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A METHOD FOR MEASURING THE DIRECTION OF THE GEOMAGNETIC FIELD TO CORRECT THE ONBOARD RUBIDIUM ATOMIC CLOCK FREQUENCY USING AN M_Z-MAGNETOMETER

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Abstract. The article presents a method developed by the authors for measuring the direction of a magnetic field using an M_Z-type quantum magnetometer, the readings of which are used to correct the frequency of an onboard small-sized rubidium atomic clock. The method was tested on a specially created experimental setup implementing a M_Z-type quantum magnetometer with optical pumping. High sensitivity of the method to a change in the angle between the optical axis of the magnetometer and the direction of the magnetic field under study for small angles was found. A conclusion was made about the applicability of the developed method for various angles limited in magnitude by the presence of 'dead zones' of the quantum magnetometer.

Keywords: magnetic field, optically pumped quantum magnetometer, atomic clock, magnetic shield

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МЕТОД ИЗМЕРЕНИЯ НАПРАВЛЕНИЯ ГЕОМАГНИТНОГО ПОЛЯ ДЛЯ КОРРЕКЦИИ ЧАСТОТЫ БОРТОВЫХ РУБИДИЕВЫХ АТОМНЫХ ЧАСОВ С ПОМОЩЬЮ M_Z-МАГНИТОМЕТРА

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Аннотация. В статье представлен разработанный авторами метод измерения направления геомагнитного поля с помощью квантового магнитометра M_Z-типа, показания которого используются для коррекции частоты бортовых малогабаритных рубидиевых атомных часов. Метод испытан на специально созданной экспериментальной установке, реализующей квантовый магнитометр с оптической накачкой M_Z-типа. Установлена высокая чувствительность метода к изменению угла между оптической осью магнитометра и направлением исследуемого геомагнитного поля для малых значений этого угла. Сделан вывод о применимости разработанного метода для различных углов, ограниченных по величине наличием «мертвых зон» квантового магнитометра.

Ключевые слова: магнитное поле, квантовый магнитометр с оптической накачкой, атомные часы, магнитный экран

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Introduction

There is considerable focus towards developing satellite navigation systems whose largely depend on the parameters of atomic clocks installed on-board [1, 2]. The frequency of their signal is influenced by various external factors, such as the geomagnetic field. As the satellite moves, both the direction and magnitude of the geomagnetic field change, affecting the frequency of the atomic clock. The values of the geomagnetic field parameters depend on the satellite orbit. The requirements to weight and dimensions of onboard rubidium atomic clocks (RAC) are crucial for small satellites, imposing restrictions on the magnetic shields used for the RAC [3–6]. Several methods have been proposed to reduce the influence of the geomagnetic field on RAC:

increasing the shielding factor of the magnetic shield,

using the averaged frequency of two RAC of the same series,

using an onboard magnetometer for RAC frequency correction,

stabilizing the operating magnetic field of the RAC by a magnetic-field-dependent transition [7–12], etc.

If an onboard magnetometer is used to compensate for RAC frequency, acceptable stability its parameters must be ensured. Additional requirements are imposed for the operability of the onboard magnetometer in a geomagnetic field close to the operating magnetic field of RAC, as well as for its parameters in a weak geomagnetic field in the presence of a magnetic field gradient inside the satellite.

An optically pumped quantum M_Z-type magnetometer (OPQM) meets such requirements and can be fabricated with low weight and dimensions, as well as with low energy consumption [13–15]. The presence of magnetic field shielding in RAC imposes less stringent requirements for accuracy and sensitivity parameters of the OPQM; however, it does not remove the requirements for stability of the magnetometer's parameters over time.

Notably, the geomagnetic field penetrates into the RAC in the direction of its optical axis (the direction of the lowest shielding factor) [8].

The amplitude of the radio-optical resonance signal in an M_z-type OPQM depends on the angle θ between the directions of the geomagnetic field and the optical axis of the OPQM: it is proportional to the function $\cos^4\theta$ [13]. In addition, such an OPQM has 'dead zones', which are characterized either by the complete absence of a resonance signal at angles θ equal to about 90 or 270°, or by a very small signal amplitude under the given conditions.

However, these characteristics of this type of OPQM are not particularly important for the considered case of its application, which is due, as noted above, to the presence of the magnetic shield in the RAC, which has a large transverse shielding factor. In such a situation, the geomagnetic field penetrates noticeably into the magnetic shield of the RAC only at small angles to its optical axis [6].

Another characteristic of this OPQM, which is crucial for the considered case of its application, is the detection bandwidth of the resonant signal, which is about 1 Hz, providing correct measurement of the geomagnetic field varying in direction and magnitude in satellite orbit.

The goal of the study was to develop a method for determining the direction of the geomagnetic field using a quantum M_Z- magnetometer to adjust the frequency of onboard rubidium atomic clocks.

Experimental setup

A specialized laboratory setup was constructed to experimentally verify the method for determining the direction of the geomagnetic field using a quantum M_z-type magnetometer (Fig. 1). The magnetic system of this setup was positioned on a rotating platform, which provided rotation of the optical axis of the magnetometer by a given angle in the $X'OZ'$ plane of the laboratory coordinate system (relative to the Z'-component of the geomagnetic field). The error in setting the rotation angle of the magnetic system was ±0.25° with a maximum rotation angle of ±10°. The OPQM was placed inside the magnetic system.

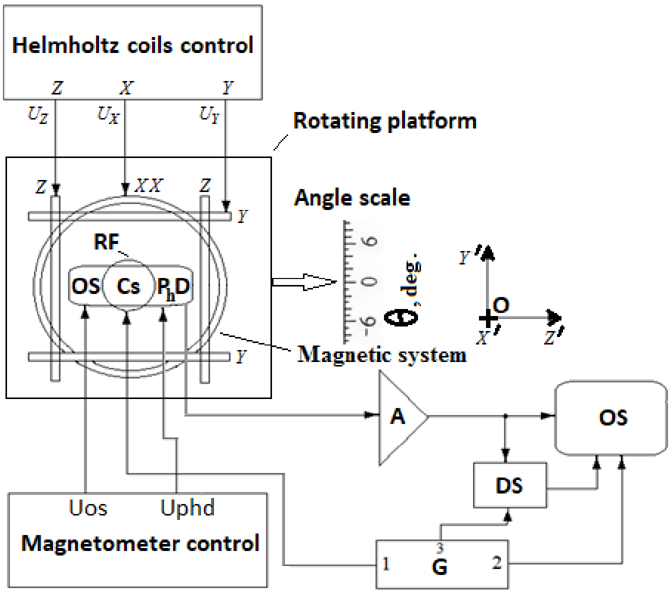

Fig. 1. Schematic of experimental setup:
optical pumping source OS with power supply U_{OS}; photodiode PhD with power supply Uphd;
gas cell Cs with antirelaxation coating on the walls (containing cesium-133 atoms);
radio frequency coils RF; broadband amplifier A; synchronous detector DS;
digital oscilloscope OS; low-frequency generator G
The axes X', Y', Z' of the laboratory (fixed) coordinate system coincide with the axes XYZ
of the coordinate system of the magnetic system at an angle $\theta = 0$

To conveniently measure the magnetic system, the vertical component of the geomagnetic field was compensated using a pair of Helmholtz coils (the coils are oriented along the Y axis in Fig. 1).

Method for measuring the direction of the magnetic field

A measurement method similar to that described in book [13] was used in the study to determine the direction of the geomagnetic field with the help of the M_Z-type OPQM. The method consists of the following steps.

Alternating magnetic fields are generated along the X, Y, and Z axes using the system of Helmholtz coils. The system, together with the OPQM, can be rotated at a given angle relative to the $X'Y'Z'$ axes of the laboratory (fixed) coordinate system. An example of determining the direction of the geomagnetic field in the $X'OZ'$ plane is shown in Fig. 2. The magnetic field is modulated in the direction of the X axis (field $\mathbf{H}_{mod}$). If the Z'-components of the geomagnetic field are directed along the optical axis of the OPQM (Fig. 2,*a*), the signal components equal in amplitude are detected at the output of the synchronous detector (points A and C in Fig. 2,*d*). If there is nonzero angle θ between the projection of the geomagnetic field vector $\mathbf{H}_Z'$ and the optical axis of the OPQM (Fig. 2, *b* and *c*), different signal amplitudes are obtained at the output of the synchronous detector at points A and C (Fig. 2,*e* and *f*). Their difference becomes dependent on the angle between the directions of the measured magnetic field and the optical axis of the OPQM.

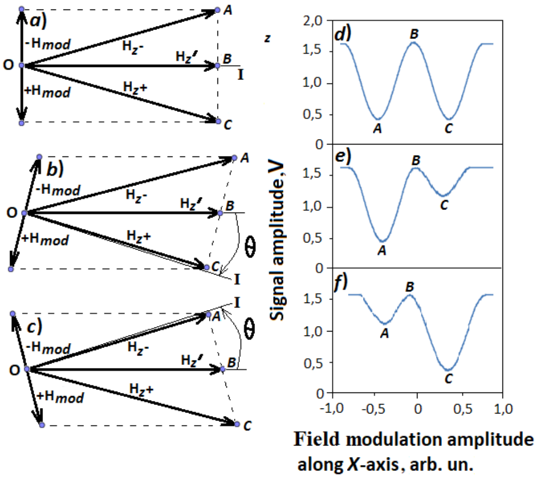

Fig. 2. Generated magnetic fields (*a*—*c*) and waveforms of corresponding signals of synchronous detector (DS) (*d*—*f*); optical axis *I* of OPQM is rotated (*b*, *e*) and counterclockwise (*c*, *f*) relative to the Z'-component of the geomagnetic field (GF) $\mathbf{H}_Z'$; cases without rotation are also shown (*a*, *d*)

$\pm\mathbf{H}_{mod}$ are the vectors of the alternating magnetic field directed along the X axis; $\mathbf{H}_Z+$ and $\mathbf{H}_Z$ are the sum vectors of GF $\mathbf{H}_Z'$ and the alternating field along the X axis; A, B, C are the points on the DS signal; θ is the rotation angle of the magnetic system

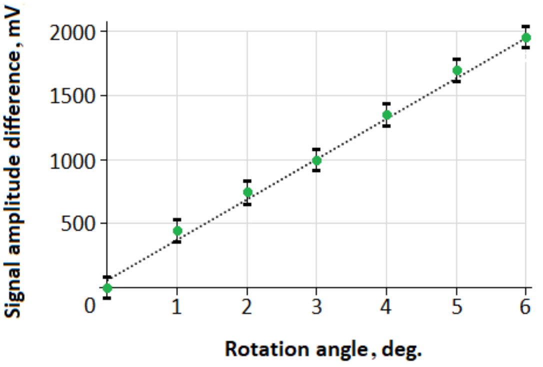

Fig. 3. Experimental (symbols) and approximating (dashes) dependences of amplitude difference between the signal components of synchronous detector (points A and C in Fig. 2) on rotation angle of magnetic system in the $X'OZ'$ plane relative to the Z' axis of the laboratory coordinate system

The method presented in the paper for determining the direction of the geomagnetic field was implemented using the laboratory setup shown in Fig. 1. The OPQM together with the magnetic system was rotated at a given angle with respect to the Z'-component of the geomagnetic field, and a signal was simultaneously recorded at the output of the synchronous detector. The frequency of the modulation signal in the X coils was selected taking into account the detection bandwidths of the synchronous detector (range ofabout 1 Hz), amounting to 240 MHz. The amplitude of the modulation signal was selected empirically, taking into account the presence of two signal components of the synchronous detector (points A and C in Fig. 2). The measurements were carried with the rotation angles θ of the magnetic system ranging from 0 to 6°. Such a narrow angle range was chosen because the detector for measuring the direction of the geomagnetic field based on the M_Z-type OPQM is intended for adjusting the frequency of onboard RAC located in a geomagnetic field varying in direction [11]. As follows from the data in [8], the value of the transverse shielding factor of the magnetic shield in this RAC is significantly higher than the longitudinal one, which is directed along the optical axis of the RAC, the same as the optical axis of M_Z-type OPQM.

As a result, it is the longitudinal component of the geomagnetic field corresponding to small angles θ that significantly affects the frequency of this RAC. Moreover, the considered application of the M_Z-type OPQM eliminates the influence of its ‘dead zones’ on the measurement results (angle $\theta = \pm 90°$).

Fig. 3 shows the experimental dependence of the amplitude difference of signal components of the synchronous detector (points A and C in Fig. 2) from the rotation angle of the magnetic system in the $X'OZ'$ plane relative to the Z' axis of the laboratory coordinate system (see Fig. 1). The sequence of experimentally obtained values of the amplitude difference, represented by green dots in Fig. 3, is approximated by a straight line (dashed line). The measurement error (shown by vertical segments) is due in this case to the inaccuracy of setting the rotation angle of the magnetic system (±0.25°); it significantly exceeds the difference between the experimental values and the linear approximation of the dependence under consideration. This indicates a higher accuracy in setting the rotation angle of the magnetic system (better than ±0.25°) and a potentially high accuracy of the method proposed.

The measured slope of the linear approximation was 0.0029 degrees/mV. With an RMS noise of 0.25 mV at the output of the synchronous detector and a resonant signal detection bandwidth of about 1 Hz, the sensitivity of the developed method to variation in the rotation angle of the magnetic system relative to the laboratory coordinate system was $7.3\cdot10^{-4}$°.

Notably, the accuracy of the developed method for determining the direction of the geomagnetic field (the accuracy of the method turned out to be significantly lower than its sensitivity) is affected by the orientation error of the OPQM, which is insignificant in magnitude at small rotation angles of the geomagnetic field. The contributors to this orientation error are the multi-component resonance line and light shifts affecting the resonance frequency [13].

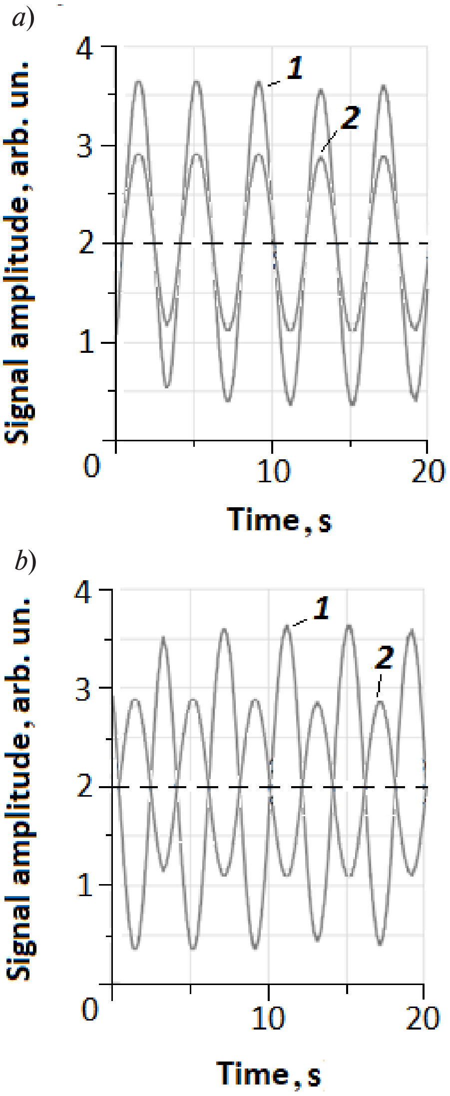

Fig. 4. Waveforms of observed signals at zero (*a*) and 180° (*b*) phase shift between them with reversed direction of the magnetic field
Alternating signal of synchronous detector (*1*) and signal modulating the magnetic field along the *Z* axis (*2*) were observed

The accuracy of determining the direction of the geomagnetic field by the developed method is also affected by the above-mentioned orientation dependence of the radio-optical resonance signal. Knowing that the amplitude of the resonance signal is proportional to $\cos^4\theta$, we can obtain an estimate of the angle measurement error. For the maximum value of the measured angle, equal to °6, the decrease in the resonance signal amplitude was approximately 2.2%. The resulting measurement error due to the orientation dependence of the resonance signal can be eliminated in measurements of the rotation angle of the geomagnetic field if the frequency of the low-frequency generator of the OPQM is automatically adjusted to the resonance frequency instead of the signal at the output of the synchronous detector. In this case, the accuracy of determining the orientation of the geomagnetic field depends on the amplitude ratio of resonant signal and noise.

In this study, the developed method for determining the direction of the geomagnetic field in the $Z'OX'$ plane was tested for the case of a modulating magnetic field applied along the X axis. To measure the orientation of the geomagnetic field in the $Z'OY'$ plane, it is necessary to generated a modulating field along the Y axis.

Measuring the required direction by the considered method, we were faced with difficulties in determining the sign of the geomagnetic field vector projection on the Z axis. The reason for this is that OPQM measures the magnitude of the magnetic field vector. To solve the problem, we used a modulating magnetic field along this axis (see Fig. 1). The frequency of the modulating field was 240 MHz, and the amplitude was chosen so that the signal visibility of the synchronous detector was sufficient against the background noise. After the given signal was measured at the modulation frequency of the magnetic field by the Z coils of the magnetic system, the direction of the magnetic field under study was reversed.

The phase of the signal at the output of the synchronous detector was recorded. Its variation amounted to 180°. The signal of the synchronous detector measured with reversed direction of the magnetic field is shown in Fig. 4.

The magnitude of the geomagnetic field should be measured simultaneously with its direction to correct the frequency of onboard RAC. If the M_Z-type OPQM is used for these purposes, it may prove necessary to adjust the frequency of the low-frequency generator of the OPQM to the frequency of radio-optical resonance at time points corresponding to point *B* on the signal of the synchronous detector (see Fig. 2).

Conclusion

We developed a method for measuring the direction of the magnetic field using an optically pumped quantum M_z-type magnetometer (OPQM). The readings of this magnetometer were used to adjust the frequency of an onboard small-sized rubidium atomic clock.

Analysis of the obtained results allows to draw the following conclusions.

1. A quantum M_Z-type magnetometer can be used to adjust the frequency of these small-sized clocks exposed to the geomagnetic field varying in direction and magnitude.

2. Experimental testing of the proposed method for measuring the direction of the magnetic field showed high sensitivity of the amplitude difference in the signal components of the synchronous detector (see Fig. 2, points *A* and *C*) to the variation in the angle between the optical axis of the OPQM and the magnetic field considered, amounting to $7.3 \cdot 10^{-4}$° in the range of °6–0. It was found that the experimental accuracy of angle measurement is limited by the accuracy of setting the rotation angle of the OPQM relative to a fixed laboratory coordinate system. Its value turned out to be better than °0.25±. The influence of the orientation dependence of the resonance signal amplitude on the accuracy of the method can be eliminated if the frequency of the low-frequency generator of the OPQM is automatically adjusted to the frequency of radio-optical resonance.

3. The method proposed in the paper for measuring the direction of the magnetic field can be used for scenarios where angles are measured in a range limited only by the ‘dead zones’ of the OPQM.

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