Development of a new method for determining the parameters of a moving object based on the study of the structure of the magnetic track of colloidal solution nanoparticles

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Abstract. A new method has been developed for the study of deep-sea areas of the marine area (more than 550 m depth) based on the measurement of the parameters of a magnetic track from a moving magnetic object. A method for detecting a magnetic track from a moving magnetic object using an optical sensor is proposed. Studies of changes in the parameters of the magnetic field in the magnetic track using ferromagnetic fluid have been conducted.

1. Introduction
Studies of magnetic fields and physical phenomena, which cause changes in their structure, are an urgent task of fundamental and applied physics [1-7]. Magnetic track is one of the most complex phenomena for research. It occurs when a magnetic object moves in a different environment (for example, a comet or a meteorite in the space, a ship at sea, etc.). The appearance of a magnetic track is associated with a change in the structure of the magnetic field lines in the zone of movement of the magnetic object.

Of particular interest are studies of the magnetic track at sea depth, where external factors (water flow, wind, etc.) have an insignificant effect on the process of its destruction. The currently developed radar methods for monitoring the situation in various areas of the water area do not allow detecting a moving object at depths of more than 550 m [6, 8–12]. Effective methods for detecting mobile magnetic objects at such depths are the use of magnetometers, especially quantum ones, which are highly sensitive to magnetic field variations [1, 5, 7, 13-15], fiber optic antennas [16, 17] and acoustic systems [18, nineteen].

When the magnetometer is immersed to a depth, it is possible to establish the presence of a magnetic track from a moving object in the marine environment. With it, you can explore the variation of the magnetic field in different parts of the magnetic track. Determine the rate of its destruction.

Conducting such experiments is quite a complicated and expensive process. Therefore, we have developed a new optical method for studying the structure and parameters of the magnetic track in the laboratory. In addition, experiments conducted with colleagues have shown that it is extremely difficult to find a magnetic track in marine space with a single magnetometer. Therefore, a reliable system is needed for its detection. This system should be resistant to diving to great depths. One of the possible ways to detect a magnetic track at a great depth is suggested in our work.
2. The method of studying the magnetic track and the method of its detection
In radar methods for detecting moving objects under water, a microwave signal reflected from a crest of a wave is registered. That occurs on a surface as a moving object moves under water. This wave is created by the turbulent motion of water molecules as the object moves at depth. The formation of the crest of this wave is described by the Bernoulli equation:

\[ p + \frac{1}{2} \rho u^2 + \rho gh = \text{const}, \tag{1} \]

where \( p \) - the density of the fluid, \( v \) - the flow velocity, \( h \) - the height, \( p \) - the pressure, \( g \) - the acceleration of gravity.

The higher the speed of the object and the larger its dimensions, the greater the value of \( h \). The turbulent process of moving molecules with a change in the structure of the magnetic field lines while moving a moving magnetic object participates in the formation of a magnetic track. At depths greater than 550 m, waves caused by turbulent fluid motion decay at the boundary of two water layers. This boundary is located at a depth of 500 - 530 m. A wave crest with a height \( h \) when moving a moving object at a depth of 550 m and more does not form on the surface of the sea water area. In addition, it is necessary to take into account that the turbulent movement of water at the indicated depths occurs at a pressure of more than 55 atm. Therefore, the process of forming a magnetic track behind a moving magnetic object that has left a certain zone is very fast. Empty space is filled with water at high speed.

Our experiments with a magnetometer showed that the higher the speed of movement of a magnetic object, the greater the variation of the magnetic field in the zone of formation of the magnetic track. To determine the direction of motion of a magnetic object according to the nature of the damping of variations in the magnetic field, we developed an experimental setup using magnetic fluid [20, 21]. An aqueous solution of magnetite with a concentration of 0.025 nanoparticles (average nanoparticle size 14 nm) was used as a magnetic fluid. Oleic acid was used as a surface-active substance (surfactant) [20-24]. The block diagram of the experimental setup is presented in figure 1.

![Block diagram of experimental setup](image)

**Figure 1.** Structural scheme of experimental setup 1 – semiconductor laser; 2 – diaphragm; 3 – lens; 4 – cell; 5 – electromagnet; 6 – polarizer; 7 – photosensitive element; 8 – processing device; 9 – electromagnet power unit; 10 – magnetic needle.
The laser radiation with \( \lambda = 632 \text{ nm} \) enters through the diaphragm 2 and lens 3 onto the transparent face of cell 4, made of quartz glass. Other faces of the cell are opaque to radiation. The cell is located in the field of an electromagnet 5 with induction \( B_0 = 86 \text{ \mu T} \) - the average magnetic field of the Earth at the considered depths [7]. The reflected radiation from magnetite nanoparticles, which are uniformly distributed over the cell volume, is recorded by the CCD camera 7. In figure 2 shows the image recorded by the camera 7 after computer processing.

![Image](image_url)

**Figure 2.** The diffraction pattern of the laser radiation in the case of the magnetic liquid placing: (a) in magnetic field of the Earth; (b) in field of a moving magnetic "needle".

The movement of a moving magnetic object in a magnetic fluid is simulated by moving along the opaque cell wall of a one-sided magnetic needle system with an induction on the tip of the order of 1 T. In the area of the magnetic needle, nanoparticles are placed on the power lines of its magnetic field. Formed agglomerates (speckle structure). It should be noted that at a high speed of movement of the magnetic "needle" 10 along the wall a wave arises on the surface of the magnetic fluid. This is due to the fact that under the action of a strong alternating magnetic field, particles quickly tend to occupy a certain position in space. In figure 2 presents the image of the reflected from the speckle structures, which were formed in the magnetic field of the moving "needle", laser radiation.

The analysis of the obtained results shows that the structure of the arrangement of nanoparticles in the liquid changes in the magnetic needle “magnetic field” interaction zone. They are placed in the area of the magnetic field lines, forming strips of different thickness [25-27]. The degree of transparency of these bands for laser radiation varies from the center of action of the “needle” field 10 to the edge. It was found that, depending on the speed of the object and the induction of the field at the end of the “needle”, the location zone (the volume occupied by the bands in the magnetic fluid) and the configuration of these bands change. This phenomenon reflects the nature of the formation of a magnetic track from a mobile marine object in real conditions.

After the magnetic needle was applied to the magnetic fluid near the cell walls, magnetic field induction measurements were made at various points. It was found that the process of attenuation of the variations of the magnetic field along the wall of the cell near the zone of formation of the magnetic track is heterogeneous. This is due to the unequal disintegration of agglomerates of
magnetized nanoparticles by the volume of the magnetic track. In a turbulent fluid flow at a great depth this process will be even more pronounced.

The results obtained, as well as data from previous studies [13, 25-28], allowed us to develop a new method for determining the presence of a magnetic track in the marine area. For the practical implementation of the proposed method, it is proposed to place optical sensors based on ferrofluidic cells [24-27] developed by us earlier in a construction in the form of squares with a side of 8-10 m. To confirm the possibility of determining the presence of a magnetic track in the water area using an optical sensor developed and assembled experimental setup. Its structural scheme is presented in figure 3.

![Figure 3](image)

**Figure 3.** Structural scheme of experimental setup: 1 - power supply; 2 – solenoid; 3 - rectangular vessel; 4 – water; 5 - non-magnetic material; 6 - ferrofluid cell; 7 – the body; 8 – the laser; 9 - diaphragm; 10 – the lens; 11 - photosensitive element; 12 - polarizer; 13 - processing device.

Magnetic fluid (an aqueous solution of magnetite nanoparticles with a concentration of 0.03 - surfactant - oleic acid) is placed on a stand made of non-magnetic material 5 in a ferrofluid cell 6. The cell is placed in a magnetic field of a solenoid 2. The induction of a magnetic field Bt in the cell area of 6.8 mT. Between the solenoid and the ferrofluid cell is a rectangular vessel 3 with a liquid medium 4 (water). The length of the vessel 3 moves the body 7, made of permalloy. To register the reflected laser radiation from speckle structures, the same registration system is used as in figure 1. In figure 4 shows the recorded image by the camera 11 of the reflected laser radiation from speckle structures formed by nanoparticles on the magnetic field lines of the solenoid. The formation of speckle structures is described in detail in [25-27].
When the body 7 moves through the vessel, the magnetic field lines of the solenoid coil close to 7. The agglomerates undergo the collapse under the action of thermal motion, and the pattern recorded changes. In figure 4 shows the image of the reflected radiation from the speckle pattern of the nanoparticles 120 seconds after the magnetic field lines of the solenoid close to the body. This is the average transit time of a moving magnetic object through a point in space at a depth in the zone of formation of the magnetic track.

Analysis of the results shows the possibility of registering changes in field variations in a magnetic track with an optical sensor. By processing images from optical sensors spaced at equal distances, one can construct diagrams of variations in the magnetic field at a depth of the water area. The experiments have shown that according to these diagrams, it is possible to establish the presence of a magnetic track at the depth of the water area.

3. Conclusion
The obtained experimental results show that the method proposed by us allowed us to conduct studies of the magnetic track. Based on these studies, a method was developed for determining the direction of movement of a moving magnetic object according to the nature of changes in the magnetic field variations. In addition, the data on the amplitude of magnetic variations, taking into account their nature of changes in the track volume, allow determining the time of its formation with an error of up to 15%. This time information is sufficient for carrying out activities to control the water area.

It has been experimentally proven that the mobile underwater system proposed by us, based on an optical sensor developed earlier using a ferrofluid cell, allows us to search for a magnetic track over a large area of the marine water area and determine its presence in a given area.

References
[1] Vershovskii A K and Dmitriev A K 2015 Technical Physics Letters 41 393-6
[2] Davydov V V, Dudkin V I, Velichko E N and Karseev A Yu Measurement Techniques 58 556-61
[3] Davydov V V, Dudkin V I and Karseev A Yu 2015 Technical Physics 60 456-60
[4] Marusina M Ya, Bazarov B A, Galaidin P A, Silaev A A, Marusin M P, Zakemoskya E Yu, Gilev A G and Alekseev A V 2014 Measurement Techniques 57 461-6
[5] Vershovskii A K, Dmitriev S P and Pazgalev A S 2013 Technical Physics Journal 83 879
[6] Kudasov Yu B, Makarov I V, Maslov D A, Platonov V V, Popov E Ya, Surdin O M, Voronov S L, Malyshev A Yu, Korotkov S V and Vodovozov V M 2015 Instruments and Experimental Techniques 58 781-6
[7] Aleksandrov E B and Vershovskii A K 2009 Physics-Uspekhi 52 573-601
[8] Zaiko A I, Vorob’ev A V, Ivanova G A and Shakirova G R 2016 Measurement Techniques 59 532
[9] Cherepov S V, Moroz O Kh, Derecha D A and Hesse O 2011 *Instruments and Experimental Techniques* **54** 273-6
[10] Petrov A A, Grebenikova N M, Lukashev N A, Davydov V V, Ivanova N V, Rodugina, N S and Moroz A V 2018 *Journal of Physics: Conference Series* **1038**(1) 012032
[11] Podstrigaev A S, Smolyakov A V, Davydov V V, Myazin N S and Slobodyan M G 2018 *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* **11118** LNCS 509-515
[12] Lenets V A, Tarasenko M Yú, Davydov V V, Rodygina N S and Moroz A V 2018 *Journal of Physics: Conference Series* **1038**(1) 012037
[13] Davydov V V, Dudkin V I and Velichko E N 2016 *Measurement Techniques* **59** 176-82
[14] Davydov V V and Myazin N S 2017 *Measurement Techniques* **60** 491–6
[15] Davydov R V, Antonov V I and Moroz A V 2018 *Proceedings of the 2018 IEEE International Conference on Electrical Engineering and Photonics, EExPolytech 2018* (Saint-Petersburg) 8564378 p. 236-9
[16] Ushakov N A and Liokumovich L B 2014 *Optical Engineering* **53**(11) 114103
[17] Bisyarina M A, Kotov O I, Yartog A H, Liokumovich L B and Ushakov N A 2017 *Applied Optics* **56**(2) 354-64
[18] Ivanov S I, Lavrov A P and Saenko I I 2017 *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* **10531** LNCS 482-9
[19] Ivanov S I, Lavrov A P and Saenko I I 2016 *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* **9870** LNCS 670-9
[20] D’yachenko S V, Kondrashkova I S and Zhernovoi A I 2017 *Technical Physics* **62** 1602-4
[21] Nepomnyashchaya E K, Velichko E N and Aksenov E T 2016 *Journal of Physics: Conference Series* **769**(1) 012025
[22] Davydov R V and Antonov V I 2017 *Journal of Physics: Conference Series* **929**(4) 012040
[23] Zaitsev N I, Ilyakov E V, Kulagin I S and Shevchenko A S 2006 *Radiophysics and Quantum Electronics* **49** 120-5
[24] Prokop’ev A V, Pleshakov I V, Bibik E E and Kuz’min Y I 2017 *Technical Physics Letters* **43** 194-6
[25] Logunov S E, Davydov V V, Vysochzyk M G, Koshkin A Y and Rud’ V Yu 2017 *Journal of Physics: Conference Series* **917**(5) 052058
[26] Logunov S E, Davydov V V, Vysochzyk M G and Titova O A 2018 *Journal of Physics: Conference Series* **1135**(1) 012069
[27] Logunov S E, Davydov V V, Vysochzyk M G and Mazing M S 2018 *Journal of Physics: Conference Series* **1038**(1) 012093
[28] Logunov S E, Koshkin A Yu, Davydov V V and Petrov A A 2016 *Journal of Physics: Conference Series* **741**(1) 012092