A new device for autonomous space devices based on a three-component quantum variometer

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Abstract. The necessity of additional study of magnetic field variations in the magnetic transition layer, in the magnetopause, as well as in the plasma layer and in the tail of the magnetosphere in a wide range of distances from the Earth is substantiated. To obtain additional information in comparison with the studies that are being carried out in outer space at the present time, it is necessary to simultaneously monitor the magnetic field at various points in outer space. It is also necessary to register the dynamics of changes in the magnetic field in time in space by three components. To accomplish this task, a small-sized three-component quantum variometer with autonomous power supply has been developed for space devices, which can be lost in the course of short-term research. The results of the operation of a quantum variometer are presented.

1. Introduction
The Earth's magnetosphere is the most important component of the ecological state of the planet [1-7]. It protects all life on Earth from streams of ionizing radiation (solar wind). An important element of the Earth's magnetosphere is the boundary (magnetopause), at which the pressure from the Earth's magnetic field is equal to the pressure of the solar wind shock wave. There are regions in the magnetosphere that are geomagnetic traps that hold particles in a limited volume. This forms the Earth's radiation belts. The magnetic field, as shown by numerous studies [8-18], carries a huge amount of information that allows you to predict many situations.

Therefore, various areas of magnetic fields, both on Earth and in outer space in near-Earth orbits, must be investigated to predict the evolution of the universe, which has a significant impact on the Earth [1, 4, 19-23]. Information about the magnetic field from several magnetometers located on the autonomous spacecraft Ulysses is insufficient for spatial monitoring of various zones of the magnetosphere and much more. This truncated information does not allow comparing the experimental data with the calculations obtained in various theoretical models to study the dynamics of various physical processes. It is also impossible to check or substantiate forecasts on the influence of magnetic storms in space on processes in the Earth's magnetosphere and on its magnetic field. This
requires information about the magnetic field from a large number of points located in outer space. This information should be received continuously (for a long time) to the station, which is in near-earth orbit [24-26]. One of the options for solving this problem can be associated with the use of autonomous small-sized meters of magnetic field variations with autonomous power supply from solar cells, which will fly in outer space. The use of a large number of simple and inexpensive devices (they can be irretrievably lost in space) will make it possible to provide studies of magnetic fields in the required areas of outer space. Therefore, the development of magnetic field meters that can be used for space exploration is an extremely urgent task, especially in the face of changes in the Earth's magnetic field. In our work, we present one of the possible options for an optical meter for magnetic field variations for space applications.

2. Three-component quantum meter of magnetic field variations

At present, a large number of models of various magnetometers have been developed to measure the magnetic field and its components [27-29]. The best precision characteristics are possessed by quantum magnetometers [27-33], which use optical pumping based on laser radiation. These are optical measuring devices based on the principle of operation, which have high stability of accuracy characteristics. But their work requires significant energy resources. In addition, they are large and very expensive. It should also be noted that in space, in some cases, the parameters of laser radiation can change under the influence of gravitational factors and temperature jumps [9-13, 29, 34-37]. Changing the wavelength $\lambda$ of laser radiation has an extremely negative effect on the operation of the magnetometer. Therefore, these instruments are currently only used on the Ulysses spacecraft. In systems performing an autonomous flight in space for the study of magnetic fields, it is more expedient to use optical systems, measurements in which are less critical to the change in $\lambda$.

In our works on the study of magnetic field variations from a moving object at sea depths, we proposed a design of an autonomous sensor based on a ferrofluid cell with a magnetic fluid [34-37]. The variation of the magnetic field in the direction of the force lines of the Earth (one component) was measured, since the moving object creates the greatest distortions in this direction. In the case of solar wind impact (the Sun's magnetic field is 100 times greater than the Earth's magnetic field - about 5 mT), the design of the optical sensor changes. In figure 1 shows the design of an optical sensor developed by us for flight in outer space as part of an autonomous module.

**Figure 1.** Block diagram of an optical sensor for measuring the magnetic field component and its variation: 1 - semiconductor laser; 2 - laser power supply; 3 - the coil of inductance; 4 - stabilized current source; 5 - ferrofluid cell; 6 - a specialized camera; 7 - processing scheme; 8 - data transmission scheme; 9 - power supply; 10 - the battery.
Unlike the designs of optical sensors developed by us earlier [33-36], almost all optical elements (lenses, prisms, etc.) are excluded from its composition. This, on the one hand, makes the new design more compact. On the other hand, the number of reflections between optical elements decreases, which increases the contrast of the bands in the recorded diffraction pattern. Radiation from semiconductor laser 1 with \( \lambda = 613 \) nm arrives at the transparent wall of ferrofluid cell 5. The cell contains a magnetic fluid - an aqueous solution of single-domain hematite nanoparticles with a volume concentration of 0.054 with a surfactant (surfactant) tetramethylammonium hydroxide. The ferrofluid cell is located in a weak uniform magnetic field (for example, with an induction \( B_0 = 0.9 \) mT and an inhomogeneity of 10-5 cm-1), which is created by special inductors 3 (specialized solenoid). The value of induction \( B_0 \) can vary from 0 to 4.2 mT.

Previous studies made it possible to establish that in the case of placing a ferrofluid cell in a magnetic field, the nanoparticles of a ferromagnetic liquid are located on the force lines of the magnetic field. For laser radiation passing through a ferromagnetic liquid placed in a cell, this configuration of nanoparticles is similar to a diffraction grating. The period of this grating is determined by the distance between the force lines of the magnetic field [34-37]. The diffraction pattern from the laser radiation passed through the cell is recorded by a specialized camera. The principle of measuring the magnetic field and its variations in the developed design of the optical sensor is implemented as follows. In the case of a high uniformity of the magnetic field created by solenoid 3, in which the ferrofluid cell is located, the photodetector (camera 6) registers a diffraction pattern in the form of stripes with symmetry from the transmitted laser radiation through the ferrofluid cell. Up to a certain value, variations in the magnetic field that will be present in the vicinity of solenoid 3 do not cause visible distortions in the diffraction pattern.

In this case, by decreasing the field of the solenoid, it is possible to obtain distortions in the diffraction pattern due to the presence of variations that worsen the uniformity of the field. Since variations in outer space are non-periodic and non-constant, after a certain period of time (when their influence weakens), it will be possible to register a symmetric diffraction image. Having performed a preliminary calibration of the optical sensor on Earth (before sending it into outer space), it is possible to determine, with an error of no more than 20%, the values of the magnetic field variations. A similar process only with an increase in the induction of the magnetic field of the solenoid can be considered with an increase in the amplitude of the variation of the magnetic field from the solar wind. The restructuring of the magnetic field in these cases does not exceed 0.2-1.0 mT. It doesn't take long. Almost everything happens automatically.

Another case is associated with a change in the induction \( B_s \) of the magnetic field of the solar wind (with respect to this value, further variations in the magnetic field arise). This process is longer in time and, as studies have shown, is associated with cosmic magnetic storms or other strong anomalies. In this case, each component of the magnetic field \( B_s \) from a certain level will make changes in the magnetic field of the solenoid. The configuration and density of the magnetic field lines in the area of the ferrofluid cell location will change. The distance between adjacent maxima in the diffraction pattern changes. This means that the density of the magnetic field lines has changed per unit area. Having carried out a preliminary calibration on Earth, it is possible to estimate the value of induction \( B \) in the area of the ferrofluid cell with an error of less than 20% from the measured values of the density of the magnetic field lines.

\[
B = \int j_B(S) dS
\]  

where \( j_B \) - the density of the force lines.
It should be noted that \( j_B(S) \sim N \) (the number of force lines per area element). Therefore, it becomes necessary to estimate \( N \), as well as the distance between the force lines.

Using a preliminary calibration performed in a stationary laboratory on Earth by the number of lines, the value of \( j_B \) is determined. Next, we define the induction.

3. Results of experimental studies and their discussion

Figure 2 shows, as an example, diffraction images from the transmitted laser radiation through a ferrofluid cell for various values of the magnetic field inhomogeneity in the area of its location.

![Figure 2](image)

Figure 2. The diffraction pattern of the laser radiation in the case of the magnetic liquid placing: (a) in a uniform magnetic field; (b) in an inhomogeneous magnetic field.

An analysis of the results obtained (Figure 2) shows that the inhomogeneity of the magnetic field caused by the presence of variations significantly distorts the recorded diffraction pattern. It is rather difficult to measure the magnetic induction using the field line density based on the recorded image (Figure 2.b). To determine the number \( N \), which is necessary for calculating the induction value \( B \) using (1), the intensity distribution \( I \) of the laser radiation is plotted over the width \( L \) or height \( h \) of the ferrofluid cell (row selection). In figure 3 as an example for the registered images (Figure 2), these lines are presented.

![Figure 3](image)

Figure 3. The dependence of the intensity \( I \) on the distance between the force lines of the magnetic field: a) in a homogeneous magnetic field; b) in a uninhomogeneous magnetic field.

The obtained result shows the validity of using this method. By controlling the magnetic field of the solenoid, it is possible to obtain a change in the diffraction image in the presence of variations in the magnetic field in the area of the ferrofluid cell, which previously led to distortions in the
diffraction pattern (Figure 2.b). In figure 4, as an example, we show some possible options for reconstructing the diffraction pattern using the adjustment of the field of solenoid 3 (Figure 1).

Figure 4. The diffraction pattern of the laser radiation in the case of the magnetic liquid placing: (a) in a uniform magnetic field; (b) in an inhomogeneous magnetic field.

An analysis of the results obtained (Figure 4) shows that by adjusting the induction $B_0$ as a result of tuning, the symmetry in the arrangement of the maxima in the diffraction pattern recorded from the transmitted laser radiation is restored. And it is possible to measure and determine the variation of the magnetic field and the value of $B_s$. Similarly, the diffraction pattern is adjusted for the case of a change in the constant component in the induction of the magnetic field of the solar wind.

4. Conclusion
The obtained experimental results confirmed the validity of the developed design of the optical sensor for space-based autonomous systems. It should be noted that laser radiation in the visible range is used to obtain a diffraction pattern. In the case of temperature fluctuations, a change in the wavelength $\lambda$ within the red range of the spectrum by 3-5 nm does not significantly affect the contrast of the recorded diffraction pattern and the error in measuring the number of field lines $N$. This fundamentally distinguishes the design of the optical sensor developed by us from the quantum magnetometer with optical pumping with using laser radiation.

If three such sensors are placed in an autonomous spacecraft with the field $B_0$ oriented along the x, y, and z axes, it is possible to study the three components of the magnetic field and their variations. The experiments have shown that the service life of such sensors with an autonomous power source is more than 1 year, with the use of solar cells it can significantly increase (until the protective layers of an autonomous object made of non-magnetic material are destroyed).

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