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On the Magnetism of Iron and Iron-Clad Ships

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Evening Meeting.

Monday, April 24th, 1865.

REAR-ADMIRAL E. OMMANNEY in the Chair.

NAMES of MEMBERS who joined the Institution between the 3rd and 24th April, 1865.

LIFE.

Curling, J. B., Lieut. Roy. Engrs. 9l.
Halkett, J. Craigie, Capt. Highd. Borderers Mil. 9l.

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Croker, Wm., Captain 27th Regt. 1l.	Nicholetts, G., Capt., 27th or 1st Belooch
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ON THE MAGNETISM OF IRON AND IRON-CLAD SHIPS.

By **FREDERICK J. EVANS**, Staff-Commander R.N., F.R.S., Superintendent of Compass Department, H.M. Navy.

IN the Session of 1859, at the request of the Council of the United Service Institution, I contributed a paper on the "Magnetism of Ships," the purport of which was "to describe in as brief and popular a manner as the subject would admit of, the progress and present state of our knowledge of the magnetic condition of iron and wood-built ships, and the consequent effect on the mariner's compass." This paper will be found in the published Journal of the Institution of that year.

Again, at the request of the Council, to contribute an account of the recent additions to our knowledge of the same subject, I appear before you this evening, and although in the short time at my disposal

it will be only possible to touch on some of the more general points of the somewhat complicated problem of the effect of the iron of a ship, yet I hope to render intelligible the advances that have been made both in the theory and practice of this important question to the seaman.

Historically we may consider that there have been three stages in the investigation of the "deviation of the compass"—the first, which dates from the commencement of the present century, was that of wood-built ships, the second that of iron ships, and the third that of iron-plated ships of war. My former paper partially comprised the two first; subsequent additions to this branch of science were made in the period 1859–61, by the following works:—

"Journal of a Voyage to Australia, and round the World, for Magnetical Research." By the Rev. W. Scoresby, D.D. London, 1859.

"Reduction and discussion of the Deviation of the Compass observed on board of all the iron-built ships, and a selection of the wood-built steam-ships in H.M. Navy, and the iron steam-ship 'Great Eastern.'" By F. J. Evans, Master R.N., Superintendent of the Compass Department of H.M. Navy. (Phil. Trans. 1860.)

"Third Report of the Liverpool Compass Committee to the Board of Trade, 1861."

With this notice I pass at once to the third stage, offering alone such prefatory remarks as are necessary for elucidation.

The introduction of armour-plating, and its application to both wood and iron hulls, combined with the general use of iron for decks and beams, shot proof transverse bulkheads, gun-turrets and iron lower masts, it was speedily found materially affected the problem of the correction of the deviation of the compass. Errors formerly taken into account were greatly increased, and errors and causes of error which formerly were safely neglected, became important, and the approximate mathematical formulæ alluded to by me in 1859, which were sufficiently exact for the then existing deviations, ceased to be applicable.

These changes led to a revision, or rather extension of the mathematical theory of the deviations of the compass and of the practical methods of ascertaining and applying the deviation. This revision, at the request of the Admiralty, was undertaken by Mr. Archibald Smith and myself, and are contained in the "Admiralty Manual for ascertaining and applying the Deviations of the Compass caused by the Iron in a Ship," published by the order of the Lords Commissioners of the Admiralty. London: Potter, 1862. 2nd edition, 1863.

The scope and design of this manual I will briefly place before you, observing that the whole is the result of much patient investigation, both experimental and theoretical, and of long practical experience. The work is divided into four parts, each part being complete as a distinct branch of the subject.

Part I. Contains the well-known practical rules drawn up originally in 1842, by a committee of distinguished naval and other men of science, among whom, and indeed the only one remaining to us, is the present President of the Royal Society, General Sabine.

These rules, which are purely practical, have undergone revision, and have been added to from time to time as theory and practice progressed.

Part 2. Is a description of the valuable graphic method known as "Napier's Method," in which the deviations of the compass are represented by the ordinates of a curve, of which the "courses" or "azimuths" of the ship's head, which correspond to the deviations, are the abscissæ. The practical advantages of the method are very great,—especially when dealing with the larger deviations of iron ships and with their ponderous hulls, which frequently cannot be steadied for the purposes of observation by hawsers,—as it enables us from observations of deviations made with the ship's head on any number of courses, whether equidistant or not, to construct a curve in which errors of observation are, as far as possible, mutually compensated, and which gives the deviation as well on the compass courses as the correct magnetic courses.

Part 3. Contains the practical application to this subject of mathematical formulæ derived from the fundamental equations deduced by M. Poisson from Coulomb's Theory of Magnetism, first given in the "*Memoires de l'Institut*," tom. v, page 533.*

Although the mathematical investigations from which these formulæ are derived can only be followed by the mathematician, yet the use of the formulæ, accompanied as they are by tabular forms and examples, may be as easily acquired as are the ordinary computations in the practice of navigation.

The formulæ, in addition to the five coefficients A, B, C, D, E, explained in my last paper, embrace expressions for separating and distinguishing the different parts of the deviation according to their respective causes, as, for example, separating the quadrantal deviation into the two constituents—that which arises from fore and aft induction, and that which arises from transverse induction. This separation has thrown great light on the cause of the quadrantal deviation, and consequently on the means of modifying its amount by the selection of a place for the compass. Expressions also are given of easy application for deducing the heeling error, from observations made on an even keel, and for separating the two parts of which it is composed.

In the second edition methods are introduced of determining the coefficients from observations of deviation and horizontal force made with the ship's head on *one* point; these furnish the means of approximately determining the deviations of a ship without swinging her, and while she is still on the stocks or on dock.

The importance of being thus able to detect the heeling error by observations of a simple kind, made with the ship upright, and of constructing an approximate table of deviations without swinging the

* Poisson's equations are derived from the hypothesis that the magnetism of the ship, except as far as it is permanent, is transiently induced, with an intensity proportional to that of the inducing force; and that the compass needle is of infinitesimal length compared to the distance of the nearest iron.—F. J. E.

ship, is unquestionable, and is one of the most practically useful of the results of the application of mathematical formulæ to this subject.

Part 4 of the manual treats briefly on Terrestrial Magnetism as connected with the deviation of the compass. It is accompanied by charts of the lines of equal magnetic variation, equal dip, and equal horizontal force. The first gives us the means of ascertaining the deviation of the compass by astronomical observations made at sea. The charts of the dip and horizontal force are useful as throwing light on the changes which the deviations undergo on a distant voyage, and as enabling the navigator further to anticipate the changes which necessarily take place on a change of geographical position.

The material assistance rendered by Mr. Archibald Smith to navigation by his simplified and clear mathematical treatment of the subject, is beyond my humble meed of praise; but it is a pleasure to bear confident testimony that in the manageable form to which Mr. Smith has reduced the exact formulæ necessary, they do most satisfactorily represent all observed phenomena. I hope that at the conclusion of this paper, that gentleman, who is present, will give to you some information connected with the subject which is not embraced in my communication.

The deviation of the compass on board ship, it is now well known, consists of three parts, namely, the "constant," the "semicircular," and the "quadrantal." Dismissing the constant part for the present from our consideration, both theory and observation distinctly prove that the whole deviation is composed of two parts, one of which (the semicircular) runs through all its values, both positive and negative, *once*, and the other (the quadrantal) *twice*, in a complete revolution of the ship. These parts have accordingly thus received their distinctive names. The semicircular deviation being easterly in one semicircle and westerly in the other, as the ship's head moves round a complete circle in azimuth. The quadrantal being easterly and westerly alternately, in the four quadrants, as the ship's head moves round the complete circle.

The distribution and amount of these two distinct errors of the compass in iron ships are very different from those in the wood-built ship; and this is a most important feature for the student to realize. The points of *no* semicircular deviation, sometimes called the neutral points, are opposite to each other, and the sine of the deviation in each semicircle is proportional to the sine of the azimuth of the ship's head, measured from the neutral points; in wood-built ships, the neutral points coincide nearly with the North and South points, and from the north end of the compass needle being drawn towards the bow, the deviation, when the ship's head is east, is (in northern latitudes) Easterly; and when the ship's head is west, Westerly. In iron-built ships, the points of *no* semicircular deviation approximate to those points of the compass to which the ship's head and stern were directed in building, and it follows that the deviation is Easterly when the *part of the ship which was south in building* is east; Westerly, when it is west. The iron ship built head north, has, in consequence, a curve of deviations opposite to the ship built head south, but both with the common feature of the

neutral points being at the North and South points; the same inversion of curves exists with ships built head east and west, but with the neutral points at the East and West points of the compass. In iron-built ships the amount is frequently found from 20° to 30° ; in wood-built ships of war it seldom exceeds 10° .

The quadrantal deviation has its four zero points coinciding very nearly with the cardinal points. In iron ships it has the distinctive feature of *invariably*, in a compass ordinarily placed, being easterly in the N.E. and S.W. quadrants; westerly, in the N.W. and S.E. quadrants. In ordinary iron ships its amount ranges from 3° to 7° , but in some of the armour-plated ships, it amounts to 12° and 14° on the main deck, and $8\frac{1}{2}^{\circ}$ at the standard compass. In wood-built ships it is invariably small, and was thus unnoticed by our early navigators. The quadrantal deviation has also the remarkable property of remaining unchanged in all magnetic latitudes, and of being little changed by the lapse of time.

Part of the increase of deviation in iron-plated ships is the indirect result of a circumstance which has other more direct effects of a prejudicial character, namely the serious diminution of the directive force of the earth's magnetism on a compass surrounded on all sides by masses of soft iron.

Thus, for example, on the main deck of these ships it has been found only equal to $\cdot 725$ of the earth's force, at the steering compass to $\cdot 760$, and at the standard compass an average of $\cdot 800$; this force in ordinary iron ships being about $\cdot 900$, and in wood-built ordinary ships scarcely differing from the earth's force, or $1\cdot 000$. The representative coefficient of the above (λ), or the ratio of the mean force to north at the place of the compass to the earth's horizontal force, has been determined in many classes of ships; indeed, observations of horizontal force have now become part of the regular series of observations made in ships in which its determination is of importance. The requisite formulæ will be found in the Admiralty Manual.

Another error of great importance has been brought into prominence in the modern class of iron-built ships, and is known as the "heeling error." It is found by experience that as the vessel heels over, the north end of the compass-needle is drawn either to the weather or lee side, generally the former in the northern hemisphere, and the deviation so produced, when the ship's head is near north or south, often exceeds the angle of heel. This not only produces a deviation which may cause a serious error in the ship's course when steering near those points of the compass, out, if the ship is rolling, produces a swinging of the compass-needle which may render the compass for the time useless. This error had been known to exist, and its amount had even been measured by heeling the ship in the case of H.M.S. "Recruit" (1846), "Bloodhound" (1847), "Sharpshooter" (1848), and in various cases recorded by the Liverpool Compass Committee (1855-61); but no method had been proposed for determining this error by observations made with the ship upright, and considerable obscurity was even supposed to rest on the causes and law of the deviation. The application of Poisson's formulæ has entirely removed the obscurity,

and furnishes an easy method of determining the heeling error by observations of vertical force made on one or more directions of the ship's head. These observations have likewise now become a regular part of the complete series of magnetic observations made in the principal iron ships of Her Majesty's Navy

The reduction of the several observations of deviation and horizontal and vertical force made in the armour-plated ships of Her Majesty's Navy, as they were severally prepared for sea, and at subsequent periods of their service, and also in certain iron-built ships of the Royal Navy, and of the Mercantile Marine, afforded such interesting results that Mr. Smith and myself felt justified in preparing a Report on the whole, which, by permission of the Lords Commissioners of the Admiralty, was presented to the Royal Society; this paper was read on the 16th March of the present year, and is now in course of publication in the "Philosophical Transactions."

The reduction gives the numerical values of the several parts of the deviation, viz., the "constant," the "semicircular," and the "quadrantal," of λ , of μ or the proportion of the vertical force on board to that on shore, of χ the heeling coefficient to windward; also of the several constituent parts of these coefficients.

The second part of this paper treats of the effect on the compass of masses of iron of various shapes, bearing some analogy to shapes for which the problem of the distribution of induced magnetism can be exactly solved, this includes such masses as solid shot, shell, transverse beams and bulkheads, armour-plates, and iron tanks.

I now propose to lay before you some of the principal conclusions derived from the discussion of the numerical values.

CONSTANT DEVIATION, *represented by the coefficient A in formulae.*

When the compass is placed in the middle line of the ship, A may be considered as zero, having in fact little or no *real* value. An *apparent* value may, however, be given to A by index error in the compass on board, index or other error in the shore compass, or error in the assumed bearing of a distant object.

In compasses out of the middle line of a ship, or when the ship heels over, an A is frequently introduced, but it seldom exceeds 1 or $1\frac{1}{2}^\circ$. A *real* value can only be caused by elongated masses of *soft* iron unsymmetrically arranged with reference to the compass, and would be the same in all parts of the globe.

SEMICIRCULAR DEVIATION, *represented by the coefficients B and C of formulae.*

On this there are four heads deserving special inquiry:—

1. On the original value and its connexion with the direction of the ship in building, and the position of the compass in the ship.

2. The changes which take place after launching.
3. The subsequent changes.
4. The changes which take place on a change of geographical position.

The remarkable law of the direction of the force causing the semicircular deviation in iron-built ships being dependent on their position in building, was established prior to the application of armour plates to ships of war. This law, provided the compass is free from the influence of individual masses of iron, may be thus expressed, "*the north point of the needle is attracted to that part of the ship which was south in building.*" The same law extends to the armour-plating of either iron or wood-built hulls; consequently we find that in those iron-built ships which have been plated after launching, and in a different position from that of building, that the direction of the semicircular force is generally intermediate between the two relative positions of the head in building and in plating.

These striking features are illustrated by a diagram annexed.

From these results we may infer that the process of plating an iron ship in the direction opposite to that of building will always produce a diminution,* and which in some cases may become a reversal of her semicircular deviation, and that by taking advantage of this circumstance the deviations of iron-plated ships may be brought within manageable limits.

As might have been anticipated, the amount of semicircular deviation in the iron-plated ships is large, more especially at the steering and main deck compasses; unfortunately, from the exigencies of the arrangements for fighting and working the ship, choice of position is very limited, and the deviations are larger than could be wished. At the standard compass an ordinary amount is 20° , at the steering and main deck compasses 25° to 30° , and recently, in the case of the "Minotaur," built head north, at the distance of 55 feet from the stern, the steering compasses had the enormous amount of 62° .

2. Immediately after launching, the semicircular deviation diminishes rapidly; one of the most instructive examples of this change was observed in 1859, in the "Great Eastern," by myself and Mr. Rundell, the secretary of the Liverpool Compass Committee. Circumstances were especially favourable for making the observations, and the results were really astounding. In the first five days there was a decrease of 12° on some points of the compass, in seven weeks of 19° , and in the first nine months of service afloat, it amounted to $32^{\circ} 10'$, or nearly three points.

* An interesting memoir on the "Magnetic character of the Iron-built Armour-plated Battery, 'Pervenetz,' of the Imperial Russian Navy," by Captain Belavenetz, R. I. N., communicated by Archibald Smith, M.A., F.R.S., will be found in the Proceedings of the Royal Society, April 27, 1865.

In this ship, built at Blackwall, advantage was taken on her removal to the Victoria Docks of the armour-plating being attached with the ship's head placed in a direction nearly opposite to that while building. The diminution of the ship's magnetic force is very remarkable during the process of plating.—F. J. E.

Changes of the same character, though not so great in amount, have been observed in the "Achilles," (the only example of a ship built and plated in the same dock), and also in the wood-built iron-plated ships. In all cases, except when the ship has been built nearly north and south, the relative changes of C , or that part due to transverse magnetic forces in the ship, is greater than in those of B , when the magnetic forces act in a fore and aft line.

This points to the necessity of newly-built iron ships being most vigilantly looked after, and their compass deviation tables constantly verified during the first twelvemonth of sea service.

3. After a certain time, which may be roughly estimated at a year after launching—the ship being supposed to have undergone a fair amount of sea service—the values of B and C remain remarkably permanent, notwithstanding the strains arising from docking, gales of wind, and especially from the concussions arising from the drilling and firing of heavy guns.

A striking example of the permanency of the magnetism of an "old" or well-seasoned iron ship after severe concussion is afforded in the case of the "Adventure," troop-ship, built in 1854. This ship, in the course of foreign service, struck on a rock during a fog with sufficient force to tear away and crush in 20 feet of the stem and bow under water; observations for deviation and horizontal force were made *before* proceeding on the foreign service, and *after* the injuries sustained had been repaired in dock; these observations made with every accuracy failed to denote any change.

4. The changes which take place on a change of geographic position remains yet one of the most important questions for consideration. The permanency of the magnetism of many iron ships is very remarkable, and we judge of this fact by their semicircular deviation being found, in different parts of the globe, to be inversely proportional to the earth's horizontal force, as also that their deviations do not vary when swung in the same geographical position.

I will here pause for a moment to consider how the parts of the semicircular deviation are theoretically treated.

B is the principal coefficient, being the maximum amount of forces acting in a fore and aft line in the ship, and is therefore due to the principal masses of iron in the ship's equipment. It is composed of two parts; one arising from vertical induction in soft iron, and the other from permanent or fixed magnetism in the hard iron of the ship; these two parts have widely different proportions on great changes of magnetic latitude, as the first varies as the tangent of the dip, and the second inversely as the horizontal force.

[Assuming for example the ship to have changed her position from the English Channel to the Cape of Good Hope, the tangents of the dip of these two localities vary from $+2.5$ to -1.5 , while the horizontal force varies only in the proportion of 1.0 to 1.2 . The part of B arising from vertical induction in soft iron therefore varies in the proportion of 4.0 to 0.17 , or as nearly 20 to 1 in excess of that part due to the permanent magnetism.]

C is the coefficient representing the maximum amount of forces

from the transverse iron of the ship; it is also composed of two parts similar to B; the part, however, arising from soft iron, at a compass placed in the middle of the ship, is probably always small, and we may consider that C in the aggregate is due to the permanent magnetism of hard iron.

The cruizes of some of the iron-plated ships have extended to about the 30th parallel of North latitude, and their compass deviations have been sedulously and carefully obtained at various intermediate ports, but the range of latitude is too small, and the change of sub-permanent magnetism too great, to derive any very certain results from these observations. After the first year's sea service, the semicircular deviations are, however, very constant for the same localities, and have an approximation to values inversely proportional to the earth's horizontal force; we might, therefore, draw the inference that these results are alone the effects of permanent magnetism. There is, however, in these ships a large quantity of soft iron, as is shewn by the large quadrantal deviation and the diminished factor λ , and it is important to define, if only approximately, the relation between the two parts; remembering that in any one geographical position, the magnetism developed in soft iron by vertical induction is not distinguishable from the permanent magnetism of hard iron.

From various methods of deduction the present values of B and of its constituent parts in certain ships are as follows:—

	B.	Part of B from soft iron.	Part of B from hard iron.
Warrior.....	-17	+12	-29
Black Prince....	+19	+23	- 4
Defence.....	+21	+14½	+ 6½

With these values we are by a simple formula enabled to compute B for any geographical position.

*QUADRANTAL DEVIATION represented by the coefficients D and E
of formula.*

This can only be caused by *horizontal* induction in soft iron. The quadrantal deviation, as before stated, has the remarkable character of not changing with a change of geographic position; when, therefore, it has once been ascertained for a particular compass in a particular spot, its unchangeableness may be relied on so long as the distribution of the iron in the ship is unchanged.

The part E requires only to be briefly alluded to; it can only be caused by horizontal induction in soft iron *unsymmetrically* distributed; an E may, therefore, be caused by the compass being placed out of the midship line and exposed to the influence of cylindrical masses, such as iron gun turrets. When the ship is upright and the compass in the midship line there are no certain indications of any real value.

As regards D, the most important point is its magnitude in different positions in ships of different classes. Its cause is, perhaps, most

simply explained by conceiving rods of soft iron to be arranged according to one or other of the following types :—

Fig. 1.

Fig. 2.

In these figures $+a$ represents masses of iron directly before or abaft the compass, such as engines, boilers, funnels, and iron masts; $-a$ represents soft iron extending through the position of the compass, such as the keel and hull of the ship, armour-plating, the screw-shaft, &c.; the effect of these last arrangements, in almost all cases, exceed the first, so that a is in general negative.

$-e$ represents the effects of all the transverse soft iron, such as the bottom of the ship, the iron decks and deck beams, &c. $+e$ would represent the masses of iron, comparatively few in number, which lie to one side of the compass, such as guns, boats, davits, &c. In every iron ship which has been examined, the effect of the transverse iron extending through the position of the compass exceeds that of any masses of iron wholly on one side, and thus e is negative in sign and greater than a .

The average value of D has greatly increased in modern iron ships, in their early days 2° to 3° would represent an average value; with the increase of horizontal iron in the fittings it is now generally 4° to 6° , and in the iron-cased ships, under certain conditions, it is found extending to 14° and 15° . This is shown in various classes of ships in the following table:—

		Black Warrior.	Black Prince.	Achilles.	Defence.	Hector.	Royal Oak.
Standard compass	..	+ 8 27	+ 7 38	+ 6 58	+ 7 0	+ 5 24	+ 3 9
Starboard steering	..	+ 11 56	+ 10 32	+ 8 51	+ 10 16	+ 8 24	+ 1 47
Main deck	.....	+ 11 43	+ 13 16	+ 12 13	+ 14 35	+ 9 47	+ 1 28

In order to see the nature of the disturbing causes we must obtain separately the two parts of the quadrantal deviation D , or the values of a and e .

		Warrior.	Black Prince.	Achilles.	Defence.	Hector.	Royal Oak.
Compass.		o /	o /	o /	o /	o /	o /
Standard	{from fore and aft induction...	+ 0 66	- 4 04	- 2 45	- 2 42	- 3 51	- 1 19
	{from transverse induction...	+ 8 24	+11 42	+ 9 40	+ 9 41	+ 9 15	+4 32
Starboard steering	{from fore and aft induction...	+ 0 14	- 3 47	- 3 47	- 2 17	- 3 23	- 2 07
	{from transverse induction...	+11 46	+14 23	+12 43	+12 35	+11 49	+3 51
Main deck	{from fore and aft induction...		- 2 35	- 3 9	- 2 10	- 5 53	- 3 51
	{from transverse induction...		+15 53	+15 26	+16 53	+13 51	+5 20
Standard {	<i>a</i>	+ '002	- '112	- '079	- '073	- '103	- '043
	<i>e</i>	- '256	- '322	- '277	- '278	- '263	- '143
Starboard steering {	<i>a</i>	+ '006	- '100	- '103	- '064	- '093	- '066
	<i>e</i>	- '310	- '380	- '343	- '343	- '325	- '122
Main deck {	<i>a</i>		- '063	- '053	- '043	- '151	- '116
	<i>e</i>		- '418	- '407	- '434	- '397	- '160

It is here obvious from the large values of $-e$, compared with those of a , that the resulting deviation is caused by the repulsion of the *north end* of the needle *from* the *north side* of the ship, being in excess of the repulsion of the needle from the *north end* of the ship; it being remembered that $+a$ would indicate an *attraction* to the north end of the ship, and $-a$, a *repulsion from* the north end of the ship.

It might appear from this that the repulsion from the sides of the ships, given as examples, was chiefly due to the armour-plates; but a comparison of the effect of these iron plates on a wood hull and on an iron hull separately, points to the conclusion that the larger amount of quadrantal deviation in the iron-built ship is attributable to the increased amount of transverse iron in decks, bulkheads, iron beams, and the iron bottom of the ship; the magnetism of which is, as it were, conducted upwards by the iron sides.

For the purpose of illustration, we may take the "Hector," iron-built, and "Royal Oak," wood-built ship, as types of the two ships which, from their arrangements of armour-plating and relative position of compasses, are directly comparable.

		Standard.		Starboard steering		Main deck.	
		<i>a</i>	<i>e</i>	<i>a</i>	<i>e</i>	<i>a</i>	<i>e</i>
Hector, iron-built	.....	- '109	- '263	- '093	- '325	- '151	- '397
Royal Oak, wood-built with	iron upper deck and supporting beams.....	- '013	- '143	- '066	- '122	- '116	- '160

In the wood ship the repulsion *from* the north side of the ship, or from the armour-plates, together with one iron deck and supporting iron beams, amounts to an average value for e of $- '142$, or an equivalent of $+ 4\frac{1}{2}^\circ$ of quadrantal deviation. In the iron ship a similar average value for e = $- '328$, or an equivalent of $+ 12\frac{1}{2}^\circ$ quadrantal deviation; the excess of nearly 8° is, consequently, due in the latter to the second iron deck, the transverse bulkheads, and the iron sides and bottom of the hull.

Some obscurity has hitherto existed as to the sources of the quadrantal deviation. It has now been traced as the resultant of two forces, acting either in conjunction or opposition, but almost always the latter in the modern iron-built ships, according to the arrangement

of the iron and the relative position of the compass—a general law prevailing in ships of similar types.

Allusion has been made to the prejudicial effect caused by the soft iron diminishing the mean directive force of the needle and so indirectly increasing the effect of all disturbing forces, as shown by the coefficient λ .

The cause of this diminution will be seen by the Figs. 1 and 2.

In Fig. 2, a little consideration will show that both $-a$ and $-e$ diminish the directive force. In Fig. 1, $+a$ increases the directive force, $-e$ diminishes it; but as $-e$ always exceeds $+a$, the result is a diminution on the whole.

We thus see that the value of λ is closely connected with that of D ,—for algebraically expressed,

$$\lambda = 1 + \frac{a + e}{2}$$

$$\text{and } D = \frac{a - e}{2\lambda},$$

and we may, therefore, consider them together.

It has been a special object of inquiry to determine the value of λ in various classes of ships, and in various parts of the same ship. The importance of this coefficient was clearly perceived by the Astronomer Royal in his early and well known magnetic experiments in iron-built ships (Phil. Trans. 1839), he terms it the prejudicial constant M ; [in the notation adopted here, $\lambda = 1 - M$].

In the earlier built iron vessels λ was very nearly equal to 1. In the "Rainbow" (1838) at four stations distributed along nearly the whole length of the ship it ranged from .972 to 1.003. In the "Ironsides" the first sailing ship it was .917 at the binnacle. In several iron-built ships purchased into the Royal Navy from 10 to 15 years after the Astronomer Royal's observations, λ at present averages about .930. In the iron-plated ships of the present day it ranges from .700 to .900.

The following are its values in some of the iron-plated ships:—

	Warrior.	Black Prince.	Achilles.	Defence.	Hector.	Royal Oak.
Standard compass ..	.873	.763	.822	.822	.814	.907
Starboard steering ..	.833	.760	.777	.794	.791	.906
Main deck		.757	.755	.759	.726	.862

A very remarkable feature in λ and D is the change which takes place with the lapse of time, indicating apparently a change in the molecular structure of the soft iron, by which it becomes less susceptible of induced magnetism. Whether this change is accompanied by any change which can affect the strength, the liability to oxidation, or any other qualities of the iron are questions yet undetermined.

The annexed tabular values illustrate these remarkable facts.

				Standard Compass.		Starboard steer- ing Compass.		Main deck Compass.	
				λ	D	λ	D	λ	D
Achilles ..	October	1864		·822	+ ·121	·777	+ ·154	·755	+ ·214
	December	1864		·854	+ ·116	·819	+ ·137	·804	+ ·188
Black Prince	November	1861		·716	+ ·145				
	September	1862		·783	+ ·134	·760	+ ·184		
	April	1864		·846	+ ·137				
	November	1864		·849	+ ·122	·881	+ ·144		
Defence ..	February	1862		·822	+ ·122	·794	+ ·179	·759	+ ·254
	December	1863		·853	+ ·123	·812	+ ·180	·810	+ ·230
	April	1864		·857	+ ·112	·853	+ ·159	·828	+ ·233
	October	1864		·852	+ ·112	·830		·812	+ ·230
Resistance..	August	1862		·758	+ ·111			·782	+ ·244
	December	1863		·850	+ ·122			·880	+ ·219
Royal Oak.. (wood built)	March	1863		·861	+ ·047				
	April	1863		·907	+ ·061	·887	+ ·067		
	June	1863		·907	+ ·055	·906	+ ·031		

Heeling Error.

The coefficients we have passed in review are those alone which affect the compass when the ship is upright; when the ship heels over, new disturbing forces are called into play, which we may consider as caused by arrangements of soft or hard iron of one or other of the following types.

Fig. 3.

Fig. 4.

$-e$, represents, as before, transverse soft iron, which as the ship heels over, will evidently produce a force to the high side of the ship, or to windward, on the north end of the needle. If the rods $+k$ and $-k$ represents soft iron, then $+k$ gives a force acting downwards on the north end of the needle, which as the ship heels, becomes a force to windward; $-k$ a force acting upwards, which, as the ship heels becomes a force to leeward.

The permanent magnetism of the ship will generally act downwards if the compass is over the end which has been south in building, upwards if over the end which has been north in building. It follows that those ships built head north will have a large heeling

error in compasses *near the stern*, and a smaller one in compasses near the bow, and that the converse exists in ships built head south.

The heeling coefficient it will thus be seen depends partly on vertical induction in transverse iron, and partly on the mean vertical force arising from permanent magnetism and vertical induction in vertical iron; the two therefore conspire together when the vertical force of the ship acts downwards, and counteract each other when the vertical force acts upwards; and hence the great differences in the heeling coefficients of different ships.

Appended is a table of the results obtained in several ships. What is striking, is the uniformity of the heeling part from transverse iron, and in all ships, as might be expected, it is of the same sign; the differences are nearly all in the part which arises from vertical force, varying from $+ 1^{\circ} 6'$ in the "Warrior" to $1^{\circ} 9'$ in the "Enterprise."

In the wood built iron-plated ships, the vertical force is generally diminished, this is doubtless the effect of the armour-plating, which acts as a $-k$. Indeed in all iron-plated ships, whether wood or iron-built, the effect may be considered the same, and that the heeling error is probably diminished and not increased by the effect of the iron plating; for we find that when observations for heeling error have been made at the main deck compasses, the value is small and to leeward.

For convenience in investigation, and also for application in practice, the heeling error is measured by degrees and parts of a degree, as produced by every degree of heel when the *ship's head is north or south by the disturbed compass, as it is then at the maximum;—vanishing when the ship's head is east or west by the disturbed compass.* It is scarcely necessary to remark that the knowledge of this simple law is highly important in the navigation of iron ships, and is explanatory of the unlooked-for errors frequently found in the ship's reckoning when steering on courses near a meridional direction, such for example as from off the coast of Portugal towards Ushant, and up the Irish Channel.

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Class of Ship.	Date.	Name of Ship.	Direction of Head in building.	Whole heeling* amount to windward. (For 1° of heel. ship's head N. or S.)	Amount arising from	
					Vertical induction in transverse iron	Vertical fore-and-aft induction in vertical iron.
Iron ships, iron-plated.	July 1862.	Warrior.....	N. 3° E.	+1 49	+0 43	+1 06
	Jan. 1863.	" <i>Lisbon</i>.....	.....	+1 22	+0 32	+0 50
	Sept. 1862.	Black Prince.....	S. 20° E.	+0 50	+1 01	-0 11
	Jan. 1863.	" <i>Lisbon</i>.....	.....	+0 52	+0 43	+0 09
	April 1864.	".....	.....	+0 43	+0 43	-0 05
	Oct. 1864.	Achilles (Standard aft).....	S. 51° 40' E.	+0 27	+0 50	-0 23
	Dec. 1864.	".....	.....	+0 25	+0 43	-0 18
	Oct. 1864.	" (Standard forward).....	.....	+1 29	+0 49	+0 40
	Dec. 1864.	".....	.....	+1 18	+0 37	+0 41
	Feb. 1862.	Defence.....	S. 47° W.	+0 59	+0 51	-0 08
Wood ships, iron-plated.	Jan. 1863.	" <i>Lisbon</i>.....	.....	+0 30	+0 33	-0 03
	April 1864.	".....	.....	+0 36	+0 42	-0 06
	Aug. 1862.	Resistance.....	S. 86½° W	+1 18	+1 04	+0 14
	Dec. 1863.	".....	.....	+0 53	+0 45	+0 08
	Feb. 1864.	Hector.....	S. 20° E.	+0 45	+0 48	-0 03
	Jan. 1865.	Valiant.....	S. 87° W.	+0 48	+0 37	+0 11
	April 1863.	Royal Oak.....	Plated S. 49° E.	+0 07	+0 21	-0 17
	June 1863.	".....	Plated S. 49° E.	+0 04	+0 23	-0 19
	Feb. 1864.	Prince Consort.....	Plated S. 39° W.	-0 08	+0 16	-0 24
	Aug. 1864.	Ocean.....	Plated S. 79° E.	-0 15	+0 19	-0 34
Iron ships.	June 1864.	Enterprise (Iron topsides)	Built and plated S. 56° W.	-0 29	+0 37	-1 09
	July 1863.	Oreutes.....	N. 66° W.	+1 04	+0 36	+0 28
	Nov. 1863.	Tamar.....	West	+0 51	+0 31	+0 20
	"	" (Binnacle over rudder)	.....	+1 10	+0 25	+0 42
	Sept. 1863.	Wye.....	Probably to E.S.E.	+1 0	+0 27	+0 34
	Feb. 1863.	Caradoc.....	Probably to N. by W.	+0 15	+0 14	+0 01
	Feb. 1863.	Glyde.....	Probably to N.E.	+1 22	+0 35	+0 47
Iron ships.	Mar. 1863.	Industry.....	Probably to S. by E.	-0 05	+0 18	-0 23
	June 1863.	City of Sydney.....	Probably to W.N.W.	+1 31	+0 46	+0 45

* — sign denotes a heeling error to leeward.

The principal conclusions to be drawn from the application of observation and theory to the magnetic phenomena in iron ships may be considered as follows :

1. The original semicircular deviation depends principally on the direction of the ship's head in building, and consists principally in an attraction of the north point of the needle to the part of the ship which was south in building. This attraction is caused by the sub-permanent magnetism induced in the ship when building by the horizontal force of the earth.

A residual part of the semicircular deviation is independent of the direction of the ship in building. It is the effect of the sub-permanent and transient magnetism induced in the ship by the vertical force of the earth, and it consists in an attraction of the north point of the needle to the bow or stern. In the usual place of the standard compass, this part is in the northern hemisphere an attraction towards the bow; but if the compass is placed nearly in front of a large vertical mass of iron, as the stern-post, it may be towards the stern.

2. The principal part of the semicircular deviation diminishes rapidly after the ship has been launched; but after a time, which may be taken roughly as a year, if the ship has been allowed to swing on all azimuths, it attains a very fixed and permanent amount, from which it does not afterwards vary to any great extent. The smaller residual part changes little, if at all, so long as the ship remains in the same latitude.

3. The changes which take place in the semicircular deviation of a ship built east and west, are generally relatively greater than in one built north and south.

4. The effect of the magnetism induced by the horizontal force when the ship is on the stocks is principally (and if the ship is built on a cardinal point, entirely), to produce a diminution of the directive force on the needle, and very little (and if built on a cardinal point not at all) to produce deviation. The same effect—nearly—is produced at a subsequent time if the ship's head is placed in the direction in which it was while building.

This diminution of the directive force is greater if the ship has been built east and west, than if built north and south.

5. The diminution of the mean directive force is the mean of the diminution caused by the transient magnetism induced by the horizontal force of the earth when the ship's head is north or south, and that induced when her head is east or west, that is, it is the mean of the thrust from the north *end* and from the north *side* of the ship.

6. The quadrantal deviation is caused by the excess of the latter over the former, that is by the excess of the thrust from the north *side* of the ship, over the thrust from the north *end*.

7. The diminution of the directive force and the amount of the quadrantal deviation are nearly the same at the same level in different parts of the ship. They increase in descending from the position of the standard compass to the steering and main deck compasses.

8. The diminution of the directive force and the quadrantal deviation both diminish with the lapse of time.

9. When a ship has been built head north, the upper part of the stern and the lower part of the bow are strongly magnetized, the upper part of the bow and the lower part of the stern are weakly magnetized. When a ship has been built head south, the upper part of the bow and the lower part of the stern are strongly, the upper part of the stern and the lower part of the bow are weakly, magnetized. Consequently in ships built head north, a compass placed near the stern will have a large semicircular deviation; there will also be a large downward force on the north point of the needle which will produce a large heeling error. In ships built head south, with a compass similarly placed, both the last errors will probably be small.

10. On the whole, for compasses to be placed in the after part of the ship, the best direction for building is head south. For compasses near the centre of the ship the directions head north and head south are nearly equally good.

I have now sketched the most striking features in the magnetism of the modern iron ship; but the matter would be incomplete without allusion to what has been done to modify the larger class of errors.

It is obvious that when the magnetic force of the ship is in antagonism to the force of the earth (which must be the case whenever the ship's head approximates to the direction in which it was when on the stocks) the compass-needle loses its directive force proportionally to the amount of deviation; for example, at the steering compasses of the "Minotaur," with 62° deviation, ship's head north, there would be only one-tenth of the earth directive force acting on the needle, and even this reduced value would be further diminished one-fifth by the mean loss of directive force due to the soft iron of the ship.

To remedy evils of this magnitude, compensation by permanent magnets on the Astronomer Royal's early-suggested plan becomes indispensable to equalise the directive power on all points of the compass; it has, accordingly, been adopted in several of the iron-clad ships.

The heeling errors of some of the more exaggerated cases have also been modified by the introduction of a vertical magnet placed directly under the centre of the compass; with our present experience this promises to be a simple operation to carry out in practice, and will be very useful, if only to stop the inconvenient oscillation due to magnetic causes when the ship rolls.

In my former remarks at this Institution, I placed fully before you the nature of the controversial opinions that existed on the subject of magnet correction; changes of circumstances necessarily have modified the opinions of those antagonistic to its adoption. I may be permitted to state my own opinions as running generally in accordance with those who are adverse to the use of magnets under all and every circumstance.

Another generation of navigators will possibly have acquired a sufficient knowledge of the laws of magnetism, and the variety of

conditions on board an iron ship, so to manipulate magnets as to render the compass correct at all times and in all places; but at the present time this knowledge is extremely limited, and I confess to hesitate the placing of so dangerous a tool as a moveable magnet in the hands of the untrained navigator. My views are now rather to place it beyond his reach; first attending to his convenience by reducing the larger errors within easy and effective limits—the residual errors to be constantly determined by observations of celestial bodies—and then securing the magnet as a part of the ship, in order that accident or design cannot disturb the effect, it being always understood that every precaution is taken to secure a position for the compass free from the effect of individual masses of vertical iron.

These brief comments on magnet correction lead to another point worthy of a moment's notice. When great evils affect us we are prone to seek any remedy to alleviate them. The troubles and anxieties attending erroneous compass action have produced a plentiful supply of professed remedies, prominent among which is that of cutting off the effect of the iron of the ship by some electrical or non-conducting medium; patrons to these schemes are found, and the minds of the many are diverted from the true direction, which should be study and observation of the subject.

I need scarcely say that all the schemes I have alluded to are chimerical, and on simple grounds; for if we cut off the effect of the disturbing cause in the ship, we are also cutting off the main supply, namely, the magnetism of the earth, which alone gives directive power to the needle.

In concluding this review of the joint labours of Mr. Archibald Smith and myself, extending now over several years, it may not be deemed presumptuous in me to draw the attention of the Institution to one feature of the subject which has forcibly presented itself in the course of our investigations.

The increasing number of our iron and iron-plated ships of war, with the actual and impending changes in the construction of wood-built ships, is assuming such magnitude, that the security of the navigation of these ships in relation to the action of the mariner's compass has become a question deserving more general consideration from the naval profession.

The art of navigation, under this changed condition of the substitution of iron for wood in ship-building, it is already found requires to be treated on broader principles than was formerly necessary, and must include a general knowledge of the elements of magnetism both in its practical application and in its general features, as one of the great forces of nature, so potent in its effects as far as relates to navigation, over the whole terrestrial globe.

That the great changes from wood to iron in the construction of the ships of all nations are bringing this change in their train, appears among other things from this, that within the last four years France and Russia have sent special agents to this country to acquire complete information as to the "compass system" pursued both in the

royal and mercantile navies, and as to the theoretical results obtained by the various investigators of this branch of science. This has led, in France, to the publication by the Minister of Marine of a special report, and also of the "*Cours de Regulation des Compas professé à l'école du Génie Maritime*" both by M. Darondeau, *Ingenieur Hydrographie de la Marine*; the latter work incorporates the most important parts of the Admiralty Manual. In Russia, to a translation of the Admiralty Manual, with notes, by Captain Belavenetz, of the Imperial Navy. In Austria, to a translation of the chief parts of the Admiralty Manual, by Dr. Schaub, Chief of the Imperial Hydrographic Academy at Trieste.

It is gratifying to observe that both in the theoretical and practical treatment of this peculiar branch of nautical science, this country has been looked to for instruction, and is still probably in advance of other nations. But it must not be forgotten that this knowledge is confined to very few of our Officers, arising chiefly from the rapid growth of the science having outstripped the provisions made for its general diffusion, and possibly, in some degree, from the growing importance of the subject not having hitherto been sufficiently set before them.

It is, however, necessary to observe that the practical determination by observations, and application of the deviation of the compass to courses and bearings are now fairly established and recognised in the naval service, and will, of course, be more appreciated as iron and iron-clad ships increase.

Little more, perhaps, can be done on this head than is done at present, but a wider acquaintance with leading general theoretical principles is an important supplement to the knowledge of practical details; and, indeed, that magnetism, in its application and connexion with the mariner's compass, must be deemed in a system of nautical education to deserve attention in common with nautical astronomy and other collateral subjects.

The CHAIRMAN: Gentlemen, I am quite sure that the thanks of this meeting are due to Captain Evans, for his able paper. I am sure that the information that has been given to this Society is very valuable. The paper displays a great deal of labour and care, and especially in regard to one or two important features for future instruction in relation to the compass, and which I hope will be attended to, as for instance that of heeling, a feature which requires to be more generally understood.

Mr. ARCHIBALD SMITH: I have been requested by my friend Captain Evans, to add to the interesting paper which he has just read to you a short account of some of the results of recent investigations in which we have been engaged into the effect of particular masses of soft iron in a ship on the compass. These effects are much more prominent in the case of modern armour-plated ships than in the case of the older iron-built ships. In the modern ships you cannot escape from masses of iron, and hitherto no care has been taken in the construction of ships to prepare a place for the standard compass. I hope the time is not far distant when it will be considered quite as important to prepare a place for the standard compass as for the main mast; but that time has not yet come, and when my friend Captain Evans has to select a place for the position of the standard compass, he has to consider the effect of all the neighbouring masses of iron, and select a place at which the effect may be as small and as regular as possible. Hence at present the great importance of being able to estimate approximately the effect of particular masses. I must apologise for introducing here some theoretical considerations, but without them it is hardly possible

to speak, or even think of the effect of the masses in question. I must explain in the first place that I do not propose to speak of what is called the "*semicircular*" deviation, which in iron ships arises chiefly from the permanent or sub-permanent magnetism of the hard iron of the ship caused by the process of hammering, and consisting chiefly of an attraction of the north point of the compass to that part of the ship which was south in building; but I propose to confine my observations almost entirely to that part of the deviation which arise from the transient magnetism induced in the soft iron of a ship which is independent of the position of the ship in building. To describe this intelligibly, I must ask leave to introduce you to the "*three soft iron rods*," the apprehension of which gives us such a command over the effect of the iron in a ship. If a thin soft iron rod is held in any position, its south end will attract and its north end will repel the north end of the compass needle. The effect of such a rod is therefore very easily estimated, and even computed, when its inductive capacity is known. Theory then furnishes us with this remarkable result, that if the compass is placed in the midship line of the ship, the effect of all the soft iron in the ship, however irregularly distributed, provided only that it is symmetrically arranged on each side of the midship line, may be represented by three imaginary soft iron rods, the direction of each of which passes through the centre of the compass; one rod called a lying fore and aft, another called e lying athwartship; the third called k being vertical. If the whole rod lies on one side of, or as it may be called "outside" the compass, its effect is to increase the directive force of the earth in the same direction. This is denoted by giving the rod a $+$ sign. If the rod passes through the compass, so as to have one end on each side of the compass, it diminishes the directive force of the earth, and this is denoted by giving the rod a $-$ sign. The effect of these rods in producing a deviation is easily traced out. It is shortly this—

- $+ a$ increases the directive force and the quadrantal deviation.
 - $- a$ has the reverse effect, neither $+ a$ nor $- a$ affects the heeling error.
 - $- e$ (and no case of $+ e$ is known) decreases the directive force, increases the quadrantal deviation, and gives a heeling error to windward.
 - $+ k$ gives a heeling error to windward.
 - $- k$ " " " leeward.
 - neither $+ k$ nor $- k$ affects the directive force or the quadrantal deviation.
- These may be illustrated by the following diagrams and tables:—

Fig. 1.

Fig. 2.

Fig. 1.

Fig. 2.

Effect of the three soft iron rods.	Quadrantal deviation (+ increases - diminishes)	Directive force (+ increases - diminishes)	Heeling error (+ to windward - to leeward)
$+ a$	$+$	$+$	no effect
$- a$	$-$	$-$	no effect
$- e$	$+$	$-$	$+$
$+ k$	no effect	no effect	$+$
$- k$	no effect	no effect	$-$

It may easily be shown that if a rod whose centre is coincident with the centre of the compass is moved in a direction at right angles to itself, as for instance, if a transverse rod is moved forward or aft, the effect it produces is exactly the same in kind as before, though diminished in amount. Thus, iron beam in a ship extending from side to side will simply produce a $- e$.

If these simpler rules are apprehended, we are in a position to estimate the effects of almost any arrangement of soft iron.

1. The effect of the hull and the iron decks of a ship on the compass, placed at a certain height above the deck, will give—

$$- a, - e, + k;$$

e being numerically greater than a .

The result is—

1. To diminish the directive force of the needle.

2. To give a quadrantal deviation.

3. To give a heeling error to windward.

2. The effect of an iron beam is, as we have said, to give $- e$, and thus—

1. To diminish the directive force.

2. To give a quadrantal deviation.

3. To give a heeling error to windward.

3. An iron bulkhead, reaching from side to side, under or nearly under the compass, particularly of the nature of an armour bulkhead, has a very formidable effect in giving a large $- e$ and a $+ k$, thus diminishing the directive force and giving a large quadrantal deviation, and a large heeling error.

4. Gun turrets or iron masts or funnels, and the boilers and engines of a vessel, if entirely before or abaft the compass, will give $+ a$ and $- e$, and so give a large quadrantal deviation, but will rather tend to increase the directive force.

5. If the boilers are immediately below the compass they will give $- a$ and $- e$ and $+ k$, and, therefore, diminish the directive force, and give a large heeling error, but will not give much quadrantal deviation.

6. The armour-plating of a ship, if continued from end to end, as in the "Royal

Oak" and "Minotaur," is not so prejudicial as might be supposed as first sight, because it will give a large $-a$, a small $-e$, and a $-k$, and, therefore, will rather diminish the quadrantal error and the heeling error, and its principal prejudicial effect will be in diminishing the directive force. If, however, as in the "Warrior" and "Black Prince," the armour-plating is not continued from end to end, but stops short near the position of the standard compass, and there is there a transverse armour bulkhead, then there is a small $-a$, a very large $-e$, and a $+k$, and there is a very large quadrantal deviation and heeling error, and a small directive force.

7. Any iron placed immediately below the compass, and within an angle of $51^{\circ} 45'$ of the vertical passing through it, is very prejudicial by giving $-a$, $-e$, and $+k$, and diminishing the directive force and giving a large heeling error.

In such cases as we have been considering, the great source of evil is a large $-e$, and it is of great importance to diminish this as much as possible. This may be accomplished to some extent by having the part of the deck immediately under the compass and for an angle of about $35^{\circ} 15'$ on each side of the vertical, constructed of wood, the iron beams being, if possible, cut, and their ends inserted in a fore and aft beam, and if this wooden space can be made a continuation of a line of hatch-ways, $-e$ may be very considerably diminished.

Another point of great importance is to avoid as much as possible placing the compass near the ends of long vertical or of horizontal masses of iron, as the spindle of a capstan, or of a steering wheel, iron masts or funnels, the sternpost, or rudder head. If, however, we must bring the compass near the ends of such masses it may sometimes be possible by a judicious selection of the place to use them as correctors.

Leaving this part of the subject I will advert to one point on which a good deal of obscurity has been supposed to rest, and as to which mistakes are not unfrequently made, viz., the comparative effects of solid and hollow masses of iron. It has sometimes been supposed that in the case of a hollow shot or tank, the magnetism exists entirely at the surface, and that the effect is the same as if it were solid. This is not the case, but theory shows, and it is completely borne out by observation, that the effect of hollow masses of iron increases very rapidly with the increase of the thickness of the iron, and whenever the thickness is more than a very small proportion of the diameter of the body, the effect of the body is sensibly the same as if it were solid.

Mr. Barlow found that the effect of a shell $\frac{1}{16}$ th of an inch thick, and 10 inches in diameter, was two-thirds that of a solid sheet of the same size. This exactly agrees with theory. In the case of iron tanks, to which this result may be compared, we get the result that a tank 4 feet diameter, and one-eighth of an inch thick, would have about half the effect on the compass of a solid mass of iron of the same dimensions.

I trust these observations will assist you in some degree in understanding in what manner the theoretical investigations to which I have referred may be put to a practical use in the correction of the deviation of the compass.