroscope no longer receives simple easterly motion (from the earth's rotation) but a mixed motion, and is accordingly deflected from the meridian to correspond with the new relative axis in space. The amount of this deflection depends upon three variables, namely, the course of the ship, the speed upon such course and the latitude. The latitude also introduces a second correction, due to certain characteristics of the compass. The formula for the total deflection is as follows:

$$D = \frac{aK \cos H}{\cos L} - b \tan L.$$

Where D = total correction for the deflection of the gyro compass from true geographical north; H = ship's heading or direction of travel on course figured in degrees from the geographical north; K = speed in knots; L = latitude; and a and b are constant reduction factors for the units employed and certain dimensions of the instrument.

Heretofore it has been necessary to make simultaneous readings of these three independent factors and compute the total correction, or else consult elaborate printed tables to determine the positive or negative correction necessary, in some cases to make various adjustments by the addition or removal of weights with changes of latitude. Mr. Sperry has produced an automatic correction apparatus which constitutes a simple part of the compass structure, by means of which all of the above components of deflection are exactly compensated for and automatically entered, so that all readings of the master compass, together with repeating compasses and other auxiliary apparatus are always held dead upon the meridian. The indication of each repeater located at remote parts of the ship is always held true and

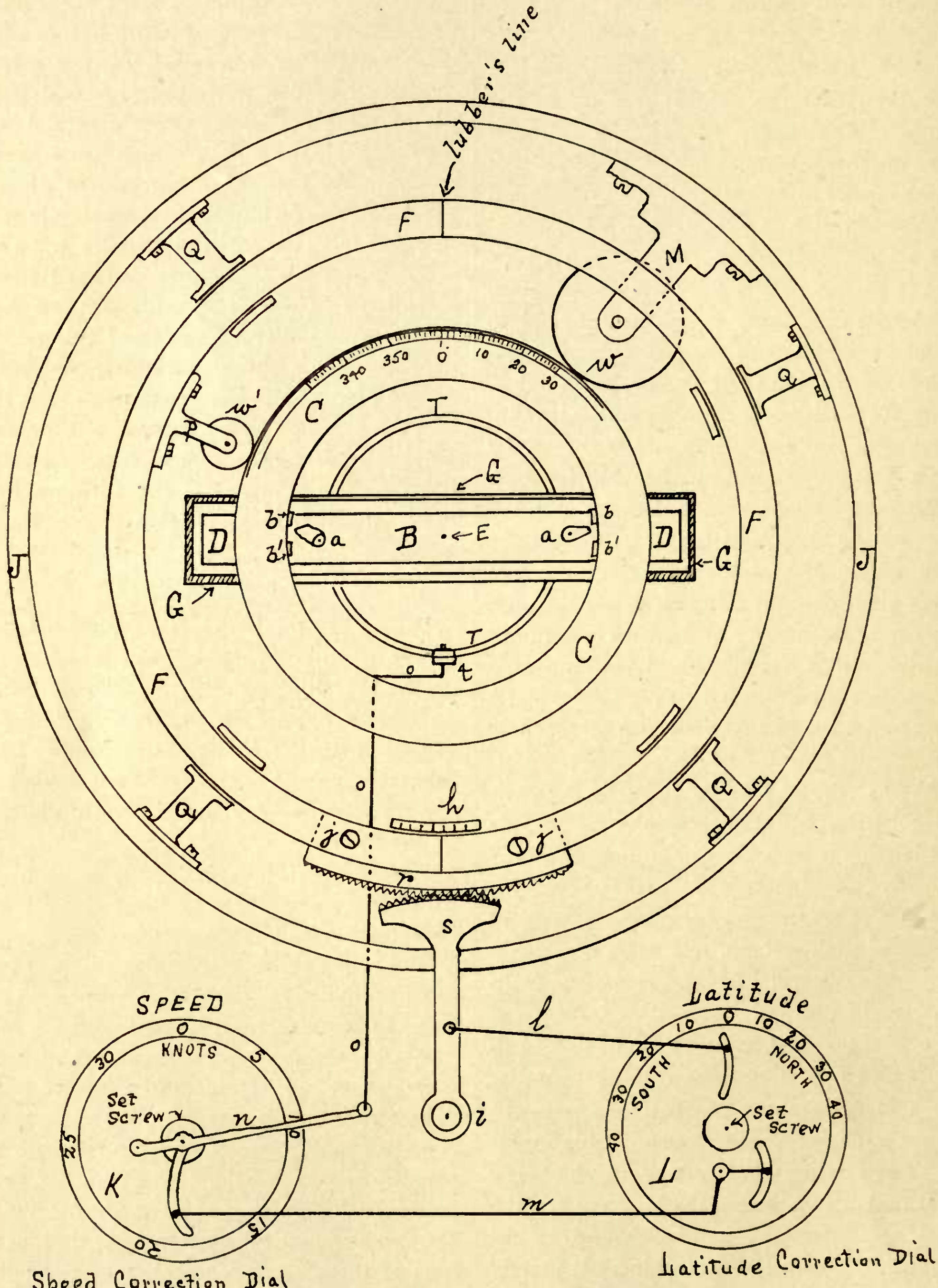

FIG. 97.—Diagram of Automatic Correction Mechanism.

found to read exactly upon the sun without any of the troublesome correcting factors mentioned above.

In Fig. 97, the compass card *CC*, the phantom *G*, sensitive element *BD*, lubber's line ring *FF*, azimuth motor *M*, repeater transmitter *Pw'* etc., are all shown, lettered and indicated as in Fig. 93.

Referring to Fig. 97, the lubber's line ring, *FF*, carries a small-toothed rack *r*, engaging in the teeth of the arm *s*, the arm *s* being pivoted at *i*. Rotation of *s* around *i* causes the lubber's line ring, *FF*, to slide around in its bearings, *QQQQ*.

An arm *l* connects *s* to the latitude correction dial *L*, which in turn is connected to the speed correction dial *K* by the arm *m*, and *K* in turn is connected by the arms *n* and *o* to a roller bearing *t* which engages in the slot of the cosine cam *T*. (See also Fig. 93.)

It will be seen that this construction is in effect a system of link work such that as *t* moves in accordance with the guide slot of the cam *T*, its motion is transmitted through *o, n, m, l, s* and *r* to the lubber's line ring, *FF*, and moves it to the right or left by an amount which is necessary to make the desired correction. The cosine cam *T* is designed to correct for the course of the ship, *i. e.*, when the ship changes her heading (or course) *T* automatically introduces that correction referred to where it stated "thus the course is introduced as a factor." When *FF* is moved by *s*, the repeating transmitter wheel *w'* rolls around *CC* which remains fixed, and thus each repeater compass in the ship is made to read exactly as the master compass. For example, if the lubber's line were moved 3° to the right of its position of 0° as shown in Fig. 97, the course by the master compass would then read N. 3° E. But while *FF* moved to the right 3° it would carry the repeater wheel *w'* with in and cause *w'* to roll around on *CC* and this movement of 3° would thus be electrically transmitted to, and simultaneously, registered on every repeater compass in the ship so that they, too, would read N. 3° E. exactly the same as the master compass.

The cosine cam *T* thus regulates the amount the lubber's line is moved to correct the error introduced by the ship steaming on any course between north and south, east and west.

For any specific course, the amount of correction introduced by the link work *l, m, n, o* will be always the same, provided the length and relative positions of the link work arms *l, m, n*, etc., remain unchanged.

The speed correction dials *K*, and the latitude correction dial *L* are a complicated series of disc cams, so constructed that by loosening up the set screws on either dial the proportional arrangement of the arms of the link work system connected to that dial may be altered *without changing the relative effect of the link arms attached to the other dial.* (The diagram does not show the mechanical details of this construction.)

Thus, to set the latitude dial so as to introduce its correction, slack up on the latitude dial set screw, turn the dial *L* to the proper latitude reading and then clamp the set screw again. The link work system now has the latitude correction combined with the course correction. To add the speed correction to the foregoing, slack up the set screw on the speed correction dial, *K*, turn this dial until it is set for the speed at which the ship is steaming, then clamp the set screw. The proportion of the arms of the link work system have now been so adjusted that the corrections for speed is automatically added to that for the latitude and course, and the lubber's line indicates, on the master compass card *CC*, the exact true course the ship is steering and all other repeater compasses in the ship indicate the same course as the master compass. ,See Fig. 98.

Fig. 99 shows a setting for 15 knots speed in latitude 40° N.

As the factor introduced by the cosine cam *T* is constant, this cam is so designed that when once installed no further adjustment of the cam itself is necessary.

When the compass is running normally and the dials are set for the correct latitude and speed there should be no error and this should be shown by the fact that true bearings or azimuths of the sun as observed by an azimuth circle on a repeater should be the same as the true bearing of the sun worked out by the azimuth tables. If these agree exactly there is no error in the compass and all bearings taken, or courses steered, by it are *true*.

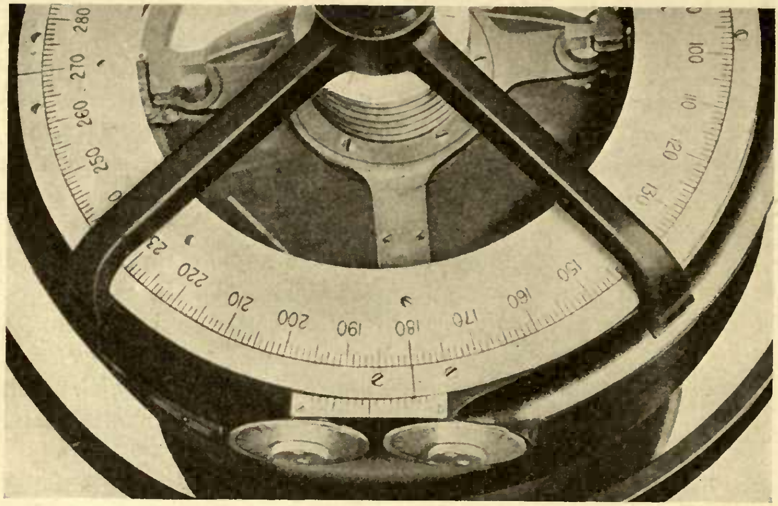

FIG. 98.—Portion of Master Compass Card, Showing Exact Meridianal Course, also the Amount of Correction being Automatically Introduced at the Moment.

If azimuths of the sun indicate an error in the compass in spite of the fact that the dials are correctly set for the correct speed and latitude, the presence of such an error indicates one of two things, viz.: (1) The presence of an oscillation, during which the error passes slowly

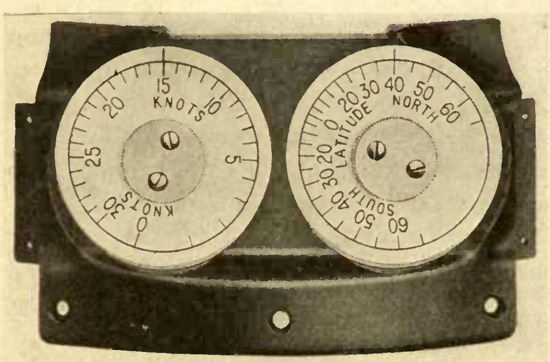

FIG. 99

to a maximum easterly error, then back to a corresponding maximum westerly error, and so continues for some time until the oscillation subsides; or (2) The compass may have changed its *settling point* so that it has a *constant* easterly, or westerly, error.

To Correct a Constant Error.—Loosen the small set screws *jj* (Fig. 97) found on each side of the lubber's line aft. Loosening these screws allows the lubber's line ring to be turned independently of the short rack *r* driven by *s*. By means of the thumb and forefinger of each hand, turn *FF* through the number of degrees measured on the scale *h* (Fig. 97) as an azimuth of the sun has shown the compass to be in error, then clamp or set up tightly on *jj*. Now if the dials are correctly set for speed and latitude the master compass and all repeaters

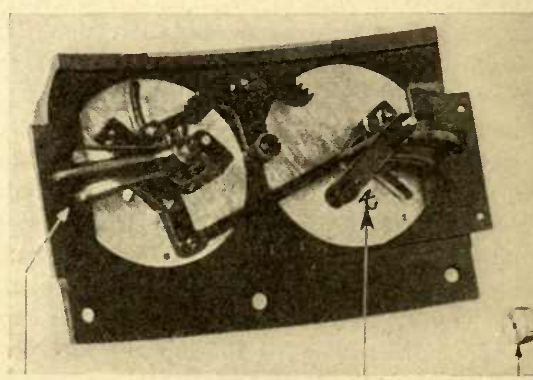

FIG. 99A.—Cosine cam engages here.

should show no error, by observation of the sun, under all conditions of service.

210. To Determine if the Compass has an Oscillation.—The period of the compass, *i. e.*, the time it takes to make one complete oscillation varies from 70 to 80 minutes, hence observations of the sun, or Polaris, for azimuth, taken every 10 or 15 minutes apart, extending over a period of 70 to 80 minutes, will show whether the compass is oscillating and, if so, the amount of such oscillation.

Or if the sea is calm and smooth, 10- to 15-minute comparisons of the ship's head per gyro compass with that per standard magnetic compass will disclose the oscillation.

Or if the ship is at rest, as at anchor in a smooth harbor, and no sun is available, the rise and fall of the axis due to an oscillation is indicated by the travel of the bubble in the spirit levels attached to the compass.

211. A Query.—To the reader not quite familiar with the principles of operation of the compass the thought may arise that the lubber's line on *FF* has been indiscriminately moved around *CC* and then said to give a true reading. How can this be so? The keel of the ship has not changed! The lubber's line on the steering compass and pelorus dials on the bridge are absolutely fixed and installed parallel to the keel of the ship and cannot be changed, yet you are constantly shifting the lubber's line on the master compass and say this gives true courses and bearings on the bridge! How can this be so?

The answer is simply this: The compass cards of each and every repeater compass are controlled and moved by the lubber's line ring *FF*. They move with *it* and not with the compass card *CC* of the master compass. The compass card of the master compass by virtue of its association and connection with the sensitive element, serves as a scale upon which to indicate the true bearing of the meridian. Hence, if we move the lubber's line, *FF*, around *CC* to a point reading, say 346° on *CC*, then each repeater compass *card* will move around to register 346° by the fixed lubber's (keel) lines on the bridge compass, and will show the ship to be steaming a true course of 346°. If 346° be not the course to be steered to reach port, then the keel of the ship *is* altered by the rudder to such a course as will bring her to the desired destination.

In other words, in the master compass we have the lubber's line travel around the master compass card, but in the repeater compass the card travels around under the lubber's line. As the movement in azimuth is identical in each case, each compass will read the same number of degrees.

212. Rolling and Pitching.—All of the foregoing notes upon the principle of operation of this compass have referred (1) to a compass mounted on shore and (2) to a compass mounted on board a ship moving in a *smooth calm* sea.

When the ship rolls and pitches, new forces and conditions arise. The forces due to the rolling and pitching of the ship may be resolved into two components; (1) the accelerating forces due to reversal of direction, and, (2) centrifugal forces due to the fact that the parts of the compass have an angular motion in addition to the motion of translation.

In the Sperry compass the effect of the acceleration forces on the compass is overcome by means of the stabilizer gyro shown in Figs. 100 and 100A while the centrifugal forces are overcome by means of the compensating weights shown in Figs. 100a and 100b.

The Sperry compass in service aboard the *Montana* gave us great comfort and satisfaction and we relied upon it. We considered it a wonderful instrument and one of the most valuable additions of modern science to the sea-going world. In the conning-tower, and below decks, its freedom from magnetic influence is most valuable.

It requires for its proper functioning the *intelligent* care and supervision of officers and electricians who *know how* to run it, but it did not require greater specialization along its particular lines than did guns, torpedoes, chronometers or any other mechanical devices installed in a modern ship.

I have only praise for it. Like everything else, though, success with it depends upon intelligent care and operation.

APPENDIX.

213. The following explanation of the deviations due to accelerating and centrifugal forces and their correction is by Mr. Harry L. Tanner, engineer of the Sperry Gyroscope Company, to whom acknowledgment is here made:

214. Compass Deviations Due to Acceleration Forces.—The compass wheel, wheel case and bail may be represented diagrammatically by a rotating disk *A*, Fig. 101, rotating on bearings *B* in a U-shaped frame *C*, which is in turn suspended by means of a flexible cord *D*.

FIG. 100.—Floating Ballistic or Stabilizer.

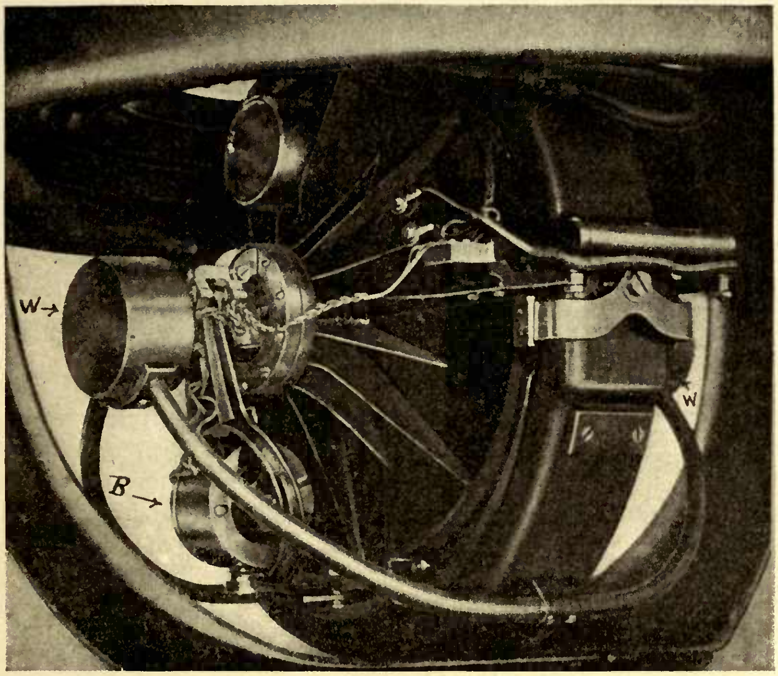

FIG. 100A.—Master Compass, North West Elevation; Showing Stabilizer or Floating Ballistic *B*, and compensating weight *WW*.

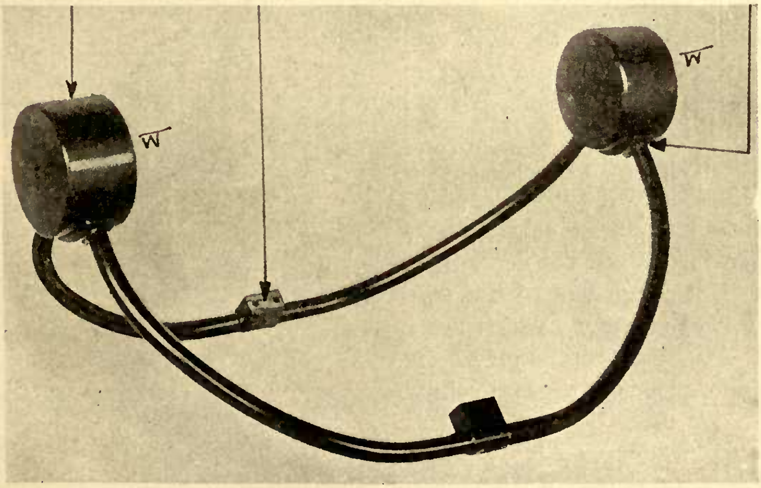

FIG. 100B.—Compensator Weight and Frame.

The ballistic factor of the compass is represented by the weight of the disk *A*, multiplied by the distance from center of the disk to point *E* when flexible cord *D* is attached to frame *C*.

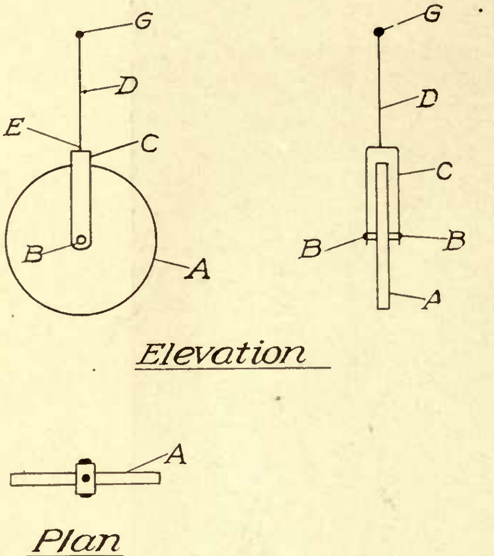

FIG. 101

Now suppose, for instance, that the compass be accelerated alternately NE. and SW., Fig. 102. The whole compass will act as a pendulum and will take up a position such that the cord *D* will be parallel to the line of the force *F*, which is the resultant of the acceleration force and gravity.

The frame *C* will respond to the *EW*. component of this force, but not to the *NS*. component on account of being stabilized in this direction by the disk *A*.

Let α, shown in projection in Fig. 102 as α', represent the angle between force *F* and the horizontal plane, then the horizontal component of *F* will be $F \cos \alpha$. When the acceleration force is NE. the *NS*. component of this force will produce a torque about *xy*, which lies in the plane of the disk. This torque may be resolved into a component about the vertical axis *zy* and a component about the horizontal *xz*. Similarly, when the acceleration force is SW. the arrows *z'y'* and *x'z'* represent components of torque about the vertical and horizontal axes respectively. It will be seen that the torques about *xz* and *x'z'* are equal and opposite and therefore cancel, but that the torque about *zy* and *z'y'* are in the same direction and therefore add, giving a torque about the vertical axis of the disk which, acting through a cycle of precessions, will cause a movement of the disk in the direction of the torque.

Similarly, it may be shown that alternate NW. and SE. accelerations will produce a torque in the opposite direction about the vertical axis.

As the direction of the acceleration pressures approaches the *EW*. line it is evident that the *NS*. component of the force $F \cos \alpha$ will approach zero and as the acceleration pressures approach the *NS*. line, the lever arm of these forces about the vertical axis will approach zero, in either case resulting in zero torque about the vertical axis.

As explained, the compass deviations, due to accelerating forces, are due to the fact that the force and lever arm reverse at the same instant, giving a torque in a constant direction about the vertical axis of the compass. By reducing either of these components to zero or making the direction of either constant while the other changes, we shall have either zero

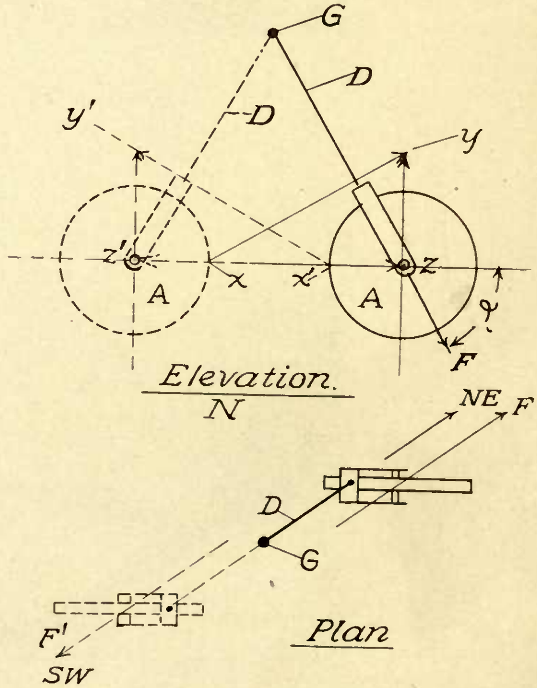

FIG. 102

torque about the vertical axis or equal positive and negative torques, which would give a resultant zero torque. The latter method is made use of in the compass.

As all of the forces acting upon the wheel in the compass are introduced through the bail, it is only necessary to hold the point of connection between the bail and wheel case fixed with respect to a vertical line passing through the center of the wheel. As far as the effect of the acceleration force goes, it makes no difference what this position is so long as it is fixed, but to secure damping it is nearly one-fourth inch to the east of the center of the wheel.

Referring to Figs. 103 and 104 it will be noted that the stablizer is mounted on the north side of the compass wheel case, the bearings at point *A* leaving it free to swing about an axis parallel to that about which the main compass wheel spins.

The small gyroscope, *B,* spins upon an EW. axis and is free to precess about a vertical axis, the bearings being shown at *CC.*

Due to the stablizing effect of the gyroscope *B,* the frame *D* will be held in a fixed relation to a vertical line passing through the center of the main compass wheel, and the small rollers, *EE,* are therefore held a fixed distance from a plane passing through the axis of the main wheel. These rollers run in tracks, *F,* attached to the wheel case and *G* attached to the bail.

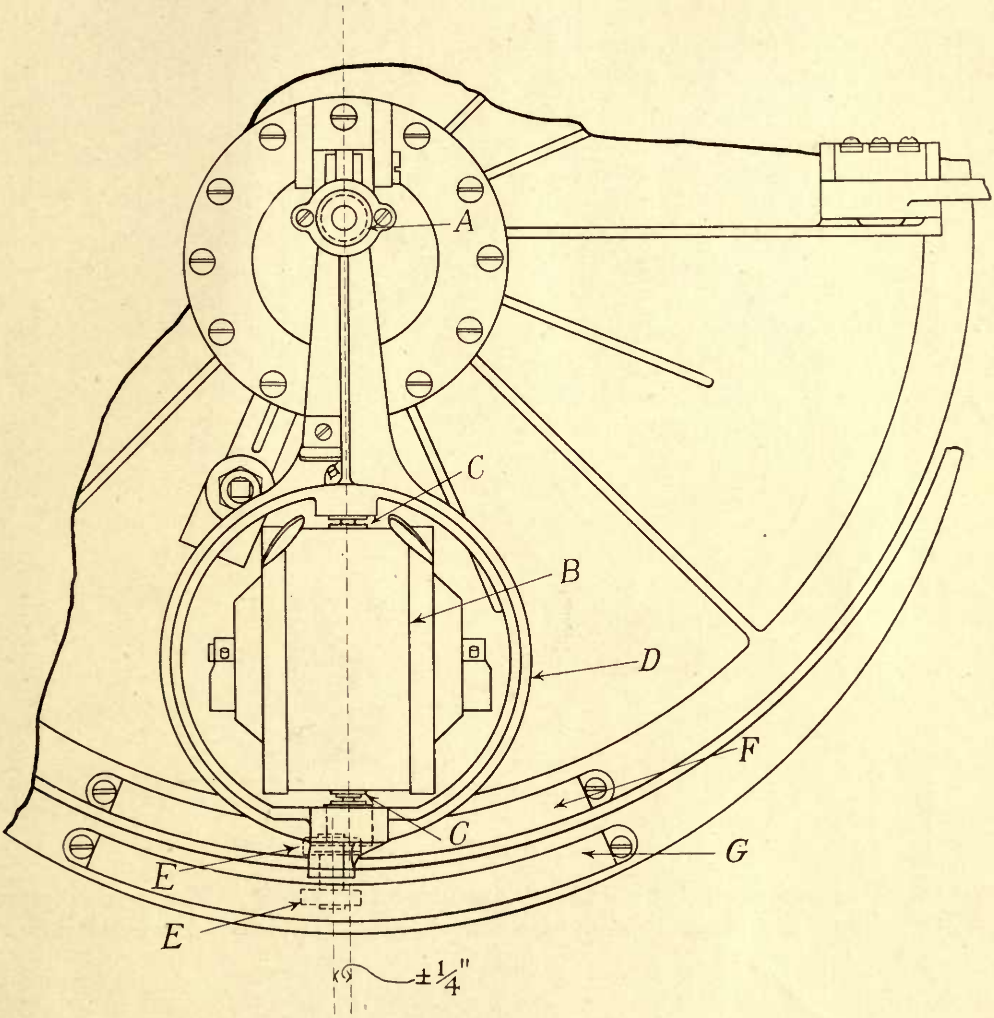

FIG. 103

215. Compass Deviations Due to Centrifugal Force.—*Cause of Deviations.*—If a bar *A,* Fig. 105, be suspended by means of a wire loop *B,* and a thread *C,* and be swung as a pendulum about an axis passing through *D*

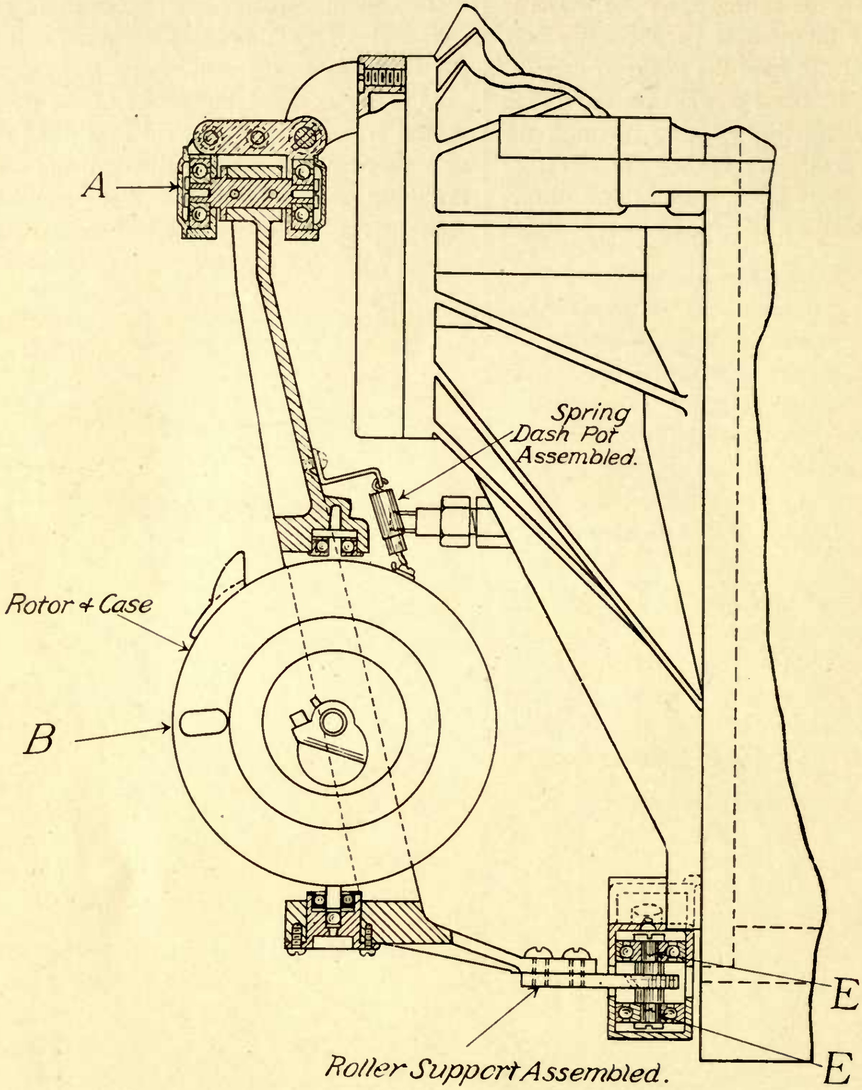

FIG. 104

it will take up a position such that the bar *A*, and thread *C*, will lie in a plane perpendicular

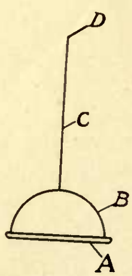

FIG. 105

to the axis of swing through *D*. This is illustrated in Figs. 106 and 106a in which *A* represents the bar and *ab* the axis about which the pendulum is swung. The arrows represent the direction in which the bar would turn. This

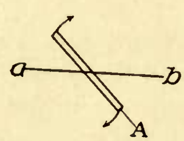

FIG. 106

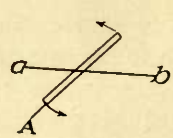

FIG. 106A

has been determined mathematically and later verified by actually constructing the apparatus as illustrated and testing.

Application to Compass.—It will at once be seen from Figs. 107 and 108 that the vertical ring, wheel case and stator of the compass, *i. e.*, the entire sensitive element with the exception of the rotor (which does not enter in any way

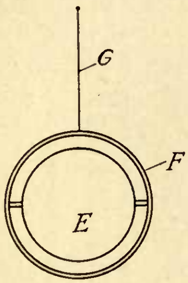

FIG. 107

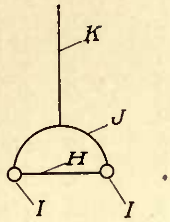

FIG. 108

on account of being free to turn on its bearings about an axis perpendicular to the plane of the paper and being stabilized about an axis passing through the horizontal bearings of the case) may be replaced by a weightless rod *H*, a weightless support *J* and thread *K* and two weights *I, I*.

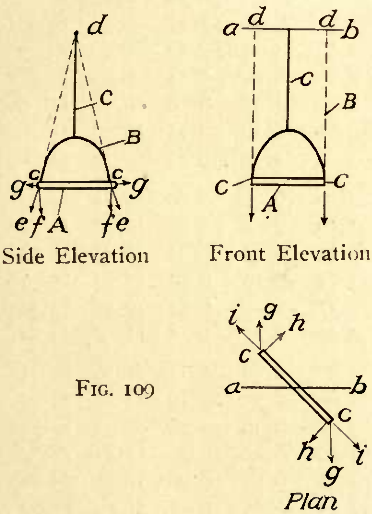

FIG. 109

Theory.—Fig. 109 shows the apparatus of Fig. 105 swinging about an axis which makes an angle of about 45° with the bar *A*. It is evident that any point in the bar will swing in a plane perpendicular to the axis *ab* and in the arc of a circle of which the center lies in the axis *ab*. Thus the particle *c* would move in an arc of a circle of radius *cd* and in a plane perpendicular to *ab*. The centrifugal force then would be directed along the line *dc*. This force can be resolved, as shown, into components *cf* and *cg*. Then *cg* can be again resolved into components *ch* and *ci*. It will be seen that all components such as *ci* have no effect other than to produce tension in the bar *A* but that all components such as *ch* produce a couple tending to rotate the bar toward a position perpendicular to *ab*.

Remedy.—From Figs. 106 and 106a it will be seen that two like bars which are 90° apart have equal torques in opposite directions. Therefore, if we should fasten two of these bars together the forces would exactly neutralize each other. This would be true when the cross is placed in any position so long as the bars are at right angles to each other, as the torque is proportional to the product of the sine and cosine of the angle with the axis of swing so comes up to a maximum at 45° and drops to zero at 0° or 90°.

It will be evident from Fig 110 (or Fig. 110a) that the effect of the crossed bars may be secured in the compass by attaching arms *MM* to the north and south sides of the vertical

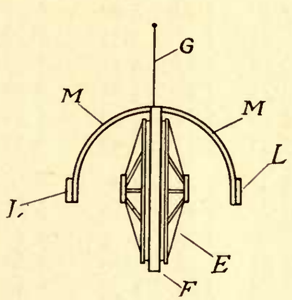

FIG. 110

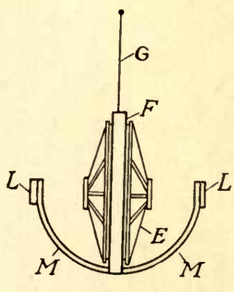

FIG. 110A

ring and attaching weights *LL* to them at points in line with the center of the wheel. These weights must be attached to the vertical ring as they would have no effect if attached to the stabilized case. See Figs. 100a and 100b.

TABLE I.

USED FOR CALCULATION OF COEFFICIENTS B, C, D, AND E.

Products of Arcs Multiplied by the Sines of 15° Rhumbs.

ARCS.	S_1 Sin. 15°	S_2 Sin. 30°	S_3 Sin. 45°	S_4 Sin. 60°	S_5 Sin. 75°	ARCS.
° ′	° ′	° ′	° ′	° ′	° ′	° ′
0 0	0 0	0 0	0 0	0 0	0 0	0 0
0 10	0 3	0 5	0 7	0 9	0 10	0 10
0 20	0 5	0 10	0 14	0 17	0 19	0 20
0 30	0 8	0 15	0 21	0 26	0 29	0 30
0 40	0 10	0 20	0 28	0 35	0 39	0 40
0 50	0 13	0 25	0 35	0 43	0 48	0 50
1 0	0 16	0 30	0 42	0 52	0 58	1 0
1 10	0 18	0 35	0 49	1 1	1 8	1 10
1 20	0 21	0 40	0 57	1 9	1 17	1 20
1 30	0 23	0 45	1 4	1 18	1 27	1 30
1 40	0 26	0 50	1 11	1 27	1 37	1 40
1 50	0 28	0 55	1 18	1 35	1 46	1 50
2 0	0 31	1 0	1 25	1 44	1 56	2 0
2 10	0 34	1 5	1 32	1 53	2 6	2 10
2 20	0 36	1 10	1 39	2 1	2 15	2 20
2 30	0 39	1 15	1 46	2 10	2 25	2 30
2 40	0 41	1 20	1 53	2 19	2 35	2 40
2 50	0 44	1 25	2 0	2 27	2 44	2 50
3 0	0 47	1 30	2 7	2 36	2 54	3 0
3 10	0 49	1 35	2 14	2 45	3 04	3 10
3 20	0 52	1 40	2 21	2 53	3 13	3 20
3 30	0 54	1 45	2 29	3 2	3 23	3 30
3 40	0 57	1 50	2 36	3 11	3 33	3 40
3 50	1 0	1 55	2 43	3 19	3 42	3 50
4 0	1 2	2 0	2 50	3 28	3 52	4 0
4 10	1 5	2 5	2 57	3 37	4 1	4 10
4 20	1 7	2 10	3 4	3 45	4 11	4 20
4 30	1 10	2 15	3 11	3 54	4 21	4 30
4 40	1 12	2 20	3 18	4 2	4 30	4 40
4 50	1 15	2 25	3 25	4 11	4 40	4 50
5 0	1 18	2 30	3 32	4 20	4 50	5 0
5 10	1 20	2 35	3 39	4 28	4 59	5 10
5 20	1 23	2 40	3 46	4 37	5 9	5 20
5 30	1 25	2 45	3 53	4 46	5 19	5 30
5 40	1 28	2 50	4 0	4 54	5 28	5 40
5 50	1 31	2 55	4 7	5 3	5 38	5 50
6 0	1 33	3 0	4 15	5 12	5 48	6 0
6 10	1 36	3 5	4 22	5 20	5 57	6 10
6 20	1 38	3 10	4 29	5 29	6 7	6 20
6 30	1 41	3 15	4 36	5 38	6 17	6 30
6 40	1 44	3 20	4 43	5 46	6 26	6 40
6 50	1 46	3 25	4 50	5 55	6 36	6 50
7 0	1 49	3 30	4 57	6 4	6 46	7 0
7 10	1 51	3 35	5 4	6 12	6 55	7 10
7 20	1 54	3 40	5 11	6 21	7 5	7 20
7 30	1 56	3 45	5 18	6 30	7 15	7 30
7 40	1 59	3 50	5 25	6 38	7 24	7 40
7 50	2 2	3 55	5 32	6 47	7 34	7 50

ARCS.	S_1 Sin. 15°	S_2 Sin. 30°	S_3 Sin. 45°	S_4 Sin. 60°	S_5 Sin. 75°	ARCS.
° ′	° ′	° ′	° ′	° ′	° ′	° ′
8 0	2 4	4 0	5 39	6 56	7 44	8 0
8 10	2 7	4 5	5 46	7 4	7 53	8 10
8 20	2 9	4 10	5 54	7 13	8 3	8 20
8 30	2 12	4 15	6 1	7 22	8 13	8 30
8 40	2 15	4 20	6 8	7 30	8 22	8 40
8 50	2 17	4 25	6 15	7 39	8 32	8 50
9 0	2 20	4 30	6 22	7 48	8 42	9 0
9 10	2 22	4 35	6 29	7 56	8 51	9 10
9 20	2 25	4 40	6 36	8 5	9 1	9 20
9 30	2 28	4 45	6 43	8 14	9 11	9 30
9 40	2 30	4 50	6 50	8 22	9 20	9 40
9 50	2 33	4 55	6 57	8 31	9 30	9 50
10 0	2 35	5 0	7 4	8 40	9 40	10 0
10 10	2 38	5 5	7 11	8 48	9 49	10 10
10 20	2 40	5 10	7 18	8 57	9 59	10 20
10 30	2 43	5 15	7 25	9 6	10 9	10 30
10 40	2 46	5 20	7 33	9 14	10 18	10 40
10 50	2 48	5 25	7 40	9 23	10 28	10 50
11 0	2 51	5 30	7 47	9 32	10 38	11 0
11 10	2 53	5 35	7 54	9 40	10 47	11 10
11 20	2 56	5 40	8 1	9 49	10 57	11 20
11 30	2 59	5 45	8 8	9 58	11 6	11 30
11 40	3 1	5 50	8 15	10 6	11 16	11 40
11 50	3 4	5 55	8 22	10 15	11 26	11 50
12 0	3 6	6 0	8 29	10 24	11 35	12 0
12 10	3 9	6 5	8 36	10 32	11 45	12 10
12 20	3 12	6 10	8 43	10 41	11 55	12 20
12 30	3 14	6 15	8 50	10 50	12 4	12 30
12 40	3 17	6 20	8 57	10 58	12 14	12 40
12 50	3 19	6 25	9 4	11 7	12 24	12 50
13 0	3 22	6 30	9 12	11 16	12 33	13 0
13 10	3 24	6 35	9 19	11 24	12 43	13 10
13 20	3 27	6 40	9 26	11 33	12 53	13 20
13 30	3 30	6 45	9 33	11 41	13 2	13 30
13 40	3 32	6 50	9 40	11 50	13 12	13 40
13 50	3 35	6 55	9 47	11 59	13 22	13 50
14 0	3 37	7 0	9 54	12 7	13 31	14 0
14 10	3 40	7 5	10 1	12 16	13 41	14 10
14 20	3 43	7 10	10 8	12 25	13 51	14 20
14 30	3 45	7 15	10 15	12 33	14 0	14 30
14 40	3 48	7 20	10 22	12 42	14 10	14 40
14 50	3 50	7 25	10 29	12 51	14 20	14 50
15 0	3 53	7 30	10 36	12 59	14 29	15 0
15 10	3 56	7 35	10 43	13 8	14 39	15 10
15 20	3 58	7 40	10 51	13 17	14 49	15 20
15 30	4 1	7 45	10 58	13 25	14 58	15 30
15 40	4 3	7 50	11 5	13 34	15 8	15 40
15 50	4 6	7 55	11 12	13 43	15 18	15 50

TABLE I.—Products of Arcs Multiplied by the Sines of 15° Rhumbs.—*Continued.*

ARCS.	S_1 Sin. 15°	S_2 Sin. 30°	S_3 Sin. 45°	S_4 Sin. 60°	S_5 Sin. 75°	ARCS.
° ′	° ′	° ′	° ′	° ′	° ′	° ′
16 0	4 8	8 0	11 19	13 51	15 27	16 0
16 10	4 11	8 5	11 26	14 0	15 37	16 10
16 20	4 14	8 10	11 33	14 9	15 47	16 20
16 30	4 16	8 15	11 40	14 17	15 56	16 30
16 40	4 19	8 20	11 47	14 26	16 6	16 40
16 50	4 21	8 25	11 54	14 35	16 16	16 50
17 0	4 24	8 30	12 1	14 43	16 25	17 0
17 10	4 27	8 35	12 8	14 52	16 35	17 10
17 20	4 29	8 40	12 15	15 1	16 45	17 20
17 30	4 32	8 45	12 22	15 9	16 54	17 30
17 40	4 34	8 50	12 30	15 18	17 4	17 40
17 50	4 37	8 55	12 37	15 27	17 14	17 50
18 0	4 40	9 0	12 44	15 35	17 23	18 0
18 10	4 42	9 5	12 51	15 44	17 33	18 10
18 20	4 45	9 10	12 58	15 53	17 43	18 20
18 30	4 47	9 15	13 5	16 1	17 52	18 30
18 40	4 50	9 20	13 12	16 10	18 2	18 40
18 50	4 52	9 25	13 19	16 19	18 12	18 50
19 0	4 55	9 30	13 26	16 27	18 21	19 0
19 10	4 58	9 35	13 33	16 36	18 31	19 10
19 20	5 0	9 40	13 40	16 45	18 40	19 20
19 30	5 3	9 45	13 47	16 53	18 50	19 30
19 40	5 5	9 50	13 54	17 2	19 0	19 40
19 50	5 8	9 55	14 1	17 11	19 9	19 50
20 0	5 11	10 0	14 9	17 19	19 19	20 0
20 10	5 13	10 5	14 16	17 28	19 29	20 10
20 20	5 16	10 10	14 23	17 37	19 38	20 20
20 30	5 18	10 15	14 30	17 45	19 48	20 30
20 40	5 21	10 20	14 37	17 54	19 58	20 40
20 50	5 24	10 25	14 44	18 3	20 7	20 50
21 0	5 26	10 30	14 51	18 11	20 17	21 0
21 10	5 29	10 35	14 58	18 20	20 27	21 10
21 20	5 31	10 40	15 5	18 29	20 36	21 20
21 30	5 34	10 45	15 12	18 37	20 46	21 30
21 40	5 36	10 50	15 19	18 46	20 56	21 40
21 50	5 39	10 55	15 26	18 54	21 5	21 50
22 0	5 42	11 0	15 33	19 3	21 15	22 0
22 10	5 44	11 5	15 40	19 12	21 25	22 10
22 20	5 47	11 10	15 48	19 20	21 34	22 20
22 30	5 49	11 15	15 55	19 29	21 44	22 30
22 40	5 52	11 20	16 2	19 38	21 54	22 40
22 50	5 55	11 25	16 9	19 46	22 3	22 50
23 0	5 57	11 30	16 16	19 55	22 13	23 0
23 10	6 0	11 35	16 23	20 4	22 23	23 10
23 20	6 2	11 40	16 30	20 12	22 32	23 20
23 30	6 5	11 45	16 37	20 21	22 42	23 30
23 40	6 8	11 50	16 44	20 30	22 52	23 40
23 50	6 10	11 55	16 51	20 38	23 1	23 50

ARCS.	S_1 Sin. 15°	S_2 Sin. 30°	S_3 Sin. 45°	S_4 Sin. 60°	S_5 Sin. 75°	ARCS
° ′	° ′	° ′	° ′	° ′	° ′	° ′
24 0	6 13	12 0	16 58	20 47	23 11	24 0
24 10	6 15	12 5	17 5	20 56	23 21	24 10
24 20	6 18	12 10	17 12	21 4	23 30	24 20
24 30	6 20	12 15	17 19	21 13	23 40	24 30
24 40	6 23	12 20	17 27	21 22	23 50	24 40
24 50	6 26	12 25	17 34	21 30	23 59	24 50
25 0	6 28	12 30	17 41	21 39	24 9	25 0
25 10	6 31	12 35	17 48	21 48	24 18	25 10
25 20	6 33	12 40	17 55	21 56	24 28	25 20
25 30	6 36	12 45	18 2	22 5	24 38	25 30
25 40	6 39	12 50	18 9	22 14	24 48	25 40
25 50	6 41	12 55	18 16	22 22	24 57	25 50
26 0	6 44	13 0	18 23	22 31	25 7	26 0
26 10	6 46	13 5	18 30	22 40	25 17	26 10
26 20	6 49	13 10	18 37	22 48	25 26	26 20
26 30	6 52	13 15	18 44	22 57	25 36	26 30
26 40	6 54	13 20	18 51	23 6	25 45	26 40
26 50	6 57	13 25	18 58	23 14	25 55	26 50
27 0	6 59	13 30	19 6	23 23	26 5	27 0
27 10	7 2	13 35	19 13	23 32	26 14	27 10
27 20	7 4	13 40	19 20	23 40	26 24	27 20
27 30	7 7	13 45	19 27	23 49	26 34	27 30
27 40	7 10	13 50	19 34	23 58	26 43	27 40
27 50	7 12	13 55	19 41	24 6	26 53	27 50
28 0	7 15	14 0	19 48	24 15	27 3	28 0
28 10	7 17	14 5	19 55	24 24	27 12	28 10
28 20	7 20	14 10	20 2	24 32	27 22	28 20
28 30	7 23	14 15	20 9	24 41	27 32	28 30
28 40	7 25	14 20	20 16	24 50	27 41	28 40
28 50	7 28	14 25	20 23	24 58	27 51	28 50
29 0	7 30	14 30	20 30	25 7	28 1	29 0
29 10	7 33	14 35	20 37	25 16	28 10	29 10
29 20	7 36	14 40	20 45	25 24	28 20	29 20
29 30	7 38	14 45	20 52	25 33	28 30	29 30
29 40	7 41	14 50	20 59	25 42	28 39	29 40
29 50	7 43	14 55	21 6	25 50	28 49	29 50
30 0	7 46	15 0	21 13	25 59	28 59	30 0
30 10	7 48	15 5	21 20	26 8	29 8	30 10
30 20	7 51	15 10	21 27	26 16	29 18	30 20
30 30	7 54	15 15	21 34	26 25	29 28	30 30
30 40	7 56	15 20	21 41	26 33	29 37	30 40
30 50	7 59	15 25	21 48	26 42	29 47	30 50
31 0	8 1	15 30	21 55	26 51	29 57	31 0
31 10	8 4	15 35	22 2	26 59	30 6	31 10
31 20	8 7	15 40	22 9	27 8	30 16	31 20
31 30	8 9	15 45	22 16	27 17	30 26	31 30
31 40	8 12	15 50	22 24	27 25	30 35	31 40
31 50	8 14	15 55	22 31	27 34	30 45	31 50

TABLE I.—Products of Arcs Multiplied by the Sines of 15° Rhumbs.—*Continued.*

ARCS.	S_1 Sin. 15°	S_2 Sin. 30°	S_3 Sin. 45°	S_4 Sin. 60°	S_5 Sin. 75°	ARCS.
° ′	° ′	° ′	° ′	° ′	° ′	° ′
32 0	8 17	16 0	22 38	27 43	30 55	32 0
32 10	8 20	16 5	22 45	27 51	31 4	32 10
32 20	8 22	16 10	22 52	28 0	31 14	32 20
32 30	8 25	16 15	22 59	28 9	31 24	32 30
32 40	8 27	16 20	23 6	28 17	31 33	32 40
32 50	8 30	16 25	23 13	28 26	31 43	32 50
33 0	8 32	16 30	23 20	28 35	31 53	33 0
33 10	8 35	16 35	23 27	28 43	32 2	33 10
33 20	8 38	16 40	23 34	28 52	32 12	33 20
33 30	8 40	16 45	23 41	29 1	32 22	33 30
33 40	8 43	16 50	23 48	29 9	32 31	33 40
33 50	8 45	16 55	23 55	29 18	32 41	33 50
34 0	8 48	17 0	24 3	29 27	32 50	34 0
34 10	8 51	17 5	24 10	29 35	33 0	34 10
34 20	8 53	17 10	24 17	29 44	33 10	34 20
34 30	8 56	17 15	24 24	29 53	33 19	34 30
34 40	8 58	17 20	24 31	30 1	33 29	34 40
34 50	9 1	17 25	24 38	30 10	33 39	34 50
35 0	9 4	17 30	24 45	30 19	33 48	35 0
35 10	9 6	17 35	24 52	30 27	33 58	35 10
35 20	9 9	17 40	24 59	30 36	34 8	35 20
35 30	9 11	17 45	25 6	30 45	34 17	35 30
35 40	9 14	17 50	25 13	30 53	34 27	35 40
35 50	9 16	17 55	25 20	31 2	34 37	35 50

ARCS.	S_1 Sin. 15°	S_2 Sin. 30°	S_3 Sin. 45°	S_4 Sin. 60°	S_5 Sin. 75°	ARCS
° ′	° ′	° ′	° ′	° ′	° ′	° ′
36 0	9 19	18 0	25 27	31 11	34 46	36 0
36 10	9 22	18 5	25 34	31 19	34 56	36 10
36 20	9 24	18 10	25 41	31 28	35 6	36 20
36 30	9 27	18 15	25 49	31 37	35 15	36 30
36 40	9 29	18 20	25 56	31 45	35 25	36 40
36 50	9 32	18 25	26 3	31 54	35 35	36 50
37 0	9 35	18 30	26 10	32 3	35 44	37 0
37 10	9 37	18 35	26 17	32 11	35 54	37 10
37 20	9 40	18 40	26 24	32 20	36 4	37 20
37 30	9 42	18 45	26 31	32 29	36 13	37 30
37 40	9 45	18 50	26 38	32 37	36 23	37 40
37 50	9 48	18 55	26 45	32 46	36 33	37 50
38 0	9 50	19 0	26 52	32 55	36 42	38 0
38 10	9 53	19 5	26 59	33 3	36 52	38 10
38 20	9 55	19 10	27 6	33 12	37 2	38 20
38 30	9 58	19 15	27 13	33 21	37 11	38 30
38 40	10 0	19 20	27 20	33 29	37 21	38 40
38 50	10 3	19 25	27 28	33 38	37 31	38 50