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Determining Flinders' Bar Correction by Heeling the Ship

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ABSTRACT

The aim of this article is to provide the compass adjuster with an innovative method of determining the length of Flinders' bar while the ship's latitude remains unaltered. In this way the definitive compass adjustment may be carried out in a single procedure. This would be valid for ships navigating in limited waters. The drawback lies in the need to heel the ship during the adjustment.

1. Introduction

When the ship remains in the same position and orientation for a long time, the steel structures rich in carbon, called hard irons, are magnetised under the induction of the earth's field and, consequently, they are turned on permanent magnets. On the other hand, the structures of soft iron poor in carbon are temporarily magnetised, turning on magnets whose polarity changes depending on their orientation with respect of the earth's field. The ship's irons create thus a disturbing magnetic field that separates the needle of the compass an angle from the magnetic meridian. The resulting angle is called deviation. This angle is reduced during the procedure called compass adjustment, during which the ship has to turn on herself 360º so that the deviation can be obtained every 10º or 15º by comparing the magnetic and compass bearings (Jenkins, 1869). The soft irons are magnetized a few minutes after the earth's field starts to affect them in the same direction and, consequently, the compass course is erratic during this interval. To avoid this error, called Gaussin error, the ship's heading must stand steady around five minutes before each bearing is read by the adjuster (Grant and Klinkert, 1970). The compass adjuster uses correctors such as horizontal or vertical permanent magnets, soft iron spheres and soft iron bars to carry out the reduction of the deviation. These correctors are set in the binnacle at a proper distant from the needle to create the necessary magnetic field to reduce the ship's magnetism. This article deals with the reduction of that part of deviation due to magnetic field caused by the disturbing vertical soft irons. The effect of these irons would be the same as a hypothetical vertical soft iron bar located at the centre line of ship.

2. Coordinate reference systems, definitions and symbols

The ship's total magnetic field is broken up into its components under different Cartesian coordinate systems. Thus it may be represented in three different coordinate systems by the vectors in (1), (2) and (3); where:

- B_h is the total field in the horizontal coordinate system where the axis x, y and z coincide respectively with the magnetic North-and-South, East-and-West lines and with the Zenit-and-Nadir line;
- B_r is the total field in the up righted ship coordinate system where the axis x, y and z coincide respectively with fore-and-aft line, the projection of atwarthship line over the horizontal plane, and Zenit-and-Nadir line;
- B_s is the total field in the heeled ship coordinate system where the axis x, y and z coincide with fore-and-aft, athwartship, and topmast-and-keel lines respectively.

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The subscripts h, r and s denote the coordinate system of the vector and the matrices $T(i)$ and $T(h)$ are used for the conversion of coordinates.

$$B_h^t = \begin{bmatrix} X_h & Y_h & Z_h \end{bmatrix} \tag{1}$$

$$B_r^t = \begin{bmatrix} X_r & Y_r & Z_r \end{bmatrix} \tag{2}$$

$$B_s^t = \begin{bmatrix} X_s & Y_s & Z_s \end{bmatrix} \tag{3}$$

The total magnetic field at compass position depends on the earth's field (B_E) as well as on the hard and soft irons of which the ship is built. Hard irons behave as permanent magnets; therefore their effect is called permanent magnetism (B_P). Soft irons, on the other hand, vary their induction with every change in the direction of the material with reference to the earth's field. This means that the direction of the induction will vary with every alteration in the direction of the ship's head. This requires that the ship, as a whole, be considered an anisotropic material. Consequently, the magnetism caused by soft irons, called induced magnetism (B_I), is measured by the coefficients of the magnetic susceptibility tensor and by the earth's field.

The vector B_{Eh} in (4) is the earth's field in the horizontal coordinate system, H and Z being the horizontal and vertical components respectively. The vector B_{Ps} in (5) is the permanent magnetism and the vector B_{Is} in (7) the induced magnetism, both of them in the heeled ship's coordinate system. Therefore, the subscripts E, P and I refer, respectively, to the earth's field, permanent magnetism and induced magnetism. The matrix χ in (6) refers to the susceptibility tensor of the induced magnetism.

$$B_{Eh}^t = \begin{bmatrix} H & 0 & Z \end{bmatrix} \tag{4}$$

$$B_{Ps}^t = \begin{bmatrix} P & Q & R \end{bmatrix} \tag{5}$$

$$\chi = \begin{pmatrix} \chi_{x,x} & \chi_{x,y} & \chi_{x,z} \\ \chi_{y,x} & \chi_{y,y} & \chi_{y,z} \\ \chi_{z,x} & \chi_{z,y} & \chi_{z,z} \end{pmatrix} \tag{6}$$

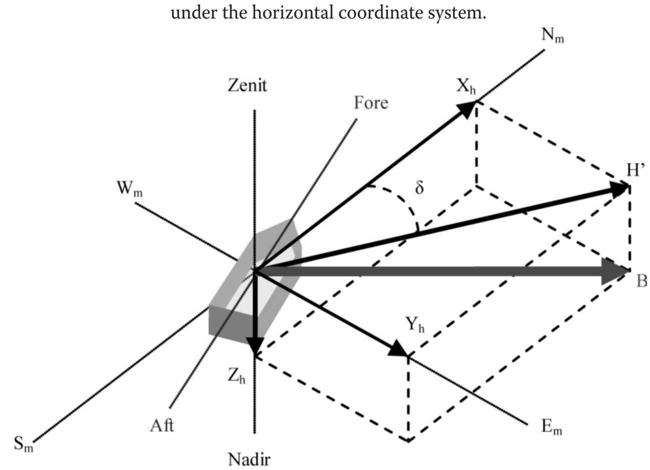
$$B_{Is} = \chi \cdot B_{Es} = \chi \cdot T^t(i) \cdot T^t(h) \cdot B_{Eh} \tag{7}$$

3. Deviation formulae when the ship is up right or heeled

In figure 1 the total magnetic field at compass position (B_h) is split in the three components under the horizontal coordinate system. The component X_h is the directive force to guide the needle towards the magnetic North. The component Y_h is the disturbing force pushing the needle away from the magnetic meridian. The resulting vector of these components (H') is the horizontal magnetic field. The deviation (δ) is the angle included between H' and X_h, the value of which is arctangent of the result of Y_h divided by X_h, as in (8). Hence, the conversion to the horizontal coordinate system is needed in order to calculate the deviation.

$$\tan \delta = Y_h / X_h \tag{8}$$

Fig. 1. Components of the total magnetic field at compass position under the horizontal coordinate system.



Source: Authors

The equation in (9) indicates the total magnetic field at compass position when the ship is heeled. It's refers to three coordinate reference systems. The matrix $T(i)$ converts the components of a vector from the heeled to up the righted ship's coordinate system. $T(\zeta)$ converts the components of a vector from the up righted ship to the horizontal coordinates. The respective transverse matrices will convert the components in the opposite direction. The equation in (10) indicates the total magnetic field at compass position when the ship is up right. In this case the matrices $T(i)$ and $T^t(i)$ are equal to the unity, since the heel is equal to zero ($i=0$).

$$B_{h_i} = B_{Eh} + B_{Ph_i} + B_{Ih_i} = B_{Eh} + T(\zeta)\cdot T(i)\cdot B_{Ps} + T(\zeta)\cdot T(i)\cdot \chi \cdot T^t(i)\cdot T^t(\zeta)\cdot B_{Eh} \tag{9}$$

$$B_h = B_{Eh} + B_{Ph} + B_{Ih} = B_{Eh} + T(\zeta)\cdot B_{Ps} + T(\zeta)\cdot \chi \cdot T^t(\zeta)\cdot B_{Eh} \tag{10}$$

In both cases, either up right or heeled, the ship may be considered symmetrical with reference to the centre line and thus the coefficients $\chi_{x,y}$, $\chi_{y,x}$, $\chi_{y,z}$ and $\chi_{z,y}$, representing the susceptibility of asymmetric soft irons, may be considered negligible. Given that the heel i is always a small angle, the value of its sine may be considered as the angle i in radians, its cosine as negligible, its square sine as negligible and its square cosine as the unity. The deviation for either an up righted ship or a heeled ship may be expressed respectively as in equations (11) and (12).

$$\tan\delta = \frac{Y_h}{X_h} = \frac{B\cdot\sin\zeta + C\cdot\cos\zeta + D\cdot\sin 2\zeta}{1 + B\cdot\cos\zeta - C\cdot\sin\zeta + D\cdot\cos 2\zeta + F} \quad (11)$$

$$\tan\delta_i = \frac{A_i + B\cdot\sin\zeta + C_i\cdot\cos\zeta + D\cdot\sin 2\zeta + E_i\cdot\cos 2\zeta}{1 + B\cdot\cos\zeta - C_i\cdot\sin\zeta + D\cdot\cos 2\zeta + E_i\cdot\sin 2\zeta + F} \quad (12)$$

In order to reduce the terms of both equations, similar mathematical expressions have been put into coefficients A_i, B, C, C_i, D, E_i and F, the value of which appears in table 1.

Table 1. Coefficients for equation of deviation

$$A_i = \frac{\chi_{x,z} - \chi_{z,x}}{2}\cdot i \quad B = \frac{(P + \chi_{x,z}\cdot Z)}{H} \quad C = \frac{(Q + \chi_{y,z}\cdot Z)}{H} \quad D = \frac{\chi_{x,x} - \chi_{y,y}}{2}$$

$$E_i = \frac{\chi_{x,z} + \chi_{z,x}}{2}\cdot i \quad F = \frac{\chi_{x,x} + \chi_{y,y}}{2} \quad C_i = \frac{[Q - R\cdot i + (e-k)\cdot Z\cdot i]}{H}$$

Source: Authors

If we use different trigonometric identities and we put different terms into groups, the equations in (13) and (14) may be replaced by those in (11) and (12).

$$\sin\delta = B\cdot\sin(\zeta-\delta) + C\cdot\cos(\zeta-\delta) + D\cdot\sin(2\zeta-\delta) - F\cdot\sin\delta \quad (13)$$

$$\sin\delta_i = A_i\cdot\cos\delta_i + B\cdot\sin(\zeta-\delta_i) + C_i\cdot\cos(\zeta-\delta_i) + D\cdot\sin(2\zeta-\delta_i) - E_i\cdot\cos(2\zeta-\delta_i) - F\cdot\sin\delta_i \quad (14)$$

4. Determination of coefficient $\chi_{x,z}$ by heeling the ship

The Flinders' bar is a vertical case installed around the binnacle, where various soft iron fragments are set to reduce the coefficients $\chi_{x,z}$ and $\chi_{y,z}$. Depending on the amount and dimension of the fragments placed in the case, the length of the Flinders' bar may be altered. The traditional method to obtain the coefficients $\chi_{x,z}$ and $\chi_{y,z}$ from a ship is to navigate between two latitudes where the earth's field components are different enough, so as to obtain two different B and C coefficients in each position (Defense Mapping Agency and Hydrographic/Topographic Center, 2004). Thus, their components and coefficients belonging respectively to permanent and induced magnetism may be separated, which gives us the possibility to calculate their values by means of a system of two equations and two unknowns. Nevertheless, the coefficient $\chi_{y,z}$ refers to asymmetrical soft irons and, bearing in mind that they are not usually found on board, the Flinders' bar is permanently installed in the centre line without slewing it. On the other hand, the coefficient $\chi_{x,z}$ refers mainly to soft irons placed below and after the compass, which means that the Flinders bar case is fixed forward and below the binnacle so that both effects cancel each other out (Denne, 1979).

The main drawback of this method lies in the impossibility of obtaining the length of Flinders bar at single latitude. Therefore, it is not possible to know this length on ships navigating in limited waters as, for example, some tugs, dredgers, fishing vessels etcetera. The aim of this article is to provide compass adjusters with a method to obtain the coefficient $\chi_{x,z}$ without changes of latitude. In this sense, the adjuster can take advantage of the heeling trials carried out in some type of vessels, since the ship may be heeled up to 15 degrees (Rawson and Tupper, 2001).

The starting point to find out the value of $\chi_{x,z}$ is the replacement of the deviation in the equations in (13) and (14) by the difference between the magnetic and compass course ($\delta = \zeta - \zeta'$). Next the ship is steered to the East compass course, either up right or heeled, and thus various trigonometric identities may be taken to determine the equations in (15) and (16), assuming that $\zeta' = 90°$. The formula in (17) is obtained from the subtraction of both equations, taking the coefficient $\chi_{x,z}$ as common factor and considering the coefficient $\chi_{x,x}$ negligible, on the assumption that the spheres have just been installed properly after a previous compass adjustment.

$$-\cos\zeta = B + D\cdot\cos\zeta + F\cdot\cos\zeta = B + \chi_{x,x}\cdot\cos\zeta \quad (15)$$

$$-\cos\zeta_i = A_i\cdot\sin\zeta_i + B + D\cdot\cos\zeta_i + E_i\cdot\sin\zeta_i + F\cdot\cos\zeta_i = \chi_{x,z}\cdot i\cdot\sin\zeta_i + B + \chi_{x,x}\cdot\cos\zeta_i \quad (16)$$

$$\chi_{x,z} = (\cos\zeta - \cos\zeta_i)/i\cdot\sin\zeta_i \quad (17)$$

5. Experience with the deviascope

The deviascope will be used to confirm the theoretical calculations cited above since it seems more realistic than other VRML simulators to carry out the required test (Wu et al., 2010). This device simulates the magnetic forces to which a compass is subjected on board a steel ship and shows how to cancel them out. Basically, it is made up of a magnetic compass mounted on the centre line of a revolving plank representing the ship deck (henceforth 'deck') which can also be heeled. At both ends of the centre line the fore and aft part of the deck can be distinguished. There are likewise various apertures on the deck for the insertion of permanent magnets and soft irons (Brown, 1961). The desviascope is, therefore, a proper device to carry out a practical experiment to prove that the formula in (17) is correct.

First of all, it is necessary to find a demagnetized place to carry out the experiment with the deviascope, since the needle should not be disturbed by any external magnetic field in the surrounding area. In order to find such a place, the desviascope has to be up righted and released from all of its magnets and soft irons. Then it has to be moved to different locations until the deviation at the four cardinal courses is nil. The marks pointing out the true cardinal points may be obtained by means of nautical charts or maps on the internet (in this case the on-line Iberpix Visor was used) and have to be far enough from the desviascope as to allow us to move it slightly without affecting the bearings. Then, if the needle is oriented to the cardinal points (*ζ'*), the relative bearings (*RBRG*) to the true marks obtained by the pelorus should be equal to the magnetic declination (*DEC*). If they are not, it means that the place is magnetized and the experiment cannot be carried out there. The value of the magnetic declination, along with *H* and *Z*, may be collected from the IGRF (International Geomagnetic Reference Field) model using the on-line GEOMAG calculator (National Geophysical Data Center, 2011). Table 2 shows the value of these parameters for the date, altitude (*h*) and position in which the experiment was carried out.

Table 2. IGRF geomagnetic parameters at Bilbao on 18th April 2012.

Date	Latitude	Longitude	h	H	Z	D
18.4.1 2	*43-19.6 N*	*003-01.4 W*	10	*23,884.1*	*39,135.2*	*1.5º(-)*

Source: Authors

Once the demagnetized place is located, a vertical soft iron rod is set in the hole which is located at the aft part of the centre line of the deck, the top rod being at the same plane as the card. In this way, the compass course is altered only by a symmetrical soft iron representing the coefficient $\chi_{x,z}$ and thus the experiment can be carried out.

$$\delta = RBRG - DEC \qquad \zeta = \zeta' + \delta \tag{18}$$

The following step consists in revolving the deck until the East compass course (*ζ'=090º*) is reached; as can be seen in Figure 2. After that, the deviation is obtained by the application of the formulae in (18), obtaining thereafter the deviation and the magnetic course for zero, five, ten and fifteen degrees of deck inclination. This allows us to calculate the coefficient $\chi_{x,z}$ for the deck, either up righted or heeled, by the application of the formulae in (19) and (17). The formula in (19) is used for the up righted ship and emerges from the equation in (13), considering that all coefficients and components are negligible except $\chi_{x,z}$. On the other hand, the disturbing magnetic field created by the vertical rod (B_r) may also be calculated by the formula in (20), according to Figure 2.

Additionally, should the up righted deck with the vertical rod be again revolved at the four cardinal compass courses, the vector of the horizontal magnetic field affecting the rose at every course (*H'*) can be obtained by the application of the formula in (21), the module being as in (22).

$$\chi_{x,z} = H/Z \cdot \sin\delta \tag{19}$$

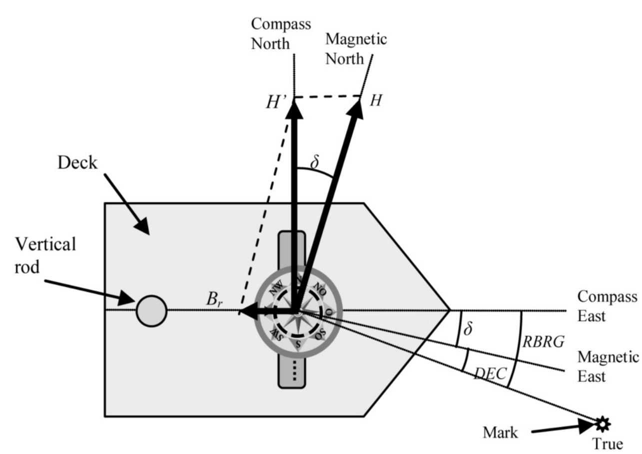
$$B_r = H \cdot \sin\delta \tag{20}$$

$$\overrightarrow{H'} = \overrightarrow{H} + \overrightarrow{B_r} \tag{21}$$

$$H' = H \cdot \cos\delta - B_r \cdot \cos\zeta' \tag{22}$$

The experimental results obtained from the desviascope are given in Table 3 and have been rounded off to the tenth for higher precision. To do this, it is preferable to obtain the data by means of a fluxgate, provided that this electrical device does not disturb the total magnetic field at compass position. On the other hand, the values of *Br* and *H'* are shown in table 4, together with the coefficient $\chi_{x,z}$ for different inclinations.

Fig. 2. Desviascope at North hemisphere with the vertical rod inserted through the deck.



Source: Authors

Table 3. Results obtained from the desviascope during the experiment.

Up right deck				Heeled deck		
i=0º	*i=0º*	*i=0º*	*i=0º*	*i=5º*	*i=10º*	*i=15º*
ζ'=000	*ζ'=090*	*ζ'=180*	*ζ'=270*	*ζ'=090*	*ζ'=090*	*ζ'=090*
ζ=000	*ζ=080.5*	*ζ=180*	*ζ=279.5*	*ζ=080*	*ζ=079.5*	*ζ=079*
δ=0	*δ=−9.5*	*δ=0*	*δ=+9.5*	*δ=−10*	*δ=−10.5*	*δ=−11*

Source: Authors

Table 4. Calculation of $\chi_{x,z}$ and the total and disturbing magnetic fields (h' and br) in the experiment.

	Up righted deck				Heeled deck		
i	*0º*	*0º*	*0º*	*0º*	*5º*	*10º*	*15º*
ζ'	*000*	*090*	*180*	*270*	*090*	*090*	*090*
ζ	*000*	*080.5*	*180*	*279.5*	*080*	*079.5*	*079*
B_r	*	*3,942*	*	*	*	*	*
H'	*19,942*	*23,557*	*27,826*	*23,557*	*	*	*
$\chi_{x,z}$ **(-)**	*	*0.100038*	*	*	*0.100076*	*0.100157*	*0.100243*

Source: Authors

Taking into account the asymmetrical irons are negligible and the coefficient $\chi_{x,z}$ has been already calculated, the length of the Flinders' bar is obtained as follows:

1. There must not be fore-and-aft B magnets set in the binnacle.
2. The spheres must be installed properly in the binnacle to reduce $\chi_{x,x}$ and $\chi_{x,z}$.
3. The compass heading must be 090º at the time the ship is heeled.
4. The part of the deviation caused by the symmetrical soft irons ($d\delta$) is equivalent to the deviation in (22). In other words, this part of deviation may be obtained by the formula in (23).

$$\sin d\delta = Z/H \cdot \chi_{x,z} \tag{23}$$

5. The following step consists in adjusting the length of the Flinders' bar until the course is altered $d\delta$ degrees.

Once the Flinders' bar is adjusted, the adjustment proceeding should be carried out installing the other correctors in the following order: spheres, heeling magnet and horizontal magnets.

6. Conclusions

The method hereby explained shows the adjusters to know the amount of the Flinders' bar set in the binnacle without having to navigate to a distant position. It is thus suitable for small vessel and crafts the use of which is reduced to limited waters. The problem lies in the heel that the vessel is capable to reach so that the resulting mass of vertical soft iron representing $\chi_{x,z}$ can be calculated accordingly. In addition to the possible difficulties found by the Master to heel deliberately the ship by reason of stability conditions, it should be noted that the measurement of the heel has to be precise enough so as not to affect the final results. For instance, an error of one degree for a heel of 15º would result in a variation of 0.15 thousandths in $\chi_{x,z}$. In the same sense, it is very important the courses at the East are obtained with great precision, whether the vessel either up righted or heeled. In the experiment a precision of one tenth is taken in obtaining the courses. Bearing this course precision in mind, the differences of $\chi_{x,z}$ with respect to the inclinations of the deck are around only 0.2 thousandths and, on the other hand, the error in $d\delta$ would be a little less than 0.2º at the time of adjusting the Flinders' bar on board a real ship. Therefore, it would be advisable to use a fluxgate sensor and a precise inclinometer to carry out the adjustment by this method.

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