Indication of a ship location by the Earth's geomagnetic field

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Abstract. The present study focuses on the need to increase the number of methods for indicating a ship location in traffic conditions on routes with heavy shipping, as well as during navigation in hard hydrometeorological conditions. The research purpose is to increase the level of safety and accuracy of ship navigation and effectively meet the requirements in the field of navigation safety and environmental protection. The issue of navigating through physical fields has a wide range of unresolved tasks despite the previously conducted studies. These tasks include investigation of geomagnetic sensors and their relationship to geomagnetic maps, as well as magnetic compasses and ways to improve them by using magnetometers and eliminating errors caused by rotation of the magnetic needle.

1. Introduction
Successful solution of the task of accurate indication of a ship location is a key factor in performing a whole range of associated tasks. Development and practical implementation of navigation algorithms for thermo- and geomagnetic fields can significantly increase the efficiency of using navigation systems. Besides, improvement of existing systems will reduce the risk of errors associated with the technical and operational features of ship navigation equipment.

2. Problem statement
The article deals with the physical properties in devices for alternative navigation [1]. We have carried out the setting of a conductor with free charge carriers defined as thermomagnetic, along which there is a temperature gradient in the transverse magnetic field. There are two types of thermomagnetic effects: longitudinal ones referred to as even, and transverse ones referred to as odd. The longitudinal effects occur in a direction parallel to the primary flow.

![Diagram of the experiment on measuring the transverse thermomagnetic effect.](image-url)
The following values are depicted in Fig. 1: $\Delta V$ – the longitudinal Nernst-Ettinshausen effect, and $\Delta T$ – the longitudinal Maggi-Righi-Leduc effect; $W$ – heat flow; $H$ – magnetic field.

The transverse effects are represented with the transverse difference of potentials $\Delta V_t$ – the Nernst-Ettinshausen effect, and the transverse difference of temperatures $\Delta T_t$ – the Righi-Leduc effect.

Further values include $a$ – the length of the semiconductor, $b$ – width of the semiconductor, $d$ – thickness of the semiconductor, $W$ – heat flux, and $H$ – magnetic field. The longitudinal effects are the thermo-EMF $\alpha$ in a transverse magnetic field:

$$\Delta \alpha(H) = \alpha(H) \pm \alpha(0)$$

– the Nernst-Ettinshausen effect and the change in thermal conductivity in a transverse magnetic field:

$$\Delta K = K(0) - K(H)$$

– the Maggi-Righi-Leduc effect $\Lambda$.

The longitudinal difference of potentials $\Delta \alpha$ and the transverse difference of potentials in the transverse magnetic field $H_z$ were discovered by Nernst and Ettinshausen. The thermal conductivity gradient and the appearance of the transverse temperature difference $\Delta T$ were discovered by Righi-Leduc [2]. The effects are described by formulas (1) and (2).

The longitudinal effect (1) and the transverse effect (2) are expressed as follows:

$$E_x(H) - E_x(0) = E_x = -\frac{\partial V}{\partial X} = \left[\alpha(H) - \alpha(0)\right] = Q|| \cdot \frac{\partial T}{\partial X}$$

$$E_y = \frac{\Delta V_t}{\alpha} = Q + H_z \cdot \frac{\partial T}{\partial X} = \frac{\partial T}{\alpha} = S \cdot \frac{\partial T}{\partial X}$$

where $E_x$, $E_y$ – components of the electric field generated in the presence of a magnetic field, along the axes $x$ and $y$,

$E(H)$, $E(0)$, $Q||$ and $Q \perp$ – coefficients of the transverse and longitudinal effects,

$\alpha(H)$ and $\alpha(0)$ – coefficients of thermo-EMF in a magnetic field and out of a magnetic field,

$S$ – coefficient of the Righi-Leduc effect,

$K(0)$ and $K(H)$ – the values of thermal conductivity at $H = 0$, $H \neq 0$,

$\Lambda$ – coefficient of the Maggi-Righi-Leduc effect, showing the relative change in thermal conductivity.

The Righi-Leduc effect takes place due to the rotation of the heat flow with respect to the gradient $\Delta T_x$, i.e. the rotation of electrons by the magnetic field $H_z$. The transverse effect is considered positive if in the presence of a positive temperature gradient $x$ and a magnetic field in the direction of the axis $z$, an electric field $E_y$, or a gradient $\frac{\partial T}{\partial Y}$ is formed in the direction of the axis $y$. The Righi-Leduc effect is positive for hole conductivity and negative for electron conductivity. The longitudinal effect of the Nernst-Ettinshausen effect is positive if $E_x(0)$ increases in the magnetic field in absolute magnitude, and negative if it decreases.
It is necessary to distinguish between isothermal and adiabatic thermomagnetic effects [3]. Isothermal effects are measured in the absence of a temperature gradient in the directions of the axes $x$ and $y$:

$$\Lambda = \frac{K_0 - K(H)}{K_0}$$

Measuring of adiabatic effects provokes no transverse heat fluxes. Therefore, the Righi-Leduc effect is only adiabatic, while the other thermomagnetic effects can be both isothermal and adiabatic. The geomagnetic field is closely related to these phenomena.

Each geomagnetic field consists of two fields. The first one is the main geomagnetic field, which is anomalous and created by magnetized rocks; the sources of this field are located in the external electrically conductive core of the Earth. The second one is the external geomagnetic field. The main geomagnetic field accounts for more than 95%. According to the general Gauss theory of geomagnetism, the main geomagnetic field consists of a dipole part and a non-dipole part.

In the first approximation of the theory, the geomagnetic field is a dipole field inclined to the axis of the Earth rotation at an angle of 10-12 degrees. The anomalous field accounts for about 3% of the geomagnetic field, while the external field associated with solar-terrestrial interactions is less than 1%.

Figure 2. Diagram of the Earth's geomagnetic field and a geomagnetic field.

Inclination and displacement of the dipole axis relative to the axis of rotation, as well as the magnitude of the magnetic moment, determine only the general picture of the Earth's magnetic field. At distances more than 6-7 radii of the Earth, the field is significantly distorted by the solar wind (a magnetic field frozen in the solar wind plasma) [4]. The magnetic field is characterized by two vector values: strength $H$ and magnetic induction $B$, connected by the equation, which is written as follows in the international system of units SI:

$$B = \mu_0 (H + J)$$

where $\mu_0$ – magnetic permeability of the vacuum;

$J$ – magnetic moment of the unit volume, the magnetization of the medium,

$$J = \frac{m}{V}$$

The equations of the relationship between the vectors are shown in the form of linear equations:
\[ J = \chi H; B = \mu_0 \cdot \mu H \] 

(6)

where \( \chi \) – magnetic susceptibility of the substance;
\( \mu \) – its magnetic permeability (relative), and:
\[ \mu = 1 + \chi \] 

(7)

The sources of the magnetic field are represented with closed electric currents and magnetized bodies. The relationship between the current strength \( i \) in a closed circuit and the resulting field strength \( H \) is determined by the Biot-Savard law and is expressed by the following ratio for a circular circuit with a radius \( r \):
\[ H = \frac{i}{2r} \] 

(8)

where \( H \) is the field strength in the center of the circular contour.

The product of the current strength by the area covered by the contour is the modulus of the magnetic moment vector \( T \) of the current contour, and the vectors \( T \) and \( H \) are directed along the normal to the contour area. For a circular contour
\[ T = i \pi r \wedge 2 \] 

(9)

Intensity of the geomagnetic field is small, on the Earth's surface it varies from 0.3 oersted at the magnetic equator to 0.6 oersted at the magnetic poles, which do not coincide with the corresponding geographical poles. Deviation of the magnetic poles from the geographical ones currently reaches 2000-3000 km. The geomagnetic field permeates all three shells of the Earth: the lithosphere, the hydrosphere and the atmosphere, and also has a significant impact on the climate and weather. Changes in its intensity can lead to significant fluctuations in temperature, in atmospheric pressure and in the frequency of precipitation, as well as to storms, hurricanes and other natural disasters.

The use of geomagnetic sensors is an alternative to the GLONASS navigation system. In this case, location of an object is determined by a point on the geomagnetic map, which is linked to the geographical one. The general principle of operation of the observational sensors is based on the sensitivity of ferrimagnetic materials to the Earth's magnetic field or the more difficult passage of a laser beam with a deviation in a diamond crystal modified by a nitrogen atom [3, 4]. The sensitivity makes about half of oersted. When the external magnetic field in the sensor changes, the frequency of the ferrimagnetic resonator becomes different. By means of mathematical processing, it is converted into the value of the magnetic field — the final result of sensor measurements. The magnetic measurements on which the main field analysis is based are carried out in the troposphere – directly above the Earth's surface. Assuming that the atmosphere is a non-conducting and non-magnetic medium, then in the regions free of magnetic field sources, the scalar potential \( U \) satisfies the condition. Moreover, the magnetic field \( B \) is determined by the ratio, where the potential \( U \) satisfies the Laplace's equation. In a spherical coordinate system \( r, q, \phi \), the origin of which coincides with the center of the Earth, and the axis – with its axis of rotation, the partial solutions of the Laplace's equation are applicable in the form \( e^k \) equal to \( n \) or \( (n+1) \) and \( m \leq n \), as applied: \( a \) – the radius of the Earth, and \( b^m_n, c^m_n, g^m_n, h^m_n \) – coefficients that can be used to optimally approximate the observed field.

3. Materials and methods.

The difficulty of navigating through geomagnetic resistant sensors consists in the need for the most accurate map of the Earth's magnetic field. The magnetic field on the Earth's surface is measured by special carriers of precise equipment. However, the magnetization of the Earth's crust and the deposits of some minerals change the field values quite strongly, although on small areas. These changes are
not detected by satellites located at high altitude. Therefore, to make maps, it is necessary to perform additional measurements of the magnetic field on the surface or at low altitudes using aeromagnetic surveys.

By the end of the last century, the World Ocean was covered by a modular survey by an average of 45%: the northern hemisphere – by 75%, and the southern hemisphere – by 22% with the accuracy of the planned reference measurements – 200-500 m. The degree of the materials suitability is determined by the task of constructing digital magnetic maps based on surveys, which are conducted at different time, scales and heights. This task is based on the analysis of the spectral structure of the anomalous magnetic field of the studied region. Therefore, following on from the field constants, we obtain:

\[ \nabla^2 U = 0; B = -\nabla U; \frac{r^k}{P_n^m} \left( \cos \theta \right) \sin (m\phi) \]
\[ U(r, \theta, \phi) = \sum_{n=1}^{\infty} \sum_{m=-n}^{n} \left( \frac{a^{m+1}}{a^{m-1}} \right) \left( b_n^m \cos m\phi + c_n^m \sin m\phi \right) P_n^m (\cos \phi) + \right. 
\[ \left. + \sum_{n=1}^{\infty} \sum_{m=0}^{n} \left( \frac{a^{m+2}}{a^{m+1}} \right) \left( g_n^m \cos m\phi + h_n^m \sin m\phi \right) P_n^m (\cos \phi) \right] \tag{10} \]

The analysis of survey errors in the regions allowed us to divide the survey data and, accordingly, digital models of the geomagnetic field into three groups with errors ranging from 3 to 25 NT, from 25 to 45 NT, and more than 40 NT, making 31%, 28%, and 31% of the total number of surveys, respectively. The data formed the basis of the geomagnetic database designed to automate the systems of collection, storage, updating and processing of magnetometric data. The use of geomagnetic sensors is complicated by the fact that the strength of the geomagnetic field changes over time at the same point due to natural and technogenic reasons, which is associated with periodic adjustment of maps.

4. Discussion of results
The main disadvantage of magnetic compasses is that the magnetic fields generated by ship's iron and cargo have a direct impact on the device's readings, which is smoothed out by deviation corrections. To eliminate errors, magnetometers as new types of magnetic compasses are being developed. These devices measure the strength of magnetic fields. The principle of operation of magnetometers is based on the Hall effect (O. Tritikov) – the phenomenon of the occurrence of a transverse potential difference when moving a conductor with a direct current in a magnetic field.

Flux-gate sensors have found the greatest use in such magnetic compasses [5]. Flux-gate magnetometers are the sensitive elements of most marine magnet compasses, called flux-gate compasses. There are flux-gate magnetometers of different types. The classic single-coordinate flux-gate sensor measures the magnetic field component \( X \) and consists of a toroid and an external (signal) coil wound on top of it. When installed on a ship, the compasses are oriented so that the measurement directions of the magnetometers coincide with the axes of a rectangular coordinate system rigidly connected to the ship's hull.

5. Conclusion
Thus, the issue of navigating through physical fields has a wide range of unresolved tasks despite the previously conducted studies. These tasks include investigation of geomagnetic sensors and their relationship to geomagnetic maps, as well as magnetic compasses and ways to improve them by using magnetometers and eliminating errors caused by the rotation of the magnetic needle. It is necessary to have results of a modular survey in order to improve the accuracy of information displayed on geomagnetic maps [6].

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