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EFFECT OF SHIELD MAGNETIZATION ON VARIATIONS IN THE FREQUENCY OF ONBOARD RUBIDIUM ATOMIC CLOCKS

S. V. Ermak✉, *V. V. Semenov*, *A. A. Baranov*,
M. A. Rogatin, *M. V. Sergeeva*

Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia

✉ serge_ermak@mail.ru

Abstract. In the paper, the results of a study of the influence of the magnetic shield magnetization on the relative frequency instability of small-sized rubidium atomic clocks have been presented. The atomic clock was placed in a rotating magnetic field, simulating the magnetic situation in the orbit of a navigation satellite, moving in orbit and rotating around its own axis. The magnetization of the magnetic shield of the atomic clock was shown to increase its shielding factor. This result makes it possible to significantly reduce the influence of geomagnetic field variations on the frequency stability of onboard atomic clocks.

Keywords: atomic clock, magnetic field, magnetic shield, Allan deviation, navigation satellite

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ВЛИЯНИЕ НАМАГНИЧИВАНИЯ ЭКРАНА НА ВАРИАЦИИ ЧАСТОТЫ БОРТОВЫХ АТОМНЫХ ЧАСОВ

С. В. Ермак✉, *В. В. Семенов*, *А. А. Баранов*,
М. А. Рогатин, *М. В. Сергеева*

Санкт-Петербургский политехнический университет Петра Великого,
Санкт-Петербург, Россия

✉ serge_ermak@mail.ru

Аннотация. В работе представлены результаты исследования влияния намагничивания магнитного экрана малогабаритных рубидиевых атомных часов на относительную нестабильность их частоты. Атомные часы размещались во вращающемся магнитном поле, имитирующем магнитную обстановку на орбите навигационного спутника, возникающую как при его орбитальном движении, так и в результате вращения спутника вокруг собственной оси. Показано, что намагничивание магнитного экрана атомных часов увеличивает его коэффициент экранирования, что позволяет существенно снизить влияние вариаций геомагнитного поля на стабильность частоты атомных часов бортового базирования.

Ключевые слова: атомные часы, магнитное поле, магнитный экран, девиация Аллана, навигационный спутник

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Introduction

As a mobile charge carrier moves in a geomagnetic field (for example, a navigation satellite in near-Earth orbit), the geomagnetic field vector changes its direction relative to the optical axis of the onboard rubidium atomic clock (AC), which generates their orientation error due to the difference in the longitudinal and transverse shielding factors of the magnetic shield [1]. The magnitude of this error is determined by the quadratic term in the dependence expressing the relationship between the resonant frequency of the atoms of the working substance ν and the strength of the working magnetic field H inside the shield. This relationship is expressed as [2]:

$$\nu = \nu_0 + \beta H^2, \tag{1}$$

where ν_0 is the frequency of the atomic transition, $\nu_0 = 6.835 \cdot 10^6$ Hz; β is the scale factor, $\beta = 0.0905$ Hz·m²/A² for rubidium-87 atoms.

It follows from expression (1) that relative instability of the AC frequency at the level of 10^{-12} for $H = 8$ A/m and operation in a geomagnetic field on the Earth's surface ($H_E = 40$ A/m) can be achieved for a rubidium-87 AC with the shielding factor of the magnetic shield exceeding 10^4. However, as the direct experiment described in [3] shows, the longitudinal (directed along the optical axis of the AC) shielding factor of the magnetic shield in rubidium AC is orders of magnitude less than this value (due to the presence of seams and holes in the shields). For example, according to [1], the ratio of the longitudinal to transverse shielding factors for miniature AC with a volume of less than 3 cm³ reaches 10^4. The absolute values of these coefficients are determined not only by the size and shape of the magnetic shield, but also by its magnetic permeability. The value of this parameter, in turn, significantly depends on the external magnetic field, which determines the change in the shielding properties of the magnetic shield during its magnetization.

The goal of this paper was to experimentally study the effect of magnetization of a magnetic shield by an external magnetic field on the relative short-term frequency instability of small-sized rubidium atomic clocks under an alternating magnetic field simulating the geomagnetic situation in the orbit of navigation satellites.

Experimental procedure and results

The experimental evaluation of AC frequency shifts under optical pumping of rubidium vapor was carried out in a rotating magnetic field with a setup similar to the one whose block diagram and measurement technique were described in detail in [3, 4].

The setup contained a magnetic system comprising three pairs of Helmholtz rings, with small-sized rubidium AC placed in the center (their linear dimensions were 75 × 75 × 35 mm), connected to a frequency detector. A working magnetic field with a strength of about 8 A/m was generated inside the magnetic shield. A rotating magnetic field H_r was generated in the plane of the optical axis of the AC; its amplitude was selected in the range of geomagnetic field strengths (in A/m) in the orbit of satellite navigation systems. Relative variations in the frequency of the AC were measured using a frequency comparator; a stationary configuration of the rubidium AC whose relative instability was 10^{-13} per 100 s was used as a reference. In addition to the relative variations in the frequency of the AC, the dependence of the Allan deviation on the measurement time was recorded.

At the preliminary stage, we obtained an experimental estimate of the longitudinal shielding factor of the AC magnetic shield. For this purpose, compensation of the vertical component of the Earth's magnetic field, amounting to approximately 36 A/m, was performed using a magnetic system. The longitudinal factor of AC shielding was estimated in the presence of a residual horizontal component of the Earth's magnetic field by measuring relative frequency shifts of the AC at the strengths of the magnetic field of 40 and 56 A/m along the optical axis as well as with a sequential change of its polarity. Fig. 1 shows the relative frequency shifts of the AC (the difference Δν between the frequency standard and the AC considered) measured in the presence of an external magnetic field H.

The obtained values of the relative frequency shift of the AC (see Fig. 1) allowed to estimate the weighted average longitudinal shielding factor, amounting to about 600. The small-sized rubidium AC selected for the study, which, as measurements showed, had a low longitudinal shielding factor, made it possible to better illustrate the influence of the external magnetizing field H_{ex} on the shielding properties of the magnetic shield.

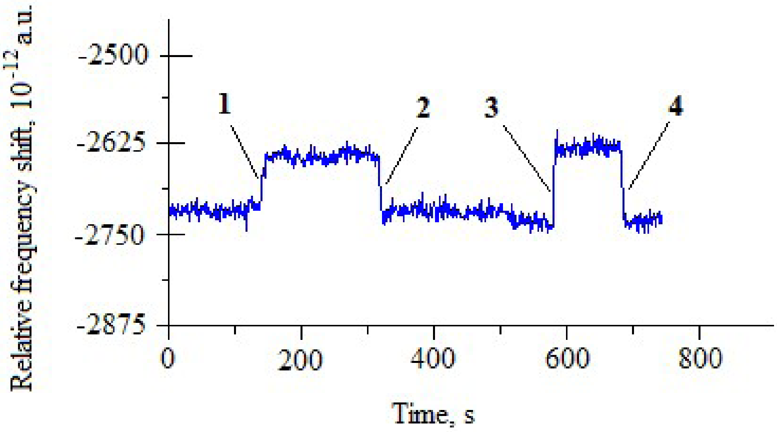

Fig. 1. Relative frequency shifts Δν of the atomic clock under an external magnetic field H, A/m: −40 (*1*), +40 (*2*), −56 (*3*), +56 (*4*). Corresponding shifts Δν, 10^{-11}: +8 (*1*), −8 (*2*), +10 (*3*), −10 (*4*)

As noted above, the influence of the external magnetic field strength on the shielding properties of magnetic shields is due to a change in the magnetic permeability of their material [5]. For this reason, the choice of material for layers of multilayer magnetic shields (especially the material of the outer layer) of the AC should take into account the magnetic environment where it is planned to use the AC. For example, the magnetic field strength in the orbit of navigation satellites (altitude is about 20,000 km) turns out to be an order of magnitude less than the magnetic field strength on the Earth's surface [6].

As satellite navigation systems travel in orbit, a change in the orientation of the geomagnetic field vector relative to the optical axis of the onboard AC occurs automatically every half-period of the satellite's rotation in orbit, i.e., in the time instants when the orientation error of the AC is manifested to the greatest extent. The half-life of the satellite's rotation lies in the range of values from 5 to 7 hours for different satellite navigation systems, which does not exclude the inversion of the geomagnetic field vector with respect to the optical axis of the AC in shorter time intervals. A similar situation arises under rotation of the satellite relative to its own axis, which causes the corresponding orientation error of the onboard AC.

This particular rotation case was investigated in experiments with AC under conditions simulating the magnetic environment in the satellite orbit at a fixed angular rotation frequency

f_m = 0.01 Hz. The variation in the field generated by the magnetic system was carried out by a sinusoidal law with an amplitude H_r = 2.5 A/m in the plane of the optical axis of the AC. The degree of influence of the rotating magnetic field on the frequency of the AC was determined due to the Allan deviation property, which reaches a maximum value during the measurement time equal to the half-period of the rotating magnetic field [1].

In the absence of an external rotating magnetic field (H_r = 0), the Allan deviation decreased in direct proportion to the square root of the measurement time (by the law $\tau^{1/2}$), which is characteristic for rubidium AC with stationary position.

Fig. 2 shows the dependences of Allan deviations of the atomic clock frequency on the measurement time in the range of 1–100 s. This time range was chosen to reduce the influence of flicker processes on the measurement results. In this case, the Allan deviation was $1.6{\cdot}10^{-12}$ at a measurement time of 50 s.

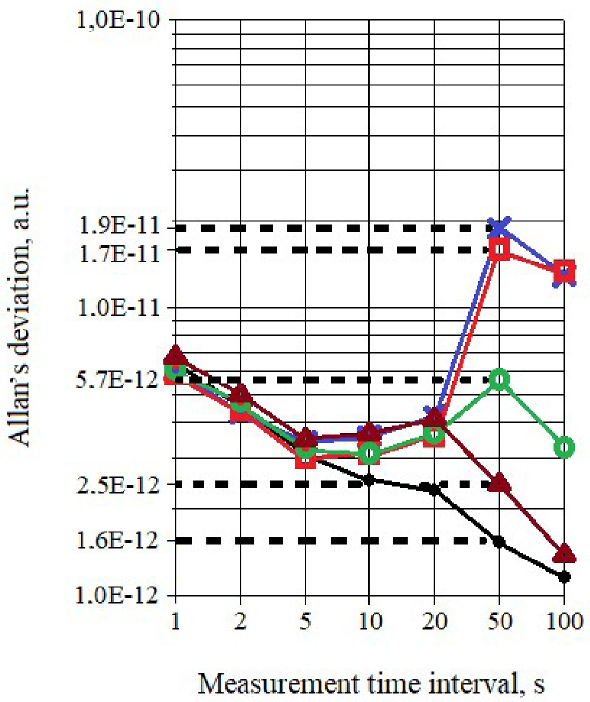

Fig. 2. Experimental dependences of Allan deviations (symbols) on the measurement time, with varying values of the external rotating (H_r) and constant magnetizing (H_{ex}) fields (in A/m): $H_r = H_{ex} = 0$ (black curve); H_r = 2.5 (all other curves); H_{ex} = 0 (black and blue curves), 4.2 (red curve), 8.5 (green), 12.8 (brown). (see Table)

The introduction of an external rotating magnetic field led to a significant change in the nature of the dependence of the Allan deviation on the measurement time: the deviation increased to the level of $1.9{\cdot}10^{-11}$ at τ = 50 s. All three components of the Earth's magnetic field were pre-compensated to preserve experimental validity. A rotating field H_r was applied in the first experiment, and there was no constant magnetizing field H_{ex} oriented along the optical axis of the AC (see Fig. 2, crosses and blue lines).

Fig. 2 also shows the results of subsequent experiments: the dependence of the Allan deviation of the AC frequency on the measurement time in the presence of two magnetic fields: H_r and H_{ex}, with the latter amounting to 4.2, 8.5 and 12.8 A/m, marked with different symbols and lines of different colors. The Allan deviation for the averaging time of 50 seconds was (10^{-12}): 17.0, 5.7 and 2.5, respectively. A certain increase in the value of the Allan deviation for a measurement time of 20 s is due to the peculiarities of the operation of the AC thermostat.

Table

Dependences of Allan deviation on range of measurement time τ at fixed amplitude of external rotating magnetic field and different values of constant magnetizing field Hex (see Fig. 2)

τ, s	Allan deviation, 10^{-12}, for H_{ex} (in A/m)			
	0.0	4.2	8.5	12.8
1	6.0	5.9	6.1	6.8
2	4.3	4.5	4.8	5.0
5	3.4	3.0	3.3	3.5
10	3.5	3.2	3.2	3.7
20	4.2	3.6	3.7	4.1
50	19.0	17.0	5.7	2.5
100	13.0	14.0	3.3	1.4

Note. The amplitude of the rotating external magnetic field H_r = 2.5 A/m.

Table compares the obtained values of the Allan deviation for the dependences shown in Fig. 2.

As follows from the above experimental data, magnetization of the magnetic shield can significantly increase the shielding factor of the AC, while the suppression of magnetic variations is manifested to a greater extent with a decrease in the intensity of the alternating magnetic field H_r, simulating the magnetic situation in the orbit of a navigation satellite. According to the data given in Table, the variations in the external magnetic field were suppressed by about 8 times in the magnetized shield of small-sized rubidium AC at an averaging time of 50 s and at H_r = 2.5 A/m.

If the magnetization field is oriented perpendicular to the optical axis of the AC, the order of Allan deviations and the dynamics of their variations with increasing averaging time are similar to the case of longitudinal orientation of the magnetizing field.

The dependence of the Allan deviation on the strength of the magnetizing field H_{ex} is notable in that it is similar to the initial segment of the curve expressing the dependence of magnetic permeability of the ferromagnetic material (permalloy) used in the magnetic shield on H_{ex} [5]. Interestingly, the magnetic field strength H_{ex} = 12.8 A/m, at which the stability of the AC can be increased by about 8 times, corresponds to a region where the magnetic permeability μ is significantly (by orders of magnitude) higher than its initial value corresponding to zero magnetic field H_{ex}.

Conclusion

Analysis of the results obtained in the experimental study allows to draw the following conclusions:

1. The shielding factor of the magnetic shield significantly depends on the magnitude of the external magnetic field where the small-sized rubidium AC is located. The obtained value of the longitudinal shielding factor increased by about 8 times for the magnetizing field strength of 12.8 A/m and the amplitude of the external rotating magnetic field of 2.5 A/m, corresponding to the geomagnetic field in the orbit of the navigation satellite.

2. The effect of increasing the shielding factor of the magnetic shield is practically independent of the direction of the applied constant magnetizing field Hex (relative to the optical axis of the AC), suggesting an isotropic nature of the influence of this field on the stability of the measured frequency.

3. Exceeding the threshold value of the external magnetic field strength (several to tens of A /m) corresponding to the maximum value of the magnetic permeability of the magnetic shield material may lead to a decrease in its shielding factor, and, consequently, to a deterioration in the stability of the AC frequency.

The experience accumulated in experiments with industrial small-sized rubidium AC can be valuable for developing rubidium AC for small satellites [7] as well as for a wide class of AC using magnetic shielding from an external magnetic field. Such devices include small-sized hydrogen masers [8], miniature AC based on the effect of coherent population trapping [9] as well as atomic-beam quantum frequency standards [10].

Predicting the optimal value of the magnetizing field strength in these devices is a rather complex problem, sing a number of factors have to be taken into account (type of AC, working magnetic field, material, shape and size of the shield).

Therefore, it is preferable to select the strength of the constant magnetizing field Hex empirically for each specific case, which was accomplished in this paper.

REFERENCES

1. **Donley E. A., Hodby E., Hollberg L., Kitching J.,** Demonstration of high-performance compact magnetic shields for chip-scale atomic devices, Rev. Sci. Instrum. 78 (8) (2007) 083102.
2. **Riehle F.,** Frequency standards: Basics and applications, Wiley-VCH, Weinheim, 2005.
3. **Lozov R. K., Ermak S. V., Semenov V. V., Ermak O. V.,** Modeling the geomagnetic field influence on the atomic clock accuracy of the satellite navigation systems on-board equipment, Journal Radioengineering. 83 (12 (20)) (2019) 32–37 (in Russian).
4. **Ermak S., Semenov V.,** The influence of the operation magnetic field modulation on the short-term frequency stability of rubidium atomic clock at magnetic gradient, Proc. 2022 Int. Conf. on Electrical Engineering and Photonics (EExPolytech), 20–21 Oct., St. Petersburg (2022) 347–350.
5. **Chikazumi S.,** Physics of ferromagnetism, Oxford University Press, Inc., Int. Series of monographs in Physics, Vol. 94. New York, 1997.
6. World magnetic model 2020 calculator, URL: http://www.geomag.bgs.ac.uk/data_service/models_compass/wmm_calc.html (Access data: 16.05.2023).
7. **Dinkelaker A. N., Kaparthy A., Reher S. E., Krutzik M.,** Optical quantum technologies for compact rubidium vapor-cell frequency standards in space using small satellites, J. Br. Interplanet. Soc. 72 (3) (2019) 74–82.
8. **Sysoyev V. P., Samokhvalov Yu. S., Vasiliev V. I., et al.,** Compact active hydrogen frequency standard, Al'manac of Modern Metrology. 4 (32) (2022) 8–17 (in Russian).
9. **Palchikov V. G.,** Sverkh-miniatyurnyy kvantovyy standart chastoty na KPN effekte [Subminiature quantum frequency standard based on the CPT effect], Abstracts of the Tenth All-Russian Conference with International Participation: "Fundamental and Applied Coordinate-Time and Navigation Support" (CTNS-2023), Apr. 17–21, 2023, St. Petersburg (2023) 141–142 (in Russian).
10. **Xie W., Wang Q., He X., et al.,** Frequency instability of a miniature optically pumped cesium-beam atomic frequency standard, Rev. Sci. Instrum. 91 (7) (2020) 074705.

СПИСОК ЛИТЕРАТУРЫ

1. **Donley E. A., Hodby E., Hollberg L., Kitching J.** Demonstration of high-performance compact magnetic shields for chip-scale atomic devices // Review of Scientific Instruments. 2007. Vol. 78. No. 8. P. 083102.
2. **Риле Ф.** Стандарты частоты. Принципы и приложения. Пер. с англ. М.: Физматлит, 2009. 512 с.
3. **Лозов Р. К, Ермак С. В., Семенов В. В., Ермак О. В.** Моделирование влияния геомагнитного поля на точность атомных часов бортовой аппаратуры систем спутниковой навигации // Радиотехника. 2019. Т. 83. № 12 (20). С. 32–37.
4. **Ermak S., Semenov V.** The influence of the operation magnetic field modulation on the short-term frequency stability of rubidium atomic clock at magnetic gradient // Proceedings of 2022 International Conference on Electrical Engineering and Photonics (EExPolytech), 20–21 October, 2022. St. Petersburg. Pp. 347–350.

5. **Тикадзуми С.** Физика ферромагнетизма. Магнитные характеристики и практические применения. М.: Мир, 1987. 420 с.

6. World magnetic model 2020 calculator. Режим доступа: http://www.geomag.bgs.ac.uk/data_service/models_compass/wmm_calc.html (Дата обращения: 16.05.2023).

7. **Dinkelaker A. N., Kaparthy A., Reher S. E., Krutzik M.** Optical quantum technologies for compact rubidium vapor-cell frequency standards in space using small satellites // Journal of the British Interplanetary Society. 2019. Vol. 72. No. 3. Pp. 74–82.

8. **Сысоев В. П., Самохвалов Ю. С., Васильев В. И., Нагирный В. П., Нестеров Н. И., Парехин Д. А., Овчинников С. Н.** Малогабаритный активный водородный стандарт частоты // Альманах современной метрологии. 2022. № 4 (32). С. 8–17.

9. **Пальчиков В. Г.** Сверхминиатюрный квантовый стандарт частоты на КПН-эффекте // Тезисы докладов Десятой всероссийской конференции с международным участием: «Фундаментальное и прикладное координатно-временное и навигационное обеспечение» (КВНО-2023), 17–21 апреля 2023 г., Санкт-Петербург. С. 141–142.

10. **Xie W., Wang Q., He X., Chen N., Xiong Z., Fang S., Qi X., Chen X.** Frequency instability of a miniature optically pumped cesium-beam atomic frequency standard // Review of Scientific Instruments. 2020. Vol. 91. No. 7. P. 074705.

THE AUTHORS

ERMAK Sergey V.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
ermak_sv@spbstu.ru
ORCID: 0000-0002-6210-4003

SEMENOV Vladimir V.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
vladimir_semenov@mail.ru
ORCID: 0000-0003-0346-8349

BARANOV Alexey A.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
79111700994@ya.ru
ORCID: 0000-0001-7095-7981

ROGATIN Maxim A.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
maxim228rog@mail.ru
ORCID: 0009-0009-6180-6538

SERGEEVA Maria V.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
mamarvel2001@mail.ru
ORCID: 0009-0005-8838-6845

СВЕДЕНИЯ ОБ АВТОРАХ

ЕРМАК Сергей Викторович – *доктор физико-математических наук, профессор Высшей школы прикладной физики и космических технологий Санкт-Петербургского политехнического университета Петра Великого, Санкт-Петербург, Россия.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
ermak_sv@spbstu.ru
ORCID: 0000-0002-6210-4003

СЕМЕНОВ Владимир Васильевич – *доктор физико-математических наук, ведущий научный сотрудник Высшей школы прикладной физики и космических технологий Санкт-Петербургского политехнического университета Петра Великого, Санкт-Петербург, Россия.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
vladimir_semenov@mail.ru
ORCID: 0000-0003-0346-8349

БАРАНОВ Алексей Анатольевич – *кандидат физико-математических наук, научный сотрудник Высшей школы прикладной физики и космических технологий Санкт-Петербургского политехнического университета Петра Великого, Санкт-Петербург, Россия.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
79111700994@ya.ru
ORCID: 0000-0001-7095-7981

РОГАТИН Максим Александрович – *инженер Высшей школы прикладной физики и космических технологий Санкт-Петербургского политехнического университета Петра Великого, Санкт-Петербург, Россия.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
maxim228rog@mail.ru
ORCID: 0009-0009-6180-6538

СЕРГЕЕВА Мария Вячеславовна – *инженер Высшей школы прикладной физики и космических технологий Санкт-Петербургского политехнического университета Петра Великого, Санкт-Петербург, Россия.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
mamarvel2001@mail.ru
ORCID: 0009-0005-8838-6845

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