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Improving metrological characteristics of a frequency standard based on cesium atoms

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Abstract. The necessity of constant modernization of quantum frequency standards (QFS) - atomic clocks, which are used in satellite navigation and telecommunication systems to solve new problems in terms of the speed of transmission of large amounts of information, etc., is substantiated. It is noted that among all atomic clocks, cesium QFSs occupy a special place. These standards are the primary frequency reference upon which the international time scale is based. The main goal of all QFS upgrades is to improve the metrological characteristics. In the case of its use on moving objects, its dimensions, weight and power consumption also become important characteristics. The article presents one of the options for reducing the influence of negative factors on the stability of the QFS. The problem of modernizing the cesium frequency standard by including a device for monitoring and stabilizing the temperature regime of its operation is considered.

Keywords: time scale, stabilization, automatic frequency control, frequency stabilizer, cesium frequency standard, operational amplifier, atomic beam tube

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Материалы конференции
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Улучшение метрологических характеристик стандарта частоты на атомах цезия

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Аннотация. Обоснована необходимость постоянной модернизации квантовых стандартов частоты (КСЧ) – атомных часов, которые используются в спутниковых навигационных и телекоммуникационных системах. Основной целью всех модернизаций КСЧ является улучшение метрологических характеристик. В случае применения его на подвижных объектах, также важными характеристиками становятся его габариты, вес и энергопотребление. Представлен один из вариантов снижения влияния негативных факторов на стабильность работы КСЧ. Рассмотрена задача модернизации цезиевого стандарта частоты посредством включения в него устройства контроля и стабилизации температурного режима его функционирования.

Ключевые слова: шкала времени, стабилизация, автоматическая подстройка частоты, стабилизатор частоты, цезиевый стандарт частоты, операционный усилитель, атомно-лучевая трубка

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Introduction

The contribution of methods for accurate measurements of frequency and time in the development of world science, technology, and economics is enormous [1–7]. As an example, we can cite global communication networks, satellite navigation systems (SNS), coordinated work using is impossible without stable frequency sources [7–13]. Frequency standards are used in GLONASS and GPS systems as synchronizing generators [7–9, 14–19]. The equipment is widely used in activities, various requirements for a high and stable frequency of master oscillators [1–7, 14–19, 20–27]. The implementation of available satellite navigation systems has a number of increased frequencies, which manifest themselves both with the observed environment and with the autonomy of the object itself. In spacecraft for remote sensing of the Earth, the quantum frequency standard plays a key role in the time scale for controlling the spacecraft and transmitting information to the ground [1–3, 7–10, 25–28].

One of the main factors affecting the accuracy is the system errors introduced by the equipment of the space complex. The errors associated with the operation of the onboard equipment of the satellite and the GNSS ground control complex are mainly due to the imperfection of the time-frequency and ephemeris support. (Satellite ephemeris - its predicted coordinates and motion parameters at a fixed point in time). Ephemeris-time support includes a set of hardware and software tools that measure the current parameters of the orbital motion of spacecraft, verify, correct and phasing onboard time scales, process measurement results and calculate ephemeris transmitted to consumers [25-29]. The accuracy of the GLONASS system at the moment is about 0.4 – 0.5 m. Such accuracy values for a number of areas are no longer enough. One way to improve the accuracy of geolocation is to improve the synchronization of the time scales of the satellites of the navigation system. So, if long-term instability of the master generators in the system is ensured at the level of $3{\cdot}10^{-14}$, then the error in matching satellite time scales will be 10 nanoseconds, which can reduce the geolocation error to 0.2 – 0.3 m. Therefore, the modernization of existing and the development of new highly stable sources of electromagnetic oscillations are one of the urgent tasks of improving the functional properties of geolocation satellite systems.

In this paper, we consider the problem of modernizing the cesium frequency standard by including in it a device for monitoring and stabilizing the temperature regime of its operation.

Materials and Methods

The error in measuring the delays between the clock signals of spacecraft (SC) at the receiving point, which determines the accuracy of calculating the coordinates of the object, is determined by the error in the formation of time scales and the frequency stability of the reference oscillators (RO). An analysis of the requirements for the accuracy characteristics of the onboard synchronizing device shows that their implementation is possible only when quantum frequency standards are used as reference generators, operating in a continuous mode throughout the entire life of the spacecraft [1–3, 7–10, 25–30].

The highest frequency stability is achieved in quantum frequency standards, which operate on the basis of the phenomenon of selective (resonant) absorption and emission of electromagnetic field energy by quantum systems (atoms, molecules, ions). Depending on the quantum objects used, QFS are called atomic or molecular. Along with QFS, quartz standards are also used, the oscillation frequency of which is determined by the natural frequency of the quartz resonator. The Cs-133 cesium frequency standard shown in Figure 1 is the primary frequency standard because the national time, frequency, and national time scale calibration schemes operate on the basis of the high-frequency energy transition in the Cs-133 atom.

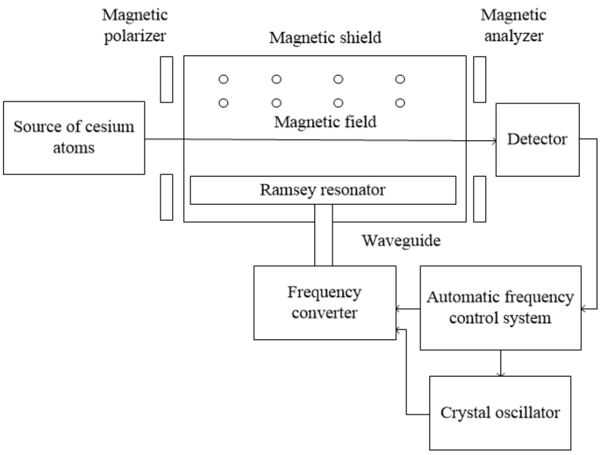

Fig. 1. The design of the cesium frequency standard

Required data for new applications AVAR < $1 \cdot 10^{-13}$ daily instability is not provided by the existing FS. To improve the characteristics of the FS, it is necessary to reduce the influence of a number of destabilizing factors, first of all, to reduce the instability of the magnetic field in the region of interaction between atoms and the electromagnetic field (long-term drift of the current source, its temperature dependence, the influence of an external magnetic field). This problem can be solved not only by creating new types of FSs, but also by modernizing existing ones. At the same time, a reduction in weight and dimensions, a reduction in energy consumption, and an improvement in their metrological characteristics can be achieved at the same time.

Traditionally, AFC circuits (Fig. 2) include a voltage-controlled oscillator, a frequency discriminator, and a reference signal source. In the AFC system of the quantum frequency standard (Fig. 4), the source of the reference signal is a quartz oscillator, and the control device acts as a frequency discriminator.

The signal from the ABT output is fed to the input of the automatic frequency control (AFC) system, which contains a matching amplifier (MU), a control device (CD), a crystal oscillator control device (CDXO) and a digital-to-analog converter (DAC).

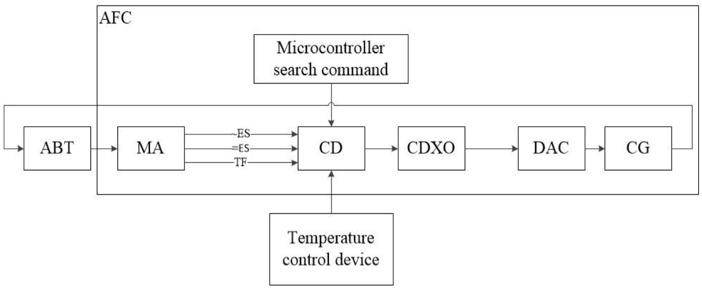

Fig. 2. Scheme of the AFC of the quantum frequency standard: ABT - atomic beam tube, MA - matching amplifier, CD - control device, QO - quartz oscillator, ES - error signal

The ABT output signal contains a constant component and a variable that characterizes the deviation of the signal from the average value of the ES components. This signal c with the help of a control device (CD) is converted into a control voltage supplied to the varicap fine-tuning the frequency of the CDXO. The AFC system generates a control voltage of magnitude and polarity, which allow compensating for the deviation of the actual frequency value (AFV) of the CG relative to the value corresponding to the frequency of the ABT atomic transition (5 MHz).

Preliminary setting of the CG frequency to the value at which the frequency of the microwave signal is close to the frequency of the atomic transition is carried out automatically.

The output voltage of the UUKG is supplied to the varicap of the CG frequency adjustment. Changing the voltage on the varicap CG leads to a change in the frequency of the CG and, consequently, to a change in the frequency of the microwave signal at the input of the ABT, which in turn leads to a change in the voltage at the output of the ABT in accordance with the resonance curve. The ambient temperature determines the voltage supplied to the control device in the automatic frequency control circuit (Fig. 2), and, consequently, the voltage supplied to the crystal oscillator. This leads to a mismatch between the frequencies of the microwave signal and the atomic transition, which leads to errors in the matching of satellite time scales. Moreover, this process occurs regardless of whether the QFS uses highly stable laser radiation [38–42] or a magnetic field [43, 44] to create a population inversion in ABT.

Results and Discussion

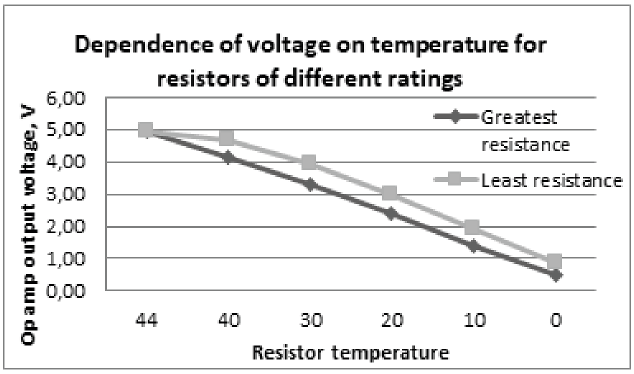

Fig. 3. Dependence of voltage on temperature for resistors of different ratings.

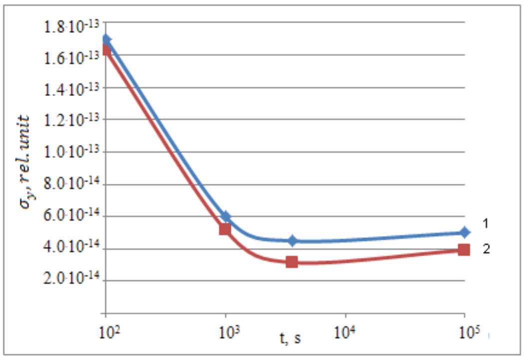

Fig. 4. Plot of the Allan variance σ_y versus time t. Graphs 1 and 2 correspond to the previously used AFC system in the QSC by us, respectively

The following principle is implemented in the system developed by us. The ambient temperature directly affects the resistance of the thermistor and the output signal of the operational amplifier (op-amp), which is located in the automatic frequency control system. Depending on the design of the resistor, there is a different change in voltage with temperature. This fact has not previously been given due attention. It was considered that dependence U(T) is linear. Our research has shown that this is not the case. On (Fig. 3) shows for example two dependencies for resistors of different ratings.

The result obtained shows that if the U(T) dependence becomes non-linear, an additional error appears. In the developed new AFC system, this error is eliminated. On (Fig. 4) shows the dependence of the change in the values of the Allan variance $\sigma_{y(\tau)}$ on time τ for the modernized and previous QFS designs.

The results obtained show an improvement in the Allan variance σ(τ) by 5%. Studies of the operation of the QFS were carried out for 12 days in a temperature chamber. As a result of the research, it was found that the temperature coefficient of the frequency of the standard decreased by 1.35 times.

Conclusion

The conducted experiments have shown the efficiency of using automatic frequency control systems with the thermal compensation device developed by us. As a result of using the device for compensating the temperature coefficient of frequency, the temperature sensitivity of the AFC system decreased by a factor of 1.3, which improves the synchronization of satellite time scales for spacecraft with Earth remote sensing systems.

REFERENCES

1. **Riehle F.,** Frequency standard. Basic and applications, WILEY-VCH Verlag CmbH Co. KGaA: New-York, 2008.

2. **Almat N., Pellaton M., Moreno W., et al.,** Rb vapor-cell clock demonstration with a frequency-doubled telecom laser, Appl. Opt. 57 (2008) 4707.

3. **Bandi T., Affolderbach C., Calosso C. E., et al.,** High-performance aser-pumped rubidium frequency standard for satellite navigation, Electron. Lett. 47 (2001) 698–699.

4. **Myazin N. S., Dudkin V. I., Grebenikova N. M., Davydov R. V., Podstrigaev A. S.,** Fiber - optical system for governance and control of work for nuclear power stations of low power, Lecture Notes in Computer Science. 11660 (2019) 744–756.

5. **Semenov V. V., Nikiforov N. F., Ermak S. V.,** Calculation of stationary magnetic resonance signal in optically oriented atoms induced by a sequence of radio pulses, Soviet journal of Communications

Technology and Electronics. 36 (4) (1991) 59–63.

6. **Davydov R., Antonov V., Moroz A.,** Parameter Control System for a Nuclear Power Plant Based on Fiber-Optic Sensors and Communication Lines, In: IEEE International Conference on Electrical Engineering and Photonics (EExPolytech), Saint-Petersburg, Russia, 13-15 October 2019. vol. 8906791 (2019) 295–297.

7. **Petrov A. A., Shabanov V. E., Zalyotov D. V., Bulyanitsa A. L., Shapovalov D. V.,** Modernization of the frequency synthesizer of cesium atomic clock, IEEE International Conference on Electrical Engineering and Photonics, EExPolytech 2018, Saint-Petersburg, October 2018. vol. 8564389 (2018) 52–55.

8. **Lukashev N. A., Davydov R. V., Glinushkin A. P., Rud' V. Y.,** Improving characteristics of microwave frequency standard on Hg-199 ions for telecommunication systems, Journal of Physics: Conference Series. 1326 (1) (2019) 012046.

9. **Lukashev N. A., Moroz A. V.,** Compact microwave frequency standard on Hg-199 ions for navigation systems, Journal of Physics: Conference Series. 1236 (1) (2019) 012068.

10. **Tarasov A. D., Milder O. B.,** Gradation traectories as an analog of gradation curves in the metric cie lab space discrete approache, Computer Optics. 43 (1) (2018) 104–110.

11. **Kuzmin M. S., Rogov S. A.,** On the use of a multi-raster input of one-dimensional signals in two-dimensional optical correlators, Computer Optics. 43 (3) (2019) 391–396.

12. **Lukashev N. A., Petrov A. A., Grebenikova N. M.,** Improving performance of quantum frequency standard with laser pumping, Proceedings of 18th International conference of Laser Optics ICLO-2018 Saint-Petersburg, 2018, vol. 8435889, (2018) 271.

13. **Valov A. P., Arinushkina K. G., Davydov V. V.,** The use of digital data processing to improve the metrological characteristics of the rubidium frequency standard, Journal of Physics: Conference Series. 2086 (1) (2021) 012070.

14. **Arinushkina K. G., Valov A. P., Davydov V. V.,** Digital processing of optical signals in the frequency standard based in rubidium atoms - 87, In: Proceedings of ITNT 2021 - 7th IEEE International Conference on Information Technology and Nanotechnology, 2021 Samara, Russia, 20-24 September 2021. vol. 44026298 (2021) 44–49.

15. **Petrov A. A.,** Improvement frequency stability of caesium atomic clock for satellite communication system, Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)/ 9247 (2015) 739–744.

16. **Lukashev N. A., Davydov V. V., Glinushkin A. P., Rud V. Yu., Lukyantsev V. S.,** Microwave low mass-dimensional frequency standard on Hg- 199 ions, Journal of Physics: Conference Series. 1410 (1) (2019) 012211.

17. **Petrov A. A., Grebenikova N. M.,** Some Directions of Quantum Frequency Standard Modernization for Telecommunication Systems, Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics). 11118 LNCS (2018) 641–648.

18. **Pashev G. P.,** Optimal algorithm for synchronizing the quantum clock timeline, Measurement Techniques. 59(6) (2016) 1005–1012.

19. **Grevtseva A., Rud V.,** Method of processing velocity increase of measuring results of quantum frequency standard parameters for information transfer velocity increase in satellite communication systems, CEUR Workshop Proceedings. 2667 (2020) 15–18.

20. **Mihov E. D., Nepomnyashchiy O. V.,** Selecting informative variables in the identification problem Journal of Siberian Federal University - Mathematics and Physics. 9 (4) (2016) 473–480.

21. **Ryzhenko I. N., Lutsenko A. E., Varygin O. G., Nepomnyashchiy O. V.,** Carrier compensation mode implementation in satellite communication channels. In: Proceedings of 2019 International Siberian Conference on Control and Communications, SIBCON 2019, vol. 8729665 (2019) 23–29.

22. **Fadeenko V. B., Pchelkin G. A., Davydov V. V., Rud V. Yu.,** Features of the transmission of microwave signals in the range of 8-12 GHz in the maritime radar station over fiber-optic communication line, Journal of Physics: Conference Series. 1400 (4) (2019) 044010.

23. **Petrov A. A., Vologdin V. A., Zalyotov D. V.,** Dependence of microwave – excitation signal parameters on frequence stability caesium atomic clock, Journal of Physics: Conference Series. 643 (1) (2015) 012087.

24. **Petrov A. A., Zalyotov D. V., Shabanov V. E., Shapovalov D. V.,** Features of direct digital synthesis applications for microwave excitation signal formation in quantum frequency standard on the

atoms of cesium, Journal Physics: Conference Series. 1124 (1) (2018) 041004.

25. **Grevtseva A. S., Dmitriev R. A.,** Features of the formation of the frequency of the microwave excitation signal in the quantum frequency standard on rubidium atoms – 87, Journal of Physics: Conference Series. 2086 (1) (2021) 012055.

26. **Petrov A. A.,** Digital Frequency Synthesizer for 133Cs-Vapor Atomic Clock, Journal of Communications Technology and Electronics. 62(3) (2017) 289–293.

27. **Lukashev N. A., Rud V. Yu.,** Microwave frequency standard on Hg-199 ions for space stations and vehicles Journal of Physics: Conference Series. 1400 (2) (2019) 022050.

28. **Petrov A. A., Zaletov D. V., Shapovalov D. V.,** Peculiarities of Constructing a Scheme for Formation of a Microwave Excitation Signal in a Cesium Atomic Clock, Journal of Communications Technology and Electronics. 66(3) (2021) 295–299.

29. **Petrov A. A.,** New scheme of the microwave signal formation for quantum frequency standard on the atoms of caesium-133 Journal of Physics: Conference Series. 769 (1) (2016) 012065.

30. **Wang D., Davydov, V. V., Rud V. Y.** Prospective directions for the development of microwave frequency standards for satellite navigation systems Journal of Physics: Conference Series. 2086 (1) (2021) 012073.

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