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LECTURE.

Friday, February 2nd, 1872.

GENERAL SIR EDWARD SABINE, K.C.B., R.A., late President of
the Royal Society, in the Chair.

ON THE PRESENT STATE OF OUR KNOWLEDGE RESPECTING THE MAGNETISM OF IRON SHIPS, AND THE TREATMENT OF THEIR COMPASSES.

By Staff-Captain FREDERICK J. O. EVANS, R.N., F.R.S., Hydrographic
Department of the Admiralty.

TWENTY years have nearly elapsed since an ardent investigator in magnetic science—the late Dr. Scoresby—delivered a lecture in this theatre particularly addressed to the naval profession, and which I had the privilege to hear. In that lecture he expounded certain principles relative to the development of magnetism of a high degree of force, in ships built of iron, during their process of construction;—the special individuality of the distribution of this acquired magnetism depending essentially on the position of the ship's keel and head while building; and also on the subsequent changes which he considered this magnetism must undergo under conditions of mechanical violence or the straining at sea of the ship. Many of his propositions were illustrated by experiments of a simple kind, which, notwithstanding their simplicity, left a lively impression on his audience.

Dr. Scoresby was no alarmist;—but the views he entertained of the instability of an iron ship's magnetism, as affecting her security in navigation, and the danger attending the use of permanent magnets to correct the consequent errors of the mariner's compass; combined with his well-known character as a skilful and bold seaman in youth, philosopher and divine in mature age; influenced the seamen of the period and created much distrust in their minds as to the soundness of certain methods of correction adopted (the result, it may be observed, of a thoroughly scientific investigation), and the consequent security of the ship.

Had Dr. Scoresby been spared to the present time, we may be as-

sured that he would have been gratified in a double sense at the progress of our knowledge of his cherished branch of science; in the first place, because those principles he had so sagaciously elucidated on theoretical considerations from experiments on a very small scale, were confirmed by modern observations embracing ships of a size undreamt of by him, culminating in the "Great Eastern," and armour-clad war-ships of nearly 7,000 tons. In the second place, he would have been gratified that those principles which he had set forth as to the insecurity attached to the navigation of the iron ship—based chiefly on the reports and opinions of others—were not justified except when the teaching of science had been neglected or evaded.

From official connection with the Admiralty Compass Department, and association with other workers in the field of magnetism, I have been for many years naturally deeply interested in that science in so far as it relates to navigation; a branch of science that I may here observe, affords a wide field for research, and which is by no means exhausted; though much, very much, has been done. It has in consequence fallen to my lot on two previous occasions, namely, in 1859 and 1865, at the invitation of the Council of this Institution, to read papers to the Members on the same subject that formed the life-long study of Dr. Scoresby. The invitation of the Council to address you is again extended to me; my endeavours, therefore, will be to place before you in the short time at my disposal, those leading facts and principles bearing on the magnetic features of iron ships, and the treatment of their compasses, which mark the progress of our knowledge from the days of Scoresby, as also the general conditions of the question at the present time.

I will first, however, give a concise review of the subjects touched on in the papers of 1859 and 1865, as my desire is to avoid, as far as possible, a repetition of what has already been before you, and to be found in the Journals of the Institution.

The Paper of 1859, gave a slight historical sketch of what had been observed in relation to the deviation of the compass on board ship by the old navigators, and of the several methods proposed for the correction of those errors. The experiments and investigations of the Astronomer Royal in 1838-9 on iron vessels, in the then early days of iron shipbuilding, were touched on, as well as the treatment of a ship's deviation table, by Archibald Smith—a name now well known in connection with magnetical science—for finding the five co-efficients A, B, C, D, E, which represent the resolved values of the magnetic disturbance at the particular compass; together with the results of this method of investigation when applied to certain wood and iron-built ships of that period. The magnetical investigations of Dr. Scoresby, and the labours of the Liverpool Compass Committee at that time actively engaged, were further noticed.

The paper of 1865 treated in much detail the magnetism of iron and ironclad ships of war, for in the interval from 1859 great advances had been made, both in the theory and practice incidental to this branch of

the navigator's art. The necessity had, as it were, been forced by the unlooked-for introduction of armour plating, gun turrets, shot-proof transverse bulkheads, and such like masses of iron in ships of war, together with the general employment of iron for decks, beams, and other internal fittings of the ordinary ship; and thus the approximate mathematical formulæ in use in 1859, and which sufficed for the moderate compass deviations of the early iron ships, ceased to be applicable.

The necessary extension of the mathematical theory was undertaken by Archibald Smith, and this revision, together with that of the practical methods for ascertaining and applying the deviation, were given in the Admiralty Compass Manual which then (1865) had reached a second edition, and, at the present time (1872), a third.

This manual is in its several parts concisely described in the paper of 1865, together with the practical adaptations of its more important formulæ; and the numerical values of the several parts into which the errors of the compass are divided in their mathematical treatment, whether with the ship upright or heeling, are given for those of the armour-plated ships of war which had been built, equipped, and undergone sea service in the interval from 1859.

The principal conclusions then drawn from the application of observation and theory to the magnetic phenomena in iron ships followed, with general remarks on magnet correction and other details incidental to the subject.

The paper appropriately closed with the substance of a *vivâ voce* explanation by Archibald Smith, on what, before the later investigations referred to in the paper, were the most obscure of the varied magnetic phenomena observed in an iron ship; namely, that part of the deviation which arises from the transient magnetism induced in the soft iron of the ship by the earth's magnetic force, and which is independent of the position occupied by the ship in building.

This *résumé* of an obscure question, illustrated as it is by the action of "three soft iron rods," and which alone appears in this form in the Journal of this Institution, has always appeared to me a model for clearness, accuracy, and conciseness of what, to most minds, would be conflicting and complicated. I regret that on the present occasion my esteemed friend and fellow-labourer cannot be present from the state of his health.

To resume the subject of the present state of our knowledge of the magnetism of iron ships, and its collateral branch, the treatment of an iron ship's compasses.

The most important feature of the first part of my subject as being the foundation of our knowledge, is its mathematical treatment; this must be understood to include the algebraical formulæ together with their arithmetical processes and the several geometrical or graphic constructions so useful to the navigator as well as to the analyst. Time will not permit me to touch on these details; there is, however, little necessity, as the Admiralty Compass Manual will be found a complete storehouse. I propose instead to confine myself mainly to a sketch of

the leading practical deductions drawn from the discussion of those observations in iron ships, which have been reduced to their several numerical values by the mathematical appliances referred to.

You will see that I am justified in this procedure by the views taken by the President and Council of the Royal Society so far back as the year 1865, as expressed in the following extract from a communication of that body to the Board of Trade on the expediency of a systematic supervision over the adjustment of the compasses of ships of the mercantile marine:—

They say "The theory of the deviation, its causes and its laws, is now thoroughly understood and reduced to simple formulæ, leaving the numerical magnitude of a certain small number of quantities to be determined by observation for each ship separately; and further by recording, reducing, and discussing the deviations which have been observed in the ships of the Royal Navy of different classes; numerical results as to the values of these quantities of ships in each class have been obtained which promise to be of the greatest use in facilitating the complete determination of the deviation and its correction"

"The science of magnetism in relation to navigation is in fact in a position in some degree analogous to that in which the science of astronomy at one time was. The principles of the science have been established, the formulæ have been obtained, but numerical values are wanted, which can only be derived from a large number of observations systematically made and discussed."

Although, as will be seen by the extracts just read, no doubts exist in the minds of those who have patiently investigated and applied the apparently slow enunciations of science in reference to the mathematical treatment of the iron ships' magnetism; still to a comparatively recent date, it had scarcely commanded the confidence of the naval profession. Seamen appeared either to fail in appreciating the true value of a scientific mode of treatment, or perhaps hoped that some short road might be discovered involving no labour or thought to follow out, and, of course, no science to evoke, and thus at once settle the question of the practical and perfect working of the mariners' compass.

I should be wanting in allegiance to scientific truth as opposed to such popular fallacies, were I not here to state my conviction that the general formulæ elaborated by the mathematician to give the navigator security and confidence in his compass, do satisfactorily represent the observed phenomena productive of error, in every class of ship yet come under investigation; and I would further add, that I cannot conceive how the complicated details of an iron ship's magnetic features can be understood, and the numerous sources of error affecting the compass recorded, and, as far as possible, eliminated, without such mode of treatment.

Before passing from these considerations of the theory, permit me to read to you an extract from an article in the *Quarterly Review* for October, 1865, on the Mariners' Compass, written by a distinguished

mathematician, who in the interests of literature had mastered the subject. In a few brief sentences you will be told to whom homage is due:—

The writer says: "It would be out of place in these pages (even if our space allowed it) to enter into any detailed examination of the extremely elegant mathematical investigation first published by Mr. Archibald Smith in the "Philosophical Transactions" of 1847, and to be found in a more mature shape in the last edition of the Admiralty Manual on Compass Deviation. The briefest possible account of the general character and broad results of the work and its relation to earlier investigations, is all that is practicable here. The first mathematician who attacked the problem of the disturbance of the compass by external attraction, was the eminent French philosopher, Poisson. After the manner of his country, Poisson treated the question in its greatest generality, and obtained formulæ giving the deviation of a needle under the combined influence of any arrangement of magnetized and unmagnetized iron. Beyond this point the labours of Poisson were of little practical service, and it remained for others to give a real significance to the arbitrary constants of his formulæ, by tracing their connection with the actual construction of a ship, and reducing them to a form which would admit of a direct application of the theory to practice.

"To the Astronomer Royal belongs the credit of having first dealt with the investigation of this practical problem, in the year 1839, in connection with his experiments on the 'Rainbow' and 'Iron-sides;' and for a time his papers, printed in the 'Philosophical Transactions' for 1839, contained the only available theory on the subject. Although it has since been found necessary to build up the formulæ for practical use upon a more rigidly accurate basis, it is impossible to over-estimate the importance of Mr. Airy's first conquest in what was then an obscure and almost untried field of science. The novelty of Mr. Archibald Smith's treatment of the subject at a later epoch, consisted simply in discarding all arbitrary assumptions whatever, and dealing with the actual problem on the footing of Poisson's equations, which by a series of elegant transformations he reduced to forms admitting of immediate practical use, and bearing their own physical interpretation on their face. Certain happy geometrical constructions, by which the theory is made available for the seamen without the necessity of referring to the mathematical formulæ, are not the least valuable and original portions of the investigations."

In my paper of 1865, you will find noticed the magnetical features of six of our earliest armour-clad war ships, with the numerical values of their co-efficients. Between the year 1865 and the present time, our armour-clad ships have been greatly increased, and several novel types of war-vessels introduced.

Five troop-ships of large dimensions have been added to the ordinary class of iron ships, together with three large cruisers sheathed with wood, and several small iron unarmoured gunboats.

A distinct class of vessel has also come into prominence in the same period; eighteen cruizers of about 450 tons each, constructed on what may be termed a complete "composite system" of wood and iron; and nearly thirty more of much larger tonnage, some reaching 1,500 tons, on a partly "composite" system. The vessels on the complete composite system have their ribs, beams, stringers, and upright supports constructed of iron, and conform in magnetic character in a very marked degree, to the iron built ship; in the partly composite vessels the iron ribs are wanting, and their magnetic character is less distinctly marked.

The custom of the Admiralty Compass Department is to allow no vessel of any of the classes to which I have referred, to proceed in the first instance to sea without their complete magnetic history being known; this includes not only the forming tables of deviations for their several compasses, but also the values of the horizontal and vertical magnetic forces of the ship at the compass stations as compared with the earth's magnetic force. The observations for this history are not unfrequently commenced when the ship is on the stocks.

These observations, together with such as may be subsequently made in the course of the ship's service, are reduced by the appropriate formulæ and the several resulting co-efficients and their constituent parts recorded for future reference.

Appended is a Table containing the magnetic elements of a few ships of various types. It is introduced as illustrative of the method of recording the several co-efficients and their constituent parts;—as also showing the increasing amount of error, especially that arising from the induced forces, the consequence of the increased amount of iron employed in the construction of the modern vessel.

The steam-ship "Rainbow" (in the first column) is the first ship experimented on (1838) to determine the nature of the magnetism of iron vessels and the co-efficients are those resulting from the Astronomer Royal's observations. The merchant ship "Clyde," in the second column, is a fair type of the modern iron ship, and is introduced to compare with the "Rainbow." The remaining examples are types of modern ships of the Royal Navy. In the last column are the co-efficients at a compass near the steering wheel between decks, on the starboard side, in the "Cyclops" turret ship: the co-efficients A and E in their large values are confirmatory of the theoretical principles established for compasses that are placed out of the midship line of the vessel—these co-efficients at compasses in the midship line are usually zero.

Table of Magnetic Elements of various Ships,

		Merchant Ships.	
		Steam-ship. 500 tons.	Sailing ship. 1,100 tons.
Ship's name		"Rainbow."	"Clyde."
Head built		to N.N.W.	to N.E.
Observed {	Place	Deptford.	Greenhithe.
	Date	1838.	1863.
Approximate Co-efficients of Deviation.	Constant.....	A .. + 0 35	+ 0 41
	Semicircular	B .. -18 45	- 7 56
		C .. -12 57	+ 7 25
		D .. + 2 30	+ 4 43
	Quadrantal.....	E .. + 0 02	+ 0 08
Exact Co-efficients of Deviation.	Constant.....	M .. + .010	+ .012
	Ship's force to head	N .. - .327	- .143
	Ship's force to starboard ..	G .. - .217	+ .124
		D .. + .044	+ .082
	Induced forces	G .. + .001	+ .002
Maximum semicircular deviation or $\sqrt{B^2 + C^2}$..		22½°	11°
Horizontal force of ship.	Mean { Amount.....	√B² + C² .. .392	.189
	Direction, or	tan $\frac{16}{23}$..	139°
	"starboard angle" ..	213°	
(Mean force to north (N) being unit.)			
Mean Horizontal force on board to north, or λ ..		.972	.870
(Earth's horizontal force = 1.0.)			
Fore and aft horizontal induction, or..... a ..		+ .015	- .059
Transverse ditto or..... e ..		- .071	- .201
Parts of D {	from fore and aft induction	+ 0° 24'	- 1° 57'
	„ transverse „	+ 2 07	+ 6 39
Mean vertical force on board, or..... μ ..		—	1.275.
(Earth's vertical force = 1.0.)			
Heeling error for 1° of heel of ship.....		—	+ 1° 22'
(+ to windward - to leeward.)			
Heeling {	from vertical induction in	—	+ 0 35
	transverse iron		
Co-efficient {	from vertical force and induction	—	+ 0 47
	in vertical iron		
Variable part of vertical force, or $\frac{g}{\tan \text{dip}}$		—	—

at selected position of Standard Compass.

<i>Indian Transport.</i> 4,173 tons. 700 h.-p.	Modern war ships.			
	<i>Composite build.</i> 4 guns. 467 tons.	<i>Iron gunboat.</i> 245 tons.	3,893 tons. 14 guns. 800 h.-p.	2,107 tons. Turret ship.
"Scrapia." { <i>Built North, fitted S.S.W.</i> } Greenhithe. 1867.	"Avon." <i>S. 57° E.</i> Portsmouth. 1863.	"Kite." <i>S. 34° W.</i> Greenock. 1871.	"Swiftsure." { <i>Built S. 56° W. fitted N.N.E.</i> } R. Tyne. 1871.	"Cyclops." <i>Lower deck compass.</i> Sheerness. 1871.
0 56 - 18 56 - 5 24 + 4 51 - 0 18	0 33 + 17 04 + 20 20 + 4 01 + 0 10	0 55 + 33 16 - 18 20 + 8 35 + 0 05	0 38 + 20 15 - 9 43 + 7 18 + 0 10	0 0 - 36 09 + 16 04 + 13 45 - 6 49
- 016 - 339 - 089 + 085 - 005	+ 009 + 300 + 333 + 070 + 003	+ 033 + 588 - 138 + 149 + 001	- 011 + 368 - 156 + 127 + 003	- 087 - 679 + 266 + 240 - 117
19½°	26½°	38°	22½°	40°
351 191½°	419 48°	604 347°	400 337°	729 159°
205	920	822	790	486
- 017 - 173 - 0° 32' + 5 27	- 016 - 144 - 0° 28' + 4 29	- 079 - 277 - 2° 46' + 9 44	- 110 - 310 - 3° 56' + 11 14	- 398 - 630 - 24° 05' + 40 24
1.170	819	705	1.118	<i>strong upward force.</i>
+ 0° 57'	- 0° 06'	- 0° 01'	+ 1° 29'	--
+ 0 29	+ 0 23	+ 1 0	+ 1 05	--
+ 0 28	- 0 29	- 1 04	+ 0 24	--
+ 024	+ 019	+ 039	+ 076	--

On examining these general records to the end of 1871, I find that, excluding our wood-built fleet, we have more or less complete the magnetic history of—

- 25 Iron armour-clad ships,
- 14 Wood armour-clad ships,
- 9 Iron armour-clad turret ships,
- 3 Unarmoured iron cruisers sheathed with wood,
- 12 Iron gunboats of small dimensions,
- 50 Iron ships of ordinary construction, varying in size from "Great Eastern" to vessels of 300 tons,
- 18 Composite build (complete) cruisers,
- 28 Composite build (incomplete) cruisers.

For these 159 vessels 1,250 deviation tables have been resolved into their several co-efficients, A, B, C, D, E. 400 of these tables have been accompanied by force observations for the determination of the co-efficient λ (*lambda*), or the mean horizontal magnetic force of the ship to the north as compared with the earth's horizontal magnetic force, and about 300 determinations of the ship's vertical magnetic force as compared with the earth's vertical force: the latter made in order to obtain the amount of deviation due to those forces, which, when the ship was upright, acted vertically and did not disturb the horizontal compass-needle, but when the ship heels over produce a sensible error, technically known as the "heeling error."*

For some of the armour-clad ships we have 30, 40, 45, and in one ship 53 deviation tables, divided between the standard compass, the steering, and other compasses, including those below decks.

The several discussions of these extended observations, combined with those made in former years by the Liverpool Compass Committee, as resulting from the varied experimental investigations made by Messrs. Towson and Rundell (see the three Reports, 1857—61) lead to certain definite conclusions, the chief of which may be thus summarized as general principles.

1. The magnetism of iron ships is distributed according to precise and well determined laws.

2. That a definite magnetic character is impressed on every iron ship while on the building-slip, which is never afterwards entirely lost.†

3. That in an iron-built ship, and in that part of her within which the navigating or standard compass is generally placed, the polar force is that from the magnetism of the whole body of the ship, and is nearly uniform; and that we cannot escape from the action of that force by any care in the selection of a place for the compass.

* The observations and reductions in late years have been made by Staff Commander William Mayes, Superintendent of Compasses, and an assistant officer, Navigating Lieutenant Ettrick W. Creak, R.N. Navigating Officers of the Fleet have also contributed observations from abroad.

† See Fig. 1. These theoretical deductions of Scoresby are amply confirmed by experiments made in iron ships of all sizes, built on various azimuths.

4. That the definite magnetic character of an iron ship, so far as relates to the polar forces developed in her during construction, is shown by the connection which exists between the direction of the ship's original magnetism and the direction of her head when on the building-slip; for the original semi-circular deviation consists principally in an attraction of the north point of the compass-needle to the part of the ship that was south (or nearly so) in building.*

5. That a great reduction takes place in the magnetism of an iron ship on first changing her position after launching, and that her magnetic state is then unstable for a short period. Then, after a few months' service, perhaps within a year for the average of ships, the time probably depending on the nature of the iron employed in the construction, the magnetism of the ship acquires a very stable character.

6. That in iron-built ships, as at present constructed, the ship's polar force is generally so great as to make it necessary to employ magnets to equalize the directive force on different azimuths of the ship's head, even at the most carefully selected position.

The investigation of the numerical values in more extended detail lead to inferences which I will now place before you.

Respecting the Semi-circular Deviation.

Though on general theoretical considerations of the distribution of magnetism in the iron ship's hull, a position for the compass could be selected where large errors might be avoided, still the practical requirements of the seaman and the architect frequently interpose to prevent choice of site; the magnetic action of the diverse interior fittings and equipment of the modern iron steam-ship are also not unfrequently of an amount sufficient sensibly to affect the resultant error as due alone to the hull, although the latter, it must be observed, will always be found to dominate. We find from these considerations that the amount of semi-circular deviation in ships of similar classes at compasses similarly placed are not comparable; in fact, we must consider each ship to have its own polar-magnetic constitution. This dissimilarity of constitution does not exist when we examine into the values of their induced forces.

The following table, for example, exhibits the values of the *maximum* semi-circular deviation in several classes of vessels at the standard compass in selected positions:—

In six iron gunboats, of 245 tons each, from	..	19° to 41°
In fifteen composite gunboats, of 465 tons each,		
from	15° to 25°
In five Indian transports, of 4,200 tons each, from	17° to 29°	
In three iron cruizers, wood-sheathed, 2,300 to		
4,000 tons each, from	32° to 43°†

* See Fig. 2.

† I am disposed to consider that the high values found in these three ships, "Inconstant," "Vulgar," "Active," arise from the extra hammering involved in sheathing their bottoms with wood preparatory to coppering.

In six armour-plated ships with central batteries,
 of 3,800 tons each, from.. .. 20° to 48°

The general proposition that a great reduction takes place in the magnetism of a ship on first changing her position after launching, but that after a few months' service the magnetism acquires a comparatively stable character, is sustained by evidence extending over many years. It is difficult to assign numerical values to these changes where so much diversity of character exists in the several types and constitutions of ships; but we may assume that in the first month or two after launching, and if in the course of equipment her head has been on different azimuths, about one-fifth of the semi-circular deviation that existed when on the stocks, would be dissipated. This is in accordance with a few cases actually observed. From this time until the period of stability is attained, the residual semi-circular deviation further decreases by about another one-fifth.

In reviewing these changes and those that subsequently arise from the changes of geographic position, we must consider that although the principal part of the semi-circular deviation is caused by permanent, or as we may more properly call it, sub-permanent magnetism: a residual part is independent of the ship's position in building, being the effect of *transient* magnetism induced in the ship by the earth's vertical force. It is the first and largest of these parts that diminishes so much in the early history of the ship, and which subsequently attains its fixed and permanent character, while the smaller residual part probably changes little, if at all, so long as the ship remains in the same magnetic latitude. On change, however, of magnetic latitude, this residual part rapidly changes, and its effect on the north end of the needle is reversed on the ship attaining the southern magnetic hemisphere.

Now if a compass is properly placed with reference to vertical iron by there being a fair distribution of the latter on either side, before or abaft the compass, the changes arising from the sub-permanent and transient magnetism induced by the earth's vertical force would be very small; while if unfavourably placed, such as being near the rudder-head and sternpost, there would assuredly be very large changes on change of magnetic latitude.*

At the standard-compass of many of the ordinary built iron ships in the Royal Navy, it is found that not only is the semi-circular deviation very constant in amount,—showing the stability of the magnetism,—but that on great changes of geographic position it is found

* There is an existing but fallacious belief that in every iron ship a place can be found where all the "magnetic influences balance," or a *neutral point* where a compass can be placed free from errors of any magnitude. At a recent discussion in the Institution of Naval Architects, this belief was put strongly forward, and it was further stated that such a neutral point existed in H.M. Ships (p. 245 of "Transactions" for 1871). The statement is erroneous, and the belief is only true thus far, that in some few ships a position may be found where, from the magnetism of a particular mass of iron—such as the rudder-head—counteracting that of the ship, the semicircular deviation will be small; yet such positions are in general to be avoided, as the change of magnetic force there will probably be larger and less regular than when the compass is only acted on by the general magnetism of the whole ship. Such positions of insecurity are certainly avoided in H.M. Ships.

to arise from permanent magnetism; a fact rendered obvious from the semi-circular deviation varying at a rate inversely proportional to the value of the earth's horizontal force, and not directly proportional to the value of the tangent of the magnetic dip. In these ships the changes of deviation ensuing on any part of their voyage can be confidently predicted.

As an approximate rule, in the ordinary iron-ship built in England at a well-placed compass, from one-fourth to one-eighth may be taken for the induced part or that affected by changes in the dip, and from three-fourths to seven-eighths of the whole magnetism for the permanent part. The changes of deviation on change of geographic position can thus be approximately predicted.

In the armour-plated ships the amounts of the induced and permanent magnetism appear to be nearly equal, although it is worthy of observation that the changes of semi-circular deviation in their early history are less marked than in the ordinary type of iron-ship, and that its settled value is sooner established; conditions probably arising from the increased amount of hammering in the progress of their construction.

*On the Loss of Directive Force in the Compass-needle
and the Quadrantal Deviation.*

One of the most remarkable features in the iron-ship's magnetism, as arising from the increased use of iron in their structure, is the increasing prejudicial effect on the action of the compass by the mean directive force of the needle being in consequence diminished; by this diminution of force, the effects of all the disturbing forces on board, especially those which may arise from the friction on the needle, due to imperfect workmanship or wear, are increased.

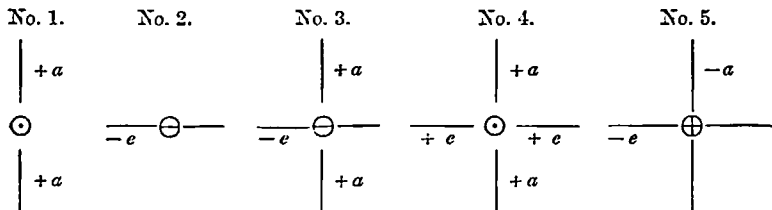
It will be seen by the tabulated coefficients of the several vessels that are appended, that while in the early constructed iron-ship experimented on by Mr. Airy, the mean directive force to the north acting on the needle, or (λ), is $\cdot970$, or a loss of only $\cdot030$, as compared with the earth's horizontal force considered unity; in a similarly placed compass on board the modern iron merchant-vessel "Clyde," it is $\cdot870$, a loss of $\cdot130$, or about one-eighth. At the standard-compass of our armour-plated ships, λ is generally not more than four-fifths, and at their main deck compass three-fourths of the earth's force, while within the breast-work of the "Cyclops" class it is reduced to nearly one-half.

As these striking facts do not appear to have been recognised by those projectors who aim at demagnetizing the iron ship, it is desirable, perhaps, here to state that it admits of experimental proof, that this diminution of force is not the effect of permanent magnetism, but alone arises from induction in the "soft" iron of the ships by the earth's horizontal force, and that were it possible to demagnetize or depolarize the ship, this diminution, or the quadrantal deviation which arises from the same cause, would not be affected.*

* If we place a compass over a circular plate of purely soft iron, no deviation will be

Now the quadrantal deviation (D), which assumes a large value in our modern ships, especially when armour-plated, admits of the same experimental proof that it can alone be caused by *horizontal* induction in *soft* iron, and thus its connection with λ .

Conceive, for example, the following arrangements of soft iron in which the ship's head is supposed to be directed towards the top or bottom of the page.



We may consider $+a$ to represent masses of soft iron entirely before or abaft the compass, as engines, boilers, funnels, iron masts, &c.

,, $-a$,, soft iron extending through the position of the compass, as the keel and hull of the ship, screw shaft, armour plating, &c.

,, $-e$,, the effect of all the transverse soft iron, as the bottom of the ship, iron decks, iron beams, &c.

,, $+e$,, masses of soft iron which lie to one side of the compass, as guns, davits, or when the compass is in or over a hatchway.

Between these various arrangements there is this important difference, that in Nos. 1 and 4 the directive force of the needle would be increased, while in Nos. 2 and 5 it would be diminished; in No. 3 it might be either increased or diminished, or left unaltered, as the effect of the longitudinal and transverse iron is ponderated.

For the deviation, as the ship swings round—

$+a$	will give a	<i>positive</i>	quadrantal deviation.*
$-a$,,	<i>negative</i>	,,
$-e$,,	<i>positive</i>	,,
$+e$,,	<i>negative</i>	,,

produced, but the directive force of the needle (as shown by the slowness of its vibrations, when compared with those made in a place free from disturbing causes) will be diminished, arising from the magnetism induced in the circular plate by the earth's magnetism, acting in a direction antagonistic to that of the earth's force. A similar effect is produced when the compass is enclosed in an iron vessel or a hollow shell; hence we see how a compass placed above an iron deck, and still more between iron decks, loses a great part of its directive force.

* *i.e.*, a deviation of the needle to the east in the 1st and 3rd quadrants, to the west in the 2nd and 4th quadrants. A *negative* quadrantal deviation is the reverse of the foregoing, *i.e.*, west deviation must be substituted for east, and east deviation for west; in both cases $+$ sign representing east deviation, $-$ sign, west deviation.

Applying these principles to the observed facts, it is found, without exception in every iron ship, at the ordinary place of the compass, that the quadrantal deviation is *positive*, or follows the sign $+$ $-$ $+$ $-$ in the successive quadrants NE., SE., SW., NW., from whence we may infer that it is caused by the co-existence of the arrangements of masses of soft iron represented by $+a$ and $-c$, as shown in Fig. 4, or the excess of $-c$ over $-a$, as shown in Fig. 5.

The investigations of the observed values of D and λ give this result, that the positive value of D arises from the transverse iron continued from side to side, such as beams, decks, bulkheads, and the ship's bottom, producing a large $-c$, and overcoming the force of the fore and aft iron, or a ; the latter is sometimes, but rarely $+$, but more generally $-$, and when $-$ always less than c (see tabulated co-efficients); and hence that it is caused by the excess of the thrust on the north end of the compass needle from the north *side* of the ship, over the thrust from the north *end* of the ship.

In this explanation of the causes of the quadrantal deviation, I have somewhat gone over the same ground as in my paper of 1865, but the facts given in that paper on the subject appear by more recent proposals and writings in reference to the magnetism of iron ships, to be entirely overlooked; a serious omission, which I now endeavour to rectify by a reiteration of the principles.

At the standard compass of ordinary iron ships the quadrantal deviation is usually from $4\frac{1}{2}^{\circ}$ to 5° , in armour-plated iron ships 6° to 7° . On the main deck of the latter class it rises to 8° and 10° , while in the batteries and between decks of the turret ships it reaches the enormous amount of 15° and 20° .

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, particularly in ships having a thick iron deck. The diminution of the directive force, and the quadrantal deviation, both diminish with the lapse of time, there are also grounds for believing that λ is affected by temperature, diminishing by increased temperature, but this consideration does not affect navigation.

Respecting the Heeling Error.

I now arrive at the question of the "heeling error" in iron ships, or that amount of deviation which is superposed on the ordinary deviation of the compass when the ship heels over to port or to starboard from an upright position, and which, for theoretical and practical purposes is in its value indicated for every degree of heel of the ship.

Theoretically considered, the heeling error is a complicated though not an obscure problem; fortunately practically considered, it does not baffle the careful navigator, nor is it without amelioration by partial correction through the aid of magnets, and especially by a proper

position being selected for the compass. In all cases we know that its *maximum* amount occurs when the ship's head is *north or south* by the disturbed compass, and that it vanishes when the ship's head is *east or west* by that compass. So forewarned, the navigator knows when he can ascertain the extreme amount of error from actual observation at sea, and when to use precaution.

The worst possible condition for producing heeling error is when an iron ship is built head north, and the compass placed near the stern,* as that part is strongly magnetised, and all the additional forces developed by the ship's heeling conspire to produce the error. These forces are—

1. Vertical induction in transverse iron, such as the beams, &c.
2. The vertical force from the permanent magnetism of the ship.
3. The vertical induction in all vertical iron situated under the compass, such as the sternpost, stanchions, &c., and each force pulls the north end of the needle downwards and to windward.†

Conversely, the best possible condition for the reduction of the heeling error is in the ship built head south (or from SW. to SE.), when the compass is placed in the after part of the ship; as then force 2, from the reversed polarity of the stern of the ship, operates against forces 1 and 3, and may exceed them in intensity;—if so, a small heeling error to leeward would result. Hence the difference in the heeling errors of individual ships: it is, applying a term I did when speaking of the semi-circular deviation, a constitutional error, and one ship affords no guide to another unless all the conditions of build are the same.

The numerical values of the heeling error in the ships of the Royal Navy are about as follows:—At the standard compass of the armoured ships, when in England, the worst type does not exceed $1\frac{3}{4}^{\circ}$ for each degree of heel, and it is always to windward; 1° and under would, perhaps, be the average: in all these ships about $\frac{3}{4}^{\circ}$ is found to arise from force 1, or that from vertical induction in transverse iron, the remainder from forces 2 and 3. On the main decks of these ships there is a strong upward force producing a heeling error to leeward.

In ordinary iron ships in England the heeling error from transverse iron averages about $\frac{1}{2}^{\circ}$ to windward, an error it must be remembered which changes with the changes of magnetic dip, and would, therefore, in the southern hemisphere be an error to leeward. The forces 2 and 3 are mixed together in such an uncertain way, depending on the build of the ship and arrangements of iron, that their proportions cannot be estimated.

Fortunately, by a simple class of observations with a dipping needle,

* See paper on the loss of the iron ship "Glenorchy." "Royal Society's Proceedings," 1869.

† See Fig. 3 in illustration, when (1) the weather or upper end of the beams and all transverse iron acquire south polarity (s) by induction from the earth (in northern magnetic latitudes); and similarly from induction in vertical iron (3) the south poles are brought nearer the north end of the needle as the ship heels over.

and with the knowledge of the co-efficients D and λ , we can approximate very closely to the error that would be found if the ship were actually heeled, and thus a formidable amount of labour is avoided. The details are fully described in the manuals* on the subject.

When it is considered necessary to correct the heeling error, the practice in the Royal Navy is to employ a magnet a few inches long, which is inserted vertically in the supporting pillar of the standard compass, exactly beneath the centre of the compass needle, a hole being accurately bored for the purpose.

The simple class of observations for finding the heeling error, without heeling the ship; together with those when a horizontal needle is employed to determine the co-efficients B and C , and thus to form a table of deviations, without swinging the ship, are, from my point of view, among the real triumphs in this branch of science. The time and labour that by these means are saved in acquiring a competent knowledge of the ship's magnetic characteristics are important considerations, with the advantages that a secure and desirable position for the compass may be selected while the ship is even on the stocks, and certainly objectionable positions be avoided.

The degree of approximation to correct results in these methods just brought to your notice, depends on the approach to accuracy with which the values of D and λ are assumed, if they are not known. From the numerous records we have now of so many types of ships, it is not difficult to estimate a value for any individual ship, even when new. As a consequence, nearly all the preliminary work of our ships in the Royal Navy is thus effected, nothing is left to chance even when the architect will scarcely give space and place for selection. With the coefficients determined, the correcting magnets are prepared and placed in accordance, and the ship is ready for the thorough "swinging" to form a table of residual errors—errors which are generally small in amount and not embarrassing to the navigator.

It is well to record here that the results obtained by these several methods, approximate closely to those determined by the complete processes of swinging and heeling, and are confidently adopted by the Admiralty Compass Department.

Notes on the Mechanical Correction of Compass Deviation.

After the investigation of the several characteristics of an iron ship's magnetism, the most important consideration is by what means can we correct or reduce the errors so produced on the action of the mariners' compass?

The now universally adopted method of mechanically correcting the deviations of the compass, was proposed by the Astronomer Royal more than 30 years ago, after a series of remarkable experiments and investigations on two of the earliest built iron merchant vessels; and consists, as is well known, in correcting the semicircular deviation produced

* See "Admiralty Compass Manual," 3rd edition, pp. 82—89; and "Elementary Manual," companion to the foregoing, pp. 89—101.

by the ship's polar magnetic force, by the application of permanent magnet-bars; and in correcting the quadrantal deviation arising from the induction in the soft iron of the ship by the earth's horizontal magnetism, by the application of soft iron in masses of diverse shapes.

In past years, as you will have gathered from my opening remarks on the labours of Scoresby, much diversity of opinion prevailed as to the necessity for, and the freedom from danger in the employment of, permanent magnets; the limits of these diverse opinions are now, from circumstances which I will hereafter explain, very much narrowed. Still among, it is to be hoped, a limited few, erroneous opinions exist on this subject, errors too of a nature that can be disproved by simple experiment.*

The general question of the mechanical correction of the deviation of the compass has, on other grounds, materially changed its aspect of late years; the cause arises from the vast increase in the employment of iron in the interior as well as the exterior fabric of the iron ship.

Ships of the mercantile marine, no less than ships-of-war, have been affected by these changes in naval architecture. Before this period of change the deviation of a standard compass, properly placed in an iron ship, seldom exceeded 20° at the maximum, and the directive force which acted on it as the ship was swung, was comprised within two-thirds and four-thirds of the mean force. In the present day it is generally impossible to find a position for this compass at which the deviation and variations of directive force do not greatly exceed these limits. Hence this change in the conditions experienced has produced a corresponding change in the practice of the Royal Navy. Magnet correction is absolutely necessary in nearly every ship-of-war afloat; and broadly I may here state that the results of the system adopted, a system suited to the magnetic knowledge of the day, are satisfactory both as to efficacy and security.

The process recommended by the Astronomer Royal for the mercantile marine and generally adopted, was, as is well known, a tentative one, or an operation simply "to the making the compasses act correctly:" it took no account of the amount or distribution of the magnetic forces at the position of the compass, due to the hull of the ship, or the disturbing action of individual masses of iron masking the magnetic force of the hull of the ship. But a second method was described by Mr. Airy, in his well-known paper on the magnetism of iron-built ships (*Phil. Trans.* 1839, p. 196), which did require the knowledge of these important details, and it is this method which is generally employed in the Royal Navy. It may be thus explained.

* It has been stated, for example, within the last five years in this theatre, by one naval authority, that the employment of correcting magnets decreases the directive force of the needle, and that "common sense dictated at once the sweeping them away;" by another, that they lessen the tendency of the seaman's "guide, philosopher, and friend" (an euphuism for the compass needle) to point truly. These misconceptions will doubtless pass away with the spread of sound knowledge, for in fact, magnets cannot affect the mean directive force, while soft iron correctors increase it.

The co-efficients B , C , λ being found by observation, or when necessary, B and C being found by observation and λ estimated; we have $\sqrt{B^2 + C^2}$ the tangent of the semicircular deviation when the polar force acts to the east or west of the compass, and $\frac{C}{B}$ the tangent of the starboard angle. If we desire to correct the semicircular deviation completely, a magnet of suitable size, adequate power, and proved permanence, is selected. The distance above or below the card at which this magnet, when placed east and west, will produce on shore a deviation of which the tangent is $\lambda \sqrt{B^2 + C^2}$ is ascertained by trial. The magnet is then inserted into the pedestal of the standard compass at the ascertained distance immediately below the centre of the card, and in the direction of the starboard angle, the pole being so placed as to counteract the polar magnetism of the ship. In newly built ships, the polar force, as before mentioned, is generally undergoing a process of gradual diminution, it is therefore generally considered best not to correct entirely the semicircular deviation, but to under correct it.

In general, no attempt is made to correct the quadrantal deviation, that deviation and the residual semicircular deviation being the subject of the tabular correction;—a correction it may be observed now thoroughly grafted in the practice of the Royal Navy, and which practice is certainly productive of security, as its foundation implies that the compass needle must never be considered to point correctly, whatever mechanical correction may be employed.

The question of quadrantal correction by soft iron is a difficult one; it is true that by its neglect a small amount of directive force is lost, and a further small correction of heeling error; the danger, however, that may arise from the large masses of iron necessary for the correction of modern ships taking up polar or permanent magnetism, must be placed as a set off, as also the further consideration that after the correction is effected, all record is lost of the ship's magnetic state.

When the quadrantal deviation is small, as in the ordinary iron ship, it may be, I consider, safely allowed as a residual error; and the omission in practice has this advantage, that it acts as a valuable check on the correctness of the deviation tables constructed by the navigator from the circumstance of the coefficient D remaining constant; or nearly so, under all changes of time and place.

With the large quadrantal deviations at the between-deck compasses of our armour-plated ships, two compasses brought together sufficiently close to produce a *negative* quadrantal deviation equal in amount to the *positive* value of the ship, and then mutually corrected by one system of magnets for semicircular deviation, have proved useful, but the loss of directive power at the place is not remedied. This is a subject now engaging the attention of the Compass Department.

It may be here naturally asked why the practice of compass-correction, which is now considered efficacious and secure, should in the earlier period of the iron ship's history, have been deemed untrustworthy and indeed dangerous? The reply is not difficult; the magnetic

conditions of the few iron ships of the Royal Navy at that period did not as a matter of necessity, require magnet correction—their compass deviations rarely, if ever, exceeded 20° —tabular corrections were readily obtained, and gave ample security. The practice of compass correction was thus confined to the mercantile marine; the process, as recommended by the Astronomer Royal and generally adopted, being purely a tentative one, was easily carried out in practice and involved little or no knowledge of principles: it soon became a branch of ordinary trade business in connection with compass manufacture, and the professional “compass adjuster” has been long established at all our chief mercantile ports.*

Unfortunately, too, the practice of furnishing the seamen with a table of residual errors was not at the same time adopted or its necessity recognized, but on the faith of the professional adjuster, the compass was considered correct.

It was further a prevailing custom at this time in the mercantile marine to use the steering or binnacle compass alone for the navigation of the ship. This compass was usually not more than two feet above the deck beams, and frequently placed in the after part of the vessel near such vertical masses as the stern-post and rudder. Large and irregular deviations were sure to obtain at this position, the large errors requiring to be corrected by large and powerful magnets; the result was that the slightest change in the magnetism of the ship produced a large compass error, and not unfrequently in foreign-going ships proceeding to the southern hemisphere, on reaching the latitude of the Cape of Good Hope, the compass was entirely useless: this arose from the induced magnetism of the rudder and other adjoining masses then acting in unison with those correcting magnets, which originally at the port of departure had been purposely placed to act in direct antagonism.

This indiscriminate use or rather abuse of the method of correction by magnets, was certainly not intended or contemplated by the Astronomer Royal when he freely gave seamen the issue of his valuable labours; but the prejudices arising from the numerous recorded failures, the result of an ignorant application of a sound scientific principle, operated for many years against a proper spirit of enquiry into the causes of failure.

In 1855, however, the Liverpool Compass Committee,† under the auspices of the Board of Trade and with a large number of iron ships of the mercantile marine of that port placed at their disposal, com-

* I am here nearly quoting the words of Mr. Rundell, many years Secretary to the Liverpool Compass Committee, and perhaps the best authority on this point in the country. In a paper read before the Institution of Naval Architects in 1866, “On Compass Equipment in Iron Ships, and Government Supervision,” he remarks:—“Experience shows that compass adjusters rarely know more than the mechanical practice of adjustment, as explained by the Astronomer Royal more than twenty-six years since—a practice so simple that any person of ordinary ability could, under good instructions, acquire it in a few hours.”

† The formation of this Committee originated from the discussions that took place at the meeting of the British Association for the Advancement of Science, held at Liverpool, in 1854, on a paper by Dr. Scoresby, “On the Loss of the ‘*Tayleur*,’ and the Changes in the Compasses in Iron Ships.”

menced a vigorous inquiry into the general question of their magnetism, and the correction of their compasses; in their Third Report, embracing the period 1857—1860, and dated February, 1861,* they state with reference to the latter—

“The compass errors occasioned by the more permanent part of a ship’s magnetism may be successfully compensated, and that this compensation equalises the directive power of the compass needle on the several courses on which a ship may be placed.”

It will of course be understood that this general statement, is subject to the qualification, that magnet correction in a newly-built iron ship must not be strictly depended on, that we ought not to disregard the magnitude of the original deviation, as also that when the correction is applied to compasses having large deviations and placed near large vertical masses of iron, as a rudder, there must always be great uncertainty as to the correction on a change of magnetic latitude.

About the same time that the Liverpool Compass Committee were engaged on their Third Report, I was engaged in the reduction and discussion of the deviations observed on board all the iron-built ships of the Royal Navy, numbering among them about fifteen vessels of ordinary types that had been employed on distant stations over several years.

In a report I made to the Admiralty on this discussion, the following passage will be found: “On examination of the Tables, it is at once observed that in the majority of examples therein given, a permanency of magnetism exists so little affected by changes of geographical position as materially to confirm the views entertained by the Astronomer Royal in his earliest discussion (1838), that the effect of transient induced magnetism in iron-built ships is very small comparatively.”†

These results were opposed to the then generally received opinion, that the magnetism of an iron ship arose chiefly from transient induction; this opinion being chiefly formed on the reports of the action of compasses frequently improperly placed and corrected by those unacquainted with the principles: they were nevertheless conclusive as to the security of magnet correction for a compass placed with due care, were in unison with the experiences of the Liverpool Compass Committee, and gave confidence when the changes in naval architecture necessitated its employment.

The introduction of magnet correction for the Royal Navy, you will have now gathered was not made until the necessity arose, and a thorough investigation of the causes of past failures and past successes in its application had cleared away the doubts that prevailed: and I may here venture the opinion that had magnet correction been as indiscriminately applied in the Royal Navy as it had been in the mercantile marine prior to these investigations, we should not have had those ample records of

* In my former papers I have borne testimony to the valuable Reports of the Committee; indeed, without a careful study of these Reports, no one could presume to pronounce authoritatively on the subjects therein reviewed.

† Printed in the “Philosophical Transactions of the Royal Society,” 1860, page 346.

the real magnetic history of individual ships, the discussion of which has so greatly conduced to clearing away the obscurity which hung over the subject.

Observations on the Treatment of an Iron Ship's Compasses.

In examining the numerous patent specifications relating to the mariner's compass, and which extend back to the year 1776, one is struck with the few real advantages that have been gained by the labours of inventors in this field.

The earlier patents relate chiefly to arrangements and contrivances for making observations at sea of the variation, and for modifying the motion of the ship. In 1813 the liquid compass, a real gain to the seaman, appears to have been first introduced.* In 1818 we have the first patent of an invention "to guard" or "protect" the compass needle from all action arising from iron in its neighbourhood. From about this date the patents increase in number, and of late years, notably since 1850, have somewhat rapidly multiplied.

The designs of the inventors may be thus generally classed:—

- a. Mechanical arrangements applied to compass bowl or its binnacle to prevent vibration of the end, or friction on the pivot.
- b. An arrangement of metals, or some presumed non-conducting substance, surrounding the compass, to prevent or cut off local attraction.
- c. Self acting apparatus for registering the ship's course by compass.
- d. Arrangements of auxiliary needles to detect or register the deviation.
- e. Arrangements of magnets outside the compass to isolate the needle or prevent action of neighbouring iron.
- f. Arrangements of magnets on the compass card to cause it to point at all times to the true north.
- g. Special arrangements of cards for visibility at elevated positions, and for adjustments to meet the deviation caused by the ship's iron.
- h. Methods for depolarizing or demagnetizing the iron ship's hull, in order to prevent the deviation of the compass.
- i. Methods for polarizing such parts of the iron ship as may be deemed requisite to correct or prevent the deviation of the compass.

With the exception of a limited number of the more simple arrangements necessary to the mariner's compass, scarcely one of these numerous inventions are to be seen employed at the present time. The mechanical contrivances for registering the ship's course, for example, are generally remarkable for ingenuity, but fail from this cause for every day use; they give, as a rule, work for the needle to do which detracts from its directive power and consequent accuracy, at a time when these conditions are most required.

* This description of compass has been improved in later years by many well known makers, and is a necessary part of every ship's equipment.

A number of those patents relating to the "prevention or cutting off" "the local attraction" have evidently emanated from minds unacquainted with the rudimentary principles of magnetism; the projectors especially overlooking the fundamental law, that the interposition of a body between the magnet and the needle on which it acts, can as little intercept the action of the magnet as the interposition of a body between the earth and another body would intercept the action of the gravitation of the earth, and also further overlooking a very obvious consideration, that if any body could intercept the action of the ship's iron it would also intercept the action of the earth's magnetic force on the needle.

In other cases, where intelligence has been displayed, the inventor has overlooked, or tried to evade—and believed he had done so—some simple but obvious law, the neglect of which produced failure.

Passing from patented inventions to the adaptations suggested by progress in scientific research, we find embodied in the Admiralty Standard-Compass many sound and elegant improvements over the compasses of olden times. In this instrument, which resulted from the labours of a Committee of well known names in magnetic science, working at the request of the Admiralty between the years 1837 and 1842; we find the application of pure copper of substantial thickness for the bowl, as being the metal next to silver known as the best conductor of electricity for quieting the vibrations of the magnetic needle—an application mainly due to the late Snow Harris. We further find the needles constructed of such a kind of steel, and on such a system as will afford the greatest directive power with little weight, a system the product of the researches of Kater, Christie, and Scoresby. Again, the pivots and caps—an all-important detail of the compass—are constructed of such materials and in such forms as had stood the best test in an extended series of experiments made by the late Captain E. Johnson, my predecessor in office, and a member of the Admiralty Compass committee; and, lastly, a remarkable arrangement, whether considered mechanically or magnetically, is to be found in the disposition of the needles on the compass card.

This arrangement and its bearings I will briefly describe. By the substitution of two or more parallel bars or needles of the compound structure adopted in the Admiralty Standard-Compass, instead of the single bar needle which was formerly in universal use, a much greater directive power was found to be obtained with the same weight. A problem then to be solved was the relative distances of the parallel bars on the card, in order that the "moments of inertia" about all horizontal axes should be equal, for if this condition was not secured, the oscillations of the card would be accompanied with a "wabbling" motion detrimental to good work.

The investigations of Archibald Smith resulted in this law, that two equal parallel bars of which the ends are 60° , or four bars of which the ends are 30° apart—i.e., 15° and 45° on each side of the diameter—secured the required conditions, and this arrangement was adopted, and for many years retained, on account of this property.

But a remarkable, and at the time unlooked for property attended this arrangement of the needles on a compass card. In later years, when the employment of very long needles was getting into fashion, it had been observed that compasses in merchant ships, corrected by magnets and soft iron on the plan of the Astronomer Royal, were affected by anomalous errors; in one case, for example, which came under my own observation, these errors amounted to 5° and 6° on some points of the ship's head. To test whether these errors were caused by the length of the needle and the proximity of the correctors, a series of experiments on the deviation produced on single-bar needles of different lengths by magnets and soft iron were made at the Admiralty Compass observatory. The following results were obtained:—*

With 3-inch single needles deflected by magnets the deviations were nearly semicircular,† but with 6-inch needles, and much more strongly with 12-inch needles, a "sextantal" error of considerable magnitude was introduced.

With soft iron correctors, deflecting a long single needle, in addition to the "quadrantal" deviation, a considerable "octantal" error was introduced.

When the same experiments were made with an Admiralty card, constructed as usual with four parallel needles, the extremities of which are 15° and 45° on each side of the extremities of the diameter to which they are parallel, there was no appreciable sextantal or octantal deviation. On Mr. Smith further investigating this subject on a mathematical basis, it appeared that this arrangement of needles, as well as the simpler arrangement of two needles each 30° on each side of the diameter, produces a complete compensation and correction of these errors.

We see here the remarkable property adverted to, that the arrangement of needles which produces the equality in the moments of inertia, is by a happy coincidence, the same as that which prevents the sextantal deviation in the case of correcting magnets, and the octantal deviation in the case of soft iron correctors.

The practical result is this, that by the employment of Admiralty standard compass cards, or of cards with two needles, each 30° from the central line, correcting magnets and soft iron correctors may be placed much nearer the compass than can be safely done with a single needle card, and that the large deviations existing in iron ships may be thus far more accurately corrected.‡

Before passing from the subject of compass-needles, I would wish to offer an opinion on the employment of those large compasses fitted

* See Fig. 6, where the several curves are shown on Napier's diagram.

† *i.e.*, followed a curve of sines.

‡ To those who may be interested in this branch of the subject, I would refer to the "Philosophical Transactions" for 1861, where will be found described the whole of the experiments, together with the mathematical investigations. I believe, as resulting from this communication to the Royal Society, that the employment of double needle cards, arranged as described, is now in nearly general use.

with needles of extraordinary length, which would appear from modern practice to be considered suitable to ships of extraordinary size. I am aware that these large compasses commend themselves from the facility afforded of steering a course to degrees, instead of the old-fashioned quarter or half-quarter points; and for a certain steadiness due in one sense to the extreme slowness of oscillation in long needles as compared with short ones. There are notwithstanding fallacies and insecurity attending their use, which appear to me borne out by the facts that have come within my own knowledge of fine and well-equipped steam-ships, navigated apparently with precision and care—the course being ostentatiously steered to degrees—and still running ashore in the finest weather in some unlooked-for manner.

Now, it is well known that small magnet bars are proportionally much more powerful than large magnet bars, and that beyond a certain limit, an increase in the length of the magnet bar is not accompanied by an increase of directive power in the same proportion; so that if the thickness of the bar be preserved, its weight and consequently, its friction when supported as a compass needle is on the pivot, increases in a greater ratio than the directive power, and a direct loss of force results.

Common experience embodying this principle, has heretofore limited compass needles for use afloat to about 6 inches (the Admiralty Compass Committee adopted about $7\frac{1}{4}$ inches as the maximum length), and we may well consider that when these lengths are doubled the increased weight of the card and appendages produce an amount of friction that far exceeds the increase of directive force derived from the added length of magnet bar; the friction further is operated on at a disadvantage from the sluggishness of movement incidental to the long needle.

As a matter of opinion, I consider that the Admiralty Standard Card is as large as should be used for the purposes of navigation, as distinguished from a steering or auxiliary compass; and that as regards safety, in the long, steady, and fast ship of modern days, the choice is really between the Admiralty card and a smaller one.

Briefly to review the question of the mariners' compass. For employment in an iron ship, the chief points to be aimed at are, great directive power and susceptibility of motion; directive power in a high degree to meet the prejudicial effect caused by the earth's horizontal magnetic force acting on the soft iron of the ship, and thus seriously diminishing the mean directive force of the needle, and susceptibility of motion to overcome any tendency of the hanging up of the needle from undue friction or wear in the pivot and cap.

A compass with these attributes is invaluable to the fast ship with little motion in smooth water—conditions, be it remembered, where errors in reckoning have often proved most serious—but such a compass would probably, from its sensibility, fail when in a heavy seaway, or when subject to the violent oscillations of some of our recent ships of war propelled at high rates of speed. I certainly know of no compass that is equally accurate and effective under these diverse conditions;

and that instrument which shall be at the same time accurate and sensitively alive in smooth water, perfect in its action when pitching or rolling to the gale of wind, capable of resisting the concussion from the firing of heavy guns, and not responding to the vibrations produced by an abnormal rate of propulsion by steam, has yet, despite the long list of patents, to be invented. I may, however, I think, venture to assert that, for a combination of all that is effective under the greatest number of conditions, no compass yet projected equals the Admiralty Standard Compass. Its patient designers, with one exception,* have passed away from us, and their labours are but little known: it fell to my lot for some years in my official capacity, to be the conservator of their admirable work when exposed to the adverse influences of rash inventors and economical arguments. I am, however, now gratified to think that lengthened experience has confirmed its merits, and that, intact as I received the Admiralty Standard Compass, so will it remain for our successors, unless, indeed, some master-mind appears to give it those attributes which eager, but, I think, unreflecting minds consider it ought to possess.

I have now passed in review the chief points connected with my subject, which appeared to me to deserve your attention; there is, however, an incident that may be considered to claim attention, from the circumstance that it created much discussion in this Institution. I allude to the "de-polarizing" or "de-magnetizing" process of the late Mr. Evan Hopkins, for rendering correcting magnets or deviation tables unnecessary, by destroying the polarity acquired while the ship is building; and which was applied to Her Majesty's ship "Northumberland." As I have already, in a paper read before the Royal Society, and published in their Transactions,† given my opinions on this proposal and the numerical data on which those adverse opinions are based, I should not, as an incident of progress in magnetic science applied to navigation, have alluded to it here; but, as the proposal has been recently revived with a vigour of announcement and assertion of practical utility scarcely surpassed by the clever but sanguine original projector, I will detain you a few moments by reading brief extracts from the paper to which allusion has been made bearing on the failure of this unsound proposal, as also the condemnatory opinions expressed thereon.

I state, as proved by observations made in ample detail, of the kind I have brought to your notice, and very thoroughly discussed numerically and graphically, "that the process"—(which, departing from the terms of the patent specifications resolved itself ultimately into rubbing the beams and iron stanchions near the compasses with powerful electro-magnets),—"is not one of general de-magnetization, but of partial counter-magnetization, and results in an irregular distribution of magnetism of very variable intensity, necessarily very

* General Sir Edward Sabine, K.C.B., late President of the Royal Society, and Chairman of the present meeting.

† For 1868, pages 487-508.

"unstable, and producing, wherever effective, a rapidly varying field of force.

"That so far from the process being in any sense of the word one of 'depolarization,' either of the whole ship or any part of it, it was, on the contrary, the 'polarization' to a high degree of intensity of a particular portion of the iron in the neighbourhood of three of the compasses." That "the iron so magnetized was iron capable of receiving only sub-permanent magnetism, and which, from its forming part of the structure of the vessel, was subject to strains and concussions from which detached magnets are wholly free. The magnetism so communicated was, therefore, necessarily unstable and transient, and, from its liability to change suddenly and unexpectedly, was a source of danger to the vessel.

"Nor would the effect produced, even if it had been much more permanent than it proved to be, be considered an advantage. In two out of the three compasses to which it was applied . . . the requisite reduction might have been effected with infinitely greater ease and certainty, as well as permanency, by the application of a single magnet to each compass."

Let us, however, in conclusion, pass from the consideration of matters unpractical and unsound to those based on secure foundations. On a review of what in this lecture I have brought under your notice—I fear in a somewhat fragmentary and imperfect manner—the question may be asked, how far has this knowledge extended, and how far has it aided the navigator? The reply, so far as I am aware, is generally satisfactory. Foreign nations interested in maritime affairs have unhesitatingly adopted the principles and the practice of the Royal Navy; their handbooks are all based on our own Admiralty Compass Manual. America, with her iron monitor fleet, having felt the necessity of establishing a Compass Committee of Inquiry some few years back, her Bureau of Navigation at Washington has collected in two volumes, in the interests of the "naval service, and, indeed, of all intelligent navigators," the various theoretical and practical investigations embodied in papers contributed by our countrymen to various learned societies from the time of Poisson's Memoir, to 1866. The preface to the first of these volumes states that "the English investigations on compass deviation, while eminently practical, have steadily advanced towards establishing a comprehensive and available theory in all that relates to this subject."

In our own mercantile marine an impetus to extended knowledge has been lately given by the Board of Trade. Masters, in order to obtain an extra certificate of competency, must pass an examination in our subject—the opportunity has been afforded me of inspecting the examination papers of a few successful candidates, and I found them stamped by a sound practical knowledge of principles and details—highly favourable to a more perfect system of "compass-adjustment" in our merchant ships of the future. The ordinary examination of masters and mates also with the present year embraces the methods of ascer-

taining and applying the deviation of the compass, the knowledge of which is equally necessary with the calculation of a day's work.

In the Royal Navy, though magnetism as a branch of nautical education has scarcely yet taken root, we have a few Officers well trained in its principles and practice as applied to navigation. This small band of experts, it is to be hoped, will be steadily kept up in the interests of the service. The fact is also assuring, and speaks well for the care and skill of our navigating Officers, that within the last twenty years, so far as I am informed, no misadventure has happened to a British ship-of-war through default of her compasses.

In the interests of navigation—and I say this with pleasure in the presence of one of our greatest masters in magnetic science, and to whom the Royal Navy and myself personally owe many debts of gratitude, I allude to our eminent Chairman—I confidently look forward at no distant date, to magnetism in its several divisions occupying a fair share of the attention of naval Officers, not only as a necessary branch of education, but as an intellectual study that carries with it an indescribable charm, and is of a high order for estimating and grasping the more secret workings of nature.
