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Analysis and Calculation of The Magnetic Moment of a Magnet Compensation for Type "A" Magnetic Needle

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ABSTRACT

Our aim is to renew the compensation system, which is been used until now, and was depending of the compensation magnets got from the market. These magnets have a relative power noted by the manufacturer and we have to calculate how many correctors we go to use as well as where to place them according to the deviations we obtain from balanced ship. With this paper, we show a new system to calculate the place of the compensation magnets but in reference to the magnetic moment of four compensation magnets, which will be placed in a plate and then turned appropriately in order to generate a complex magnetic field, which is been used to compensate the deviations of the magnetic compass.

Having this idea in mind, by different experiments and measurements, we have calculated the magnetic moment of one compensation magnet, and thereinafter inserted in a complex formula to calculate the combined magnetic field generated by four magnets.

1. Introduction

The compensation of the magnetic needles or magnetic compasses has been always carried out in the same manner. First the ship is balanced to the different courses starting from the North, and taking the true course and magnetic course at different specified steered courses. With those different types of courses are calculated the different deviations of the magnetic compass and the deviation table is constructed.

In the compensation process, after calculated the deviations, these are used to try to compensate, not to eliminate, to the maximum possible the errors that appear in the deviation chart, for which certain types of compensating magnets are used and at specific positions of them in the binnacle.

We intend to modify, in principle, the compensation system that has been used, implementing another system based on the magnetic moments of the compensating magnets instead of the relative power of them used today. This then, explains the method for calculating of that magnetic moment which will be used to calculate the magnetic field generated by four compensation magnets and the combination of them into a corrector plate.

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2. Methodology

Until the present moment, all we have had clear that compensation had to be made with hard and soft magnets. The hard magnets are those that show a great retentivity, and that compensation magnets were from a defined size of 25 cm in length, which could be of two different diameters, the largest of 1 cm and 0.5 cm smallest. They could be used invariably in the compensation of both longitudinal and athwart deviations. The produced effect: one transverse compensation magnet 1 cm in diameter compensates a number of degrees equal to a half of the number of the cell where it will be placed, i.e., half of degrees of the cell number where is located the corrector magnet. A athwart magnet of 0.5 cm diameter compensates for a number of degrees equal to one eighth of the number of the cell wherein the corrector is located. Moreover, following the same rule, the longitudinal magnets 1 cm in diameter or also called large, corrected an equal number of degrees that the cell number where it is located, while small or 0.5 cm diameter do in a quarter of the number of the cell where it is located. Longitudinal magnets being two, they correct more degrees than the athwart one which is only one (García de Paredes y Castro, n.d.).

The cells are numbered from bottom to top with the numbers 6, 7, 8, 9, 10, 11, 12, 13, 14, 16, 18, 20. The compensating magnets which will keep closer to the magnetic needle, at No.

20, will never be less than twice the length of the magnet that is used to compensate the deviations (Gea Vazquez, 2003).

This was the system that has been long used to empirically compensate somehow the deviation errors of the magnetic needle, caused by various factors.

Another way to perform the calculation of compensation is usually to calculate a relative power P_r of the magnet that we will use in that compensation, that will give us in terms of absolute power where:

$$P_r = \frac{P_a}{H} \tag{1}$$

Being P_a the absolute power of the compensation magnet and H the horizontal component in the place where we will make compensation. As well, it can be calculated by placing a magnet in a particular numbered cell, for example at 18. The compensation magnet generates a needle deviation of a certain number of degrees. Placed like that we take the bearing of a distant point with respect to a new Ra (compass course) which will give us a D_a (compass bearing) of that point. Once defined the 1st bearing, we change, in the same cell, the polarity of the same magnet, which will produce a new compass course R'_a with which we will take a new compass bearing D'_a of the same previous point. The deviation produced by the magnet in that cell will be:

$$\Delta^{\text{o}}_{18} = \frac{D_a - D'_a}{2} \tag{2}$$

Having this in mind usually we proceed in calculating the cell in which we will place the compensating magnets being *n* the location cell where:

$$n = \frac{\Delta_n}{P_r} = \frac{\Delta_n . H}{P_a} \tag{3}$$

From where:

$$P_r = \frac{\Delta^{\text{o}}_{18}}{18} \tag{4}$$

With this, it is enough to provide the place where we should locate the compensating magnet or magnets of a particular power to correct a determined deviation (Gaztelu-Iturri Leicea, 1998).

From the above, we are trying to vary the empirical calculation of the compensation used until now, and define it as a calculation, theoretical in the beginning, which defines us the most accurate place and as effective as possible for compensation.

We all know that our compensation never came to a complete correction of the errors of the magnetic needle, but the needle will be only compensated to minimize the deviation it has, so when we talk about adjusting a magnetic needle we never can say that we have corrected it but simply that we have compensated it.

3. Development

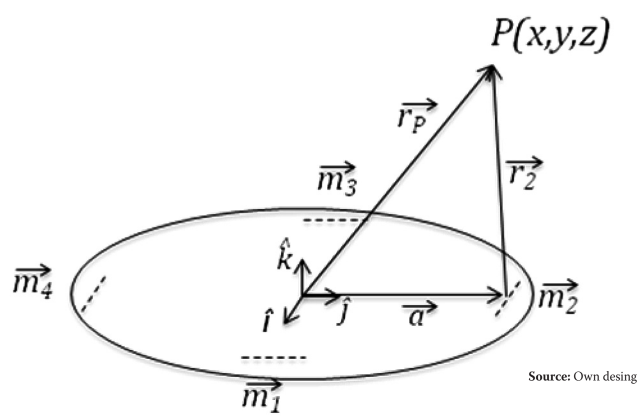
Therefore we have decided that perhaps we could define a more accurate system, and more in keeping with the times we live in, to determine the distance at which place the different compensation magnets. To do this we need to try to find a mathematical relationship that defines us that distance to magnetic compass and depending on what we will determine that.

After several readings of different bibliographies we have believed acceptable to use the formula which is written in the following paragraph (Reitz et al., 1996), which is defining that the magnetic field at a distant circuit depends only on the magnetic moment. This is clearly seen in the same book comparing the formula that will be used with other defined as (2-36) which is of the same form as (8-74) we use, where we can see that is of the same form as the electric field generated by an electric dipole, so named after magnetic dipole field.

$$\vec{B} = \frac{\mu_0}{4\pi}\left[\frac{\vec{m}}{r^3} + \frac{3(\vec{m}.\vec{r})\vec{r}}{r^5}\right] \tag{5}$$

To do this we look at what data we know $\frac{\mu_0}{4\pi}$ that have a value of 10^{-7} and other unknown data that are the magnetic moment *m* which is the magnetic dipole moment and radius *r* as the effective distance of the generated field. The new system that we go to study consists of 4 dipoles of the same size that will be used for compensation. So first we need to calculate the magnetic moment *m* of each of the magnets that we will use in the new prototype.

Figure 1 Schematic magnetic field calculation



Source: Own desing

We will use a cylindrical magnets which are made of Al-NiCo alloy with specific dimensions of 40 mm length and 4 mm in diameter.

Now, instead of using the power to define the cell and thus compensate for the deviations of the needle, we will try to determine corrections depending on the magnetic moment of the compensation magnets and thus define at what distances these magnets can compensate the different deviations, and adjust the magnets to the compendium of compensation.

We define the magnetic moment of a single compensation magnet and determine the effect at different distances between compensation magnet, or dipole field, and the magnetic needle latter referred as another dipole. The determination of the straight magnetic moment can be performed in two ways: using a static method or by using the dynamic method.

The first method for determining the magnetic moment *m*, is based on the representation of the experimental values of the magnetic field created by the compensation magnet.

We perform different measurements of the basic magnet that we will use in the experience and we make it with a Hall sensor (Hall probe) by first performing transverse readings of the magnet in relation to its longitudinal position against the Hall probe.

We conducted a first approaching reading and give us the results expressed in the following table:

Table 1: 1st Test with 1 magnet. Longitudinal measurement.

d (cm)	B (μT)	
5	450	
7,5	135	
10	85	
12.5	95	
15	110	
17,5	130	

Source: Own source

We generate with this data and using a simple computer spreadsheet program, a graphic representation from which we deduce that in nearby and moderately distant magnet distances a distort is generated in the linearity of the readings that in principle is defined by excessive proximity, near magnet, and towards the end by excessive remoteness of it. Therefore, being able to be affected by an induced magnetism of metallic elements in the vicinity of the measurement.

We continue with a second measurement for better delineation and in an area were data shown more linear, as can be between 3 and 12 cm away.

Table 2: 2nd Test with 1 magnet. Longitudinal measurement.

	1ª lectura	2ª lectura	3ª lectura	
d (cm)	B (μT)	B (μT)	B (μT)	
3	3400	3350	3270	
4	1100	1100	1010	
5	450	450	430	
6	260	260	250	
7	170	175	163	
8	118	130	112	
9	95	100	87	
10	83	84	75	
11	80	81	70	
12	85	91	75	

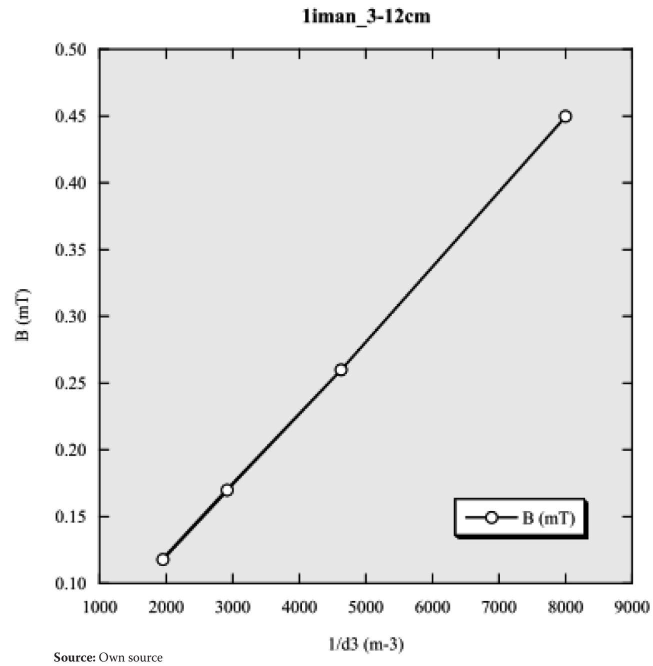
Source: Own source

From this second battery of measurements passed to the software to see its linearity and define the limits of the measurement were we found a higher linearity of the function.

Recorded the results, we see that has a higher linearity in a stretch between 5 and 10 cm of the measuring magnet, recording a more regular linearity than the values represented in other distances, closer and more distant, and be influenced by important factors of the linearity distortion.

All the readings are in nanotesla unit.

Figure 2: Graphic equivalent to Table 2.



Source: Own source

With the greater reliability section, defined between 5 and 10 cm, we proceed to make a new measurement every 1/2 cm and see the variation of the linearity in the sector defined as stable and linear.

Table 3: 3rd Test with 1 magnet. Longitudinal measurement.

	1ª lectura	2ª lectura	3ª lectura	4ª lectura	5ª lectura	
d (cm)	B (μT)	B (μT)	B (μT)	B (μT)	B (μT)	
5	457	450	450	452	450	
5,5	340	335	335	335	331	
6	282	280	260	252	264	
6,5	230	225	208	196	203	
7	180	190	165	170	173	
7,5	145	140	143	139	142	
8	120	120	127	120	123	
8,5	110	105	110	106	107	
9	98	95	101	96	98	
9,5	84	87	90	89	92	
10	—	83	83	84	85	

Source: Own source

From processed data transformed in graphical representation, the linearity in all of them is rather continuous, which shows that a general slope remains the same and of a value of 5.4×10^{-5} $mT.m^{-3}$, where the moment $m = 0.27\ Am^2$.

To verify that all this complimented may be correct, we decided to perform the same measurements at the previous distances but with 2 compensation magnet units to see if both, the linearity and the generation of the slope are common slope.

We conducted a test mode the next measurement with 2 magnets in the same values range previously determined ranging from 5 to 11 cm each half cm.

Table 4: 4th Test with 2 magnets. Longitudinal measurement.

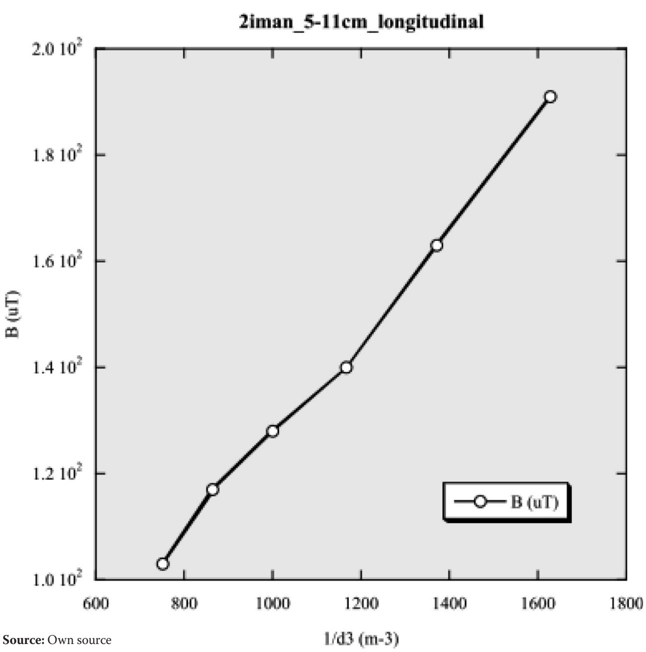
	1ª lectura	
d (cm)	B (μT)	
5	1195	
5,5	830	
6	631	
6,5	475	
7	374	
7,5	284	
8	230	
8,5	191	
9	163	
9,5	140	
10	128	
10,5	117	
11	103	

Source: Own source

Having 2 compensating magnets, for measuring the field strength or what is the same the density of magnetic field, this is bigger, due to this we will take some additional measurement from further point defined in previous tests, i.e. from the maximum at 10 cm we go a little further and perform measurements up to 11 cm.

The first discrepancy we observe is that with a double magnet at the same distance, the reading doesn't indicate the double value of the measurement of a single magnet, a fact that leads us to doubt about the results. We can think that may be a displacement or off-set because the result is not linear in terms of measurement.

Figure 3: Graphic equivalent to Table 4.



Source: Own source

We proceed to the realization of the resulting graph with the data obtained and clearly see that movement is not an offset measurement but the measurements generate a different slope from the first comparison that has been done before with a compensation magnet. This recorded a value with a slope of 9.3 x10^{-5}mT.m^{-3} that indicates that it is more than double of the previous reading we have used as comparison, with what we believe the readings are affected by somehow environment in which we performed this measurements, by the effect of apparatus or by metal structures located in such an environment.

Anyway, to see if we are making measurement errors, we determined to make a new measurement with two compensating magnets but transversely, in which we assume that the measurement should be about half the value obtained in the previous measurement referred to as 4th measurement with two magnets.

In addition we define a distance reading between 4 and 10 cm every 1/2 cm.

Table 5: 5th Test with 2 magnets. Transverse measuring.

	1ª lectura	2ª lectura	3ª lectura	
d (cm)	B (μT)	B (μT)	B (μT)	
4	617	654	630	
4,5	493	507	505	
5	387	389	410	
5,5	347	324	346	
6	300	280	298	
6,5	271	260	260	
7	243	234	230	
7,5	223	223	215	
8	218	202	200	
8,5	205	197	193	
9	198	185	193	
9,5	190	183	193	
10	187	190	180	

Source: Own source

We clearly see the results of the readings at the same distance, which should be about half value, no such relationship holds and makes us think without fear we are making measurement in a place with too much external magnetic influence, structures such as metallic tables, condition of electrical and electronic components near the measurement site etc. They are directly affecting the measurement readings.

We decided to carry out further tests in an environment where the external influence is zero talking about to the condition of the measurements. After several tests we decided that the triaxis utilization is expendable, so we proceed to make a measurement of one of the compensation magnets. For that, one of them is placed in the center of a goniometer (Figure 1), which is made of non-magnetic materials, by means of which the compensation magnet can rotate accurately on its center.

The goniometer has an angular resolution of 1 °, from 0 ° to 360 °. The field produced by the compensation magnet will be measured with a fluxgate magnetometer. The center of the goniometer, where the center of the magnet is placed, and the point of measurement have been placed from the point of measurement of the fluxgate at *r* distance. We have defined three distances *r* at what perform such measurements. These will be at distances of 164mm, 244mm and 325mm from the cen-

Figure 4: Fixing magnet on goniómeter.

Source: Own source

Figure 5: Positioning of the magnet relative to the fluxgate.

Source: Own source

ter of the compensation magnet or of the goniometer to the edge of fluxgate reader.

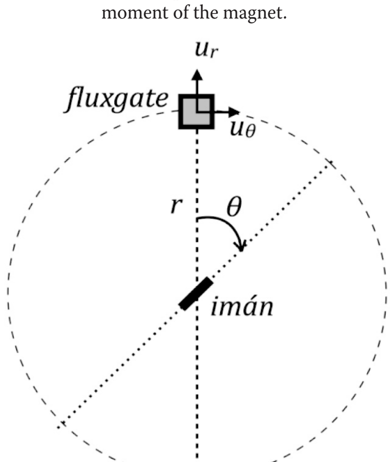
Initially we had planned; as we have indicated above, generate a cancellation of the ambient magnetic field surrounding, mainly terrestrial, but also any other that may be present in the test lab, using a triaxis Helmholtz coil system. Finally, and after considerable thought, it was decided that it would not be necessary, because we can consider the environment magnetic field as a constant and the information that matters most, and where the magnetic moment derived from, the various measures taken to make turn is obtained the magnet with the goniometer. Therefore, as shown in Figure 5, the Helmholtz coil system is not used more than for the fluxgate sensor placed in its center for measurement.

Moreover, we have that the components of the magnetic field B created by a moment m in a point (r, θ), in polar coordinates are:

$$B_r = \frac{\mu_0}{4\pi}\frac{m}{r^3} 2\cos\theta \tag{6}$$

$$B_\theta = \frac{\mu_0}{4\pi}\frac{m}{r^3} \sin\theta \tag{7}$$

Figure 6: Calculation of the polar coordinates of the magnetic moment of the magnet.

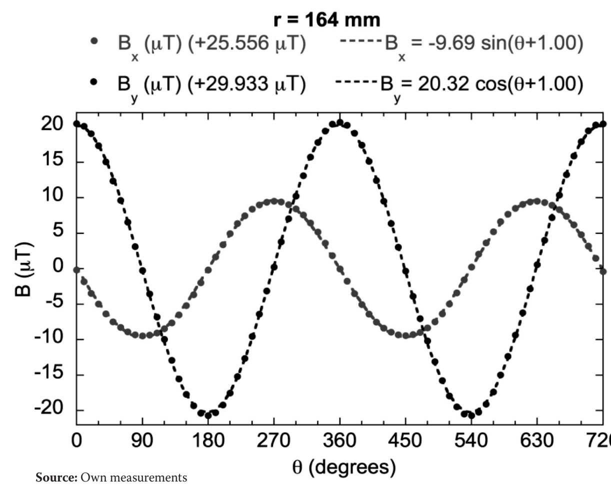


Source: Own design

In the approach of the experiment in the preceding figure (Figure 6) we can see the two components B, which are measured by the fluxgate in its x and y axes, for each angle of rotation of the magnet on the goniometer (considering their signs). A specific computer program was generated to collect data generated by the fluxgate.

We collect all the results obtained by placing the magnet at a distance of 164mm and translated with the program it will generate a diagram shown in Fig. 7.

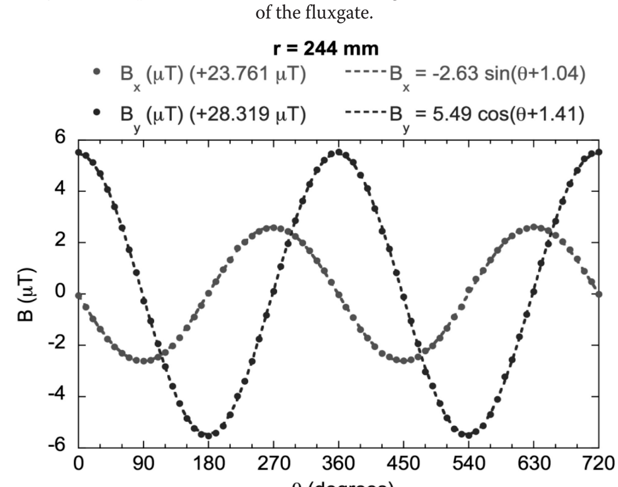
Figure 7: Graphic of measurements of the magnetic moment at 164mm from the fluxgate.



Source: Own measurements

Constant contribution is subtracted in both components. On one hand are represented the values from measurements at different angles of positioning the magnet with a certain symbol, represented by point. Moreover, the adjustment is made that

Figure 8: Graphic of measurements of the magnetic moment at 244 mm of the fluxgate.



Source: Own measurements

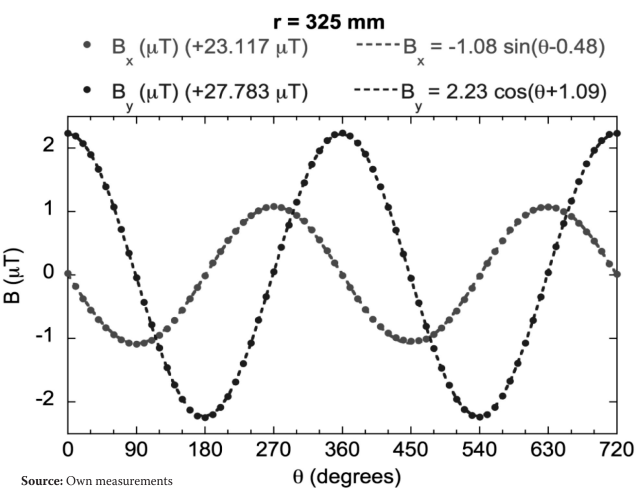
function generates a more homogeneous and lineal, for both sin and cos functions, shown in dashed lines. It is seen that the amplitudes of the field components are not exactly the double one of the other, as they should be according to the equations we handle (6) and (7). Calculating m with both expressions, and then calculating its mean value we obtain that $m = 0.44Am^2$.

In the second measurement made at a greater distance, 244mm, we perform the corresponding readings, ensuring that the new situation improve over the previous one.

Making the necessary adjustments as in the previous graph and symbolizing the results in the same way, and calculating the mean value obtained for m we can see that the solution is $m = 0.39Am^2$.

We conducted a third measurement for a refinement of the results, with which distance of 325mm from a meter of fluxgate we get the following chart:

Figure 9: Graphic of measurements of the magnetic moment at 325mm of the fluxgate.



Source: Own measurements

Performing as in previous measurements, adjusted, and finally calculated the mean value, gives us the result that the value of $m = 0.38\ Am^2$.

With this final value we complete the measurement of the magnetic moment of the standard magnet that we will use to perform the compensation of magnetic needle that we will use for the prototype binnacle. We could further refine the distance, and therefore the moment of the magnet, but the variation from this point would be so small that we would enter the thousandths, which does little to adjust compensation.

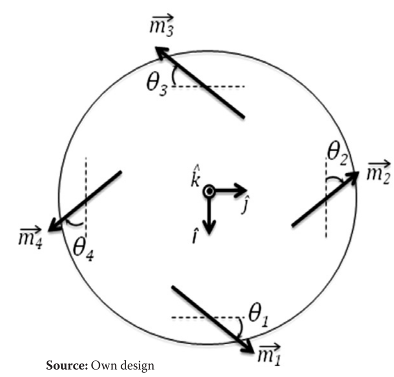
From this value we will calculate in the general formula of composition of the magnetic field generated by the combination of positions of four corrector magnets in a compensator plate.

$$\vec{B} = \vec{B_1} + \vec{B_2} + \vec{B_3} + \vec{B_4} \tag{8}$$

By having the single spin dipoles in the horizontal plane, we define the angles of the dipole relative to its initial rest position or all of them.

Finally if we calculate $\vec{B}$ Total magnetic field, according to the formula (8) we have the final equation of the total field generated by 4 dipoles:

Figure 10: Schematic of the initial position of the magnets and the turning of them.



Source: Own design

$$\vec{B} = \vec{B_1} + \vec{B_2} + \vec{B_3} + \vec{B_4} =$$

$$= \frac{\mu_0}{4\pi}\left\{\frac{m\sin\vartheta_1}{[(x-a)^2+y^2+z^2]^{3/2}} + \frac{3[m(x-a)\sin\vartheta_1 + my\cos\vartheta_1](x-a)}{[(x-a)^2+y^2+z^2]^{5/2}}\right\}\hat{\imath} +$$

$$+\frac{\mu_0}{4\pi}\left\{\frac{m\cos\vartheta_1}{[(x-a)^2+y^2+z^2]^{3/2}} + \frac{3[m(x-a)\sin\vartheta_1 + my\cos\vartheta_1]y}{[(x-a)^2+y^2+z^2]^{5/2}}\right\}\hat{\jmath} +$$

$$+\frac{\mu_0}{4\pi}\left\{\frac{3[m(x-a)\sin\vartheta_1 + my\cos\vartheta_1]z}{[(x-a)^2+y^2+z^2]^{5/2}}\right\}\hat{k} +$$

$$+\frac{\mu_0}{4\pi}\left\{\frac{m\cos\vartheta_2}{[x^2+(y-a)^2+z^2]^{3/2}} + \frac{3[-mx\cos\vartheta_2 + m(y-a)\sin\vartheta_2]x}{[x^2+(y-a)^2+z^2]^{5/2}}\right\}\hat{\imath} +$$

$$+\frac{\mu_0}{4\pi}\left\{\frac{m\sin\vartheta_2}{[x^2+(y-a)^2+z^2]^{3/2}}+\frac{3[-mx\cos\vartheta_2+m(y-a)\sin\vartheta_2]y}{[x^2+(y-a)^2+z^2]^{5/2}}\right\}\hat{\jmath}+$$

$$+\frac{\mu_0}{4\pi}\left\{\frac{3[-mx\cos\vartheta_2+m(y-a)\sin\vartheta_2]z}{[x^2+(y-a)^2+z^2]^{5/2}}\right\}\hat{k}+$$

$$+\frac{\mu_0}{4\pi}\left\{\frac{m\sin\vartheta_3}{[(x+a)^2+y^2+z^2]^{3/2}}+\frac{3[-m(x+a)\sin\vartheta_3-my\cos\vartheta_3]x}{[(x+a)^2+y^2+z^2]^{5/2}}\right\}\hat{\imath}+$$

$$+\frac{\mu_0}{4\pi}\left\{\frac{-m\cos\vartheta_3}{[(x+a)^2+y^2+z^2]^{3/2}}+\frac{3[-m(x+a)\sin\vartheta_3-my\cos\vartheta_3]y}{[(x+a)^2+y^2+z^2]^{5/2}}\right\}\hat{\jmath}+$$

$$+\frac{\mu_0}{4\pi}\left\{\frac{3[-m(x+a)\sin\vartheta_3-my\cos\vartheta_3]}{[(x+a)^2+y^2+z^2]^{5/2}}\right\}\hat{k}+$$

$$+\frac{\mu_0}{4\pi}\left\{-\frac{m\cos\vartheta_4}{[x^2+(y+a)^2+z^2]^{3/2}}+\frac{3[mx\cos\vartheta_4-m(y+a)\sin\vartheta_4]x}{[x^2+(y+a)^2+z^2]^{5/2}}\right\}\hat{\imath}+$$

$$+\frac{\mu_0}{4\pi}\left\{\frac{m\sin\vartheta_4}{[x^2+(y+a)^2+z^2]^{3/2}}+\frac{3[mx\cos\vartheta_4-m(y+a)\sin\vartheta_4]y}{[x^2+(y+a)^2+z^2]^{5/2}}\right\}\hat{\jmath}+$$

$$+\frac{\mu_0}{4\pi}\left\{\frac{3[mx\cos\vartheta_4-m(y+a)\sin\vartheta_4]z}{[x^2+(y+a)^2+z^2]^{5/2}}\right\}\hat{k} \tag{9}$$

4. Conclusions

Once calculated the field generated by the 4 magnets, we will calculate from what distance will begun to make effect, and therefore, from that point of initial effect, study how to combine the position of the 4 magnets with respect to its axis of rotation, we compensate for the different errors that appear in the previous study of the deviations of the magnetic needle.

The maximum effect of each magnet is when the magnet is perpendicular to the course at which we have to correct the deviation. Turning different angles of each magnet, the effect will be different, and as we know how the corrector magnet will affect to the magnetic compass needle, we can correct the different deviations at different courses.

This will be done, previously in a computer program designed for that porpoise with the formulae calculated above, and we can simulate the different combinations of the 4 corrector magnets till get the proper action against the magnetic compass. With this we will see the equivalent amount of degrees of angle is necessary to compensate each degree of deviation and what will be the effect over the deviations at other different courses.

The final interest is to facilitate to the seamen the compensation operation, with reliability to trust in the magnetic compass as a very effective navigational instrument.

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