The use of digital data processing to improve the metrological characteristics of the rubidium frequency standard

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Abstract. The necessity of improving the metrological characteristics of a quantum frequency standard when determining the coordinates of an object on the Earth's surface or long-term transmission of large amounts of data in satellite communication systems is substantiated. A new algorithm for digital processing of optical signals in the frequency standard is proposed. The results of experimental studies of the metrological characteristics of a quantum frequency standard based on rubidium atoms - 87 are presented.

1. Introduction

In the modern world, devices and systems for determining the time are given increased attention [1-10]. These devices are used in communication systems, radar, navigation and scientific experiments [10-21]. Various devices have been developed to solve the problem of determining the exact value of time or frequency [1-3, 14, 15, 22-29].

A special place among devices for determining the frequency and time is occupied by frequency standards [2, 3, 14, 27, 28, 30-36]. The main advantage of the frequency standards over other devices is the use of laser radiation frequency stabilization systems and optical elements in it for stable operation [2, 3, 26-28, 32-39]. A slight deviation of the frequency from the nominal value leads to large errors, especially when transmitting large data streams and determining the coordinates of an object. One of the main problems of the satellite system is the mutual synchronization of the time scales of satellites down to nanoseconds or less. For example, an error in navigation signals emitted by different satellites with a time mismatch of 10 ns causes an additional error in determining the location of an object of 10-15 meters. The solution of new problems in the transmission of information and determination of coordinates requires constant modernization of satellite navigation systems, including quantum frequency standards [32-41]. In this paper, we consider one of the options for upgrading the rubidium frequency standard (RFS) to improve its metrological characteristics.

2. Principle of operation of the rubidium frequency standard

For many years, the general structural scheme of RFS has not undergone fundamental changes for various models of this type of RFS. In the design of rubidium RFS, individual elements or blocks are
mainly changed, as well as control systems for various parameters to improve metrological characteristics [41, 42].

The operation of the RFS is based on the principle of tuning a highly stable voltage-controlled crystal oscillator (VCXO) to the rubidium quantum-frequency transition. To implement the noted frequency tuning of the quartz oscillator, the microwave signal from the frequency synthesizer (FS) is fed into a glass vacuum cell filled with rubidium-87 atoms and a buffer gas. When the frequency of the microwave signal coincides with the rubidium frequency of the quantum transition, stimulated emission of photons occurs, which is registered by the photodetector. In this case, the maximum signal-to-noise ratio (S / N) is observed. If the frequency of the microwave signal \( f_{mw} \) deviates from the resonant transition frequency, the S / N ratio decreases and the automatic frequency control circuit generates an error signal. This signal is used to adjust the frequency of the voltage-controlled crystal oscillator (VCXO). One of the key aspects of the rubidium RFS operation is the formation of a microwave signal. The process of forming a microwave signal is carried out in a frequency synthesizer.

Therefore, it is extremely important to develop a method that provides, on the one hand, high accuracy of the output frequency when it is tuned in an autonomous mode, regardless of communication with a ground station. In the methods considered in for the RFS, the frequency tuning step is more than 1 Hz using the voltage setting of the voltage-controlled crystal oscillator. This is not enough to meet the new precision requirements. Therefore, the new method uses the design of a frequency synthesizer that provides a fractional conversion factor to a hundredth of a hertz. The frequency tuning of the crystal oscillator is controlled by the automatic frequency tuning system, which includes a crystal oscillator control unit (CO CU) and a control unit that converts the signal coming from the quantum discriminator and calculates a tuning code for further sending it to the CO CU.

In the previous version of the software for the RFS control device, a simple accumulation of all received data at different frequencies was used, followed by the calculation of the value of the microwave signal error signal. The new version proposes to use the median filtering method as one of the data filtering methods.

The median filtering method uses the ordering of several elements received at the input of the control unit, and the subsequent selection of a value equidistant from the beginning and the end of the ordered row of elements.

The median filtering algorithm has a pronounced selectivity to array elements with a non-monotonic component of the sequence of numbers within the aperture and most effectively excludes single outliers, negative and positive, from signals.

The basic principle of operation of the modified automatic frequency control algorithm of the frequency standard using median filtering of the input data is as follows:

1. Accumulation of data at the first frequency \( f_1 \). In this case, accumulation begins with a delay, since switching the frequency causes a transient process of approximately \( 1/5F_m \). Samples are sampled synchronously with a \( 256F_m \) signal with a frequency of 9984 Hz fed to the microcontroller from a frequency synthesizer.

2. Ordering in ascending order of the received samples and further filtering by the median filtering method.

3. Experimental studies and discussion

During long-term operation of the FS, especially in space, there is an imbalance in the parameters of its operation. To adjust them, it is necessary to calculate the values of the error signal. This signal is greatly influenced by various noises that are present in optical signals. Using median filtering of data from optical signals can reduce the effects of random noise in the error signal, thus reducing phase noise. When using optical light signals for recording resonance conditions on photodetectors, an important characteristic is the power spectral density \( S_\phi \). The optical signal arriving at the photodiode is digitized and fed to a control device based on a microcontroller. The data received by the control
device are filtered and on their basis the control signal of the crystal oscillator is calculated to adjust to a more highly stable frequency of the rubidium junction. Figure 1 shows as an example the spectral density of noise in the frequency range of tuning the resonant frequency of a quantum transition.

![Figure 1](image1.png)

**Figure 1.** The phase noise spectral power density of error signal: a - the previous version of the software; b - the new version.

In figure 2 as an example, the dependences of the change in the error signal when using median filtering and previously applied methods are presented.

![Figure 2](image2.png)

**Figure 2:** The values of the reference signals $\delta y$. Graph (a) corresponds to the earlier value of the error signal with simple accumulation, graph (b) - to the error signal with median filtering.

Analysis of the results obtained shows that the error signal decreases several times. When using optical light signals to register resonance conditions on photodetectors, an important characteristic is the spectral density $S_{\phi}$ [28, 37, 41, 42]. The $S_{\phi}$ value has a significant impact on the $S/N$ ratio. Figure 3 shows the spectral densities of phase noise of the previously used design of the QFS and the new one, which uses the method of improving the parameters of the microwave signal.

The analysis of the results of experimental studies obtained in figure 1 showed that the use of median filtering and a microcontroller for control in the FS allows to reduce the power of phase noise in the output signal spectrum. The use of median data filtering in the automatic frequency control ring of the
microwave excitation signal allows one to reduce one of the most important disturbing factors affecting the short-term frequency stability - the spectral noise density.

4. Conclusion
The analysis of the obtained results showed the expediency of using the developed method of automatic frequency control of the RFS microwave excitation signal. The proposed solutions for digital processing of optical signals made it possible to obtain an additional improvement in the metrological characteristics of the RFS.

Studies have shown that an improvement in long-term frequency stability by 5% using the new algorithm reduces the number of bit errors during long-term data transmission by at least 3%. It also increases the accuracy of determining the coordinates of an object by at least 15%. The obtained improvements in the short-term and long-term frequency stability make it possible to increase the degree of reliability of the satellite coordinate determination systems.

References
[1] Lukashev N A, Petrov A A, Grebenikova N M and Valov A P 2018 Proceedings of 18th International conference of Laser Optics ICLO-2018 (Saint-Petersburg), vol. 8435889 (IEEE), p. 271
[2] Polyakov V M, Viktorov E A, Kovalev A V and Orlov O A 2014 Proceedings of 16th International conference of Laser Optics ICLO-2014 (Saint-Petersburg), vol. 6886216 (IEEE), p. 123
[3] Kovalev A V, Polyakov V M and Mak A A 2016 Proceedings of 17th International conference of Laser Optics ICLO-2014 (Saint-Petersburg), vol. 6886216 (IEEE), p. 201
[4] Moroz A V and Davydov R V 2019 Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 11660 LNCS 710-718
[5] Davydov R V, Dmitrieva D S, Pilipova V M, Dudkin V I and Andreeva E I 2020 Proceedings of International conference of Laser Optics ICLO-2020 (Saint-Petersburg), vol. 9285820 (IEEE), p. 171
[6] Smirnov K J, Medzakovskiy V I, Vysocký M G and Glagolev S F 2017 Journal of Physics: Conference Series 917(6) 062019
[7] Smirnov K J, Glagolev S F and Tushavin G V 2018 Journal of Physics: Conference Series 1124(2) 022014
[8] Hoang T, Kirichek R, Paramonov A and Koucheryavy A 2016 Lecture Notes in Electrical Engineering 376 1249-1259
[9] Davydov R, Antonov V, Makeev S, and Batov Y 2019 E3S Web of Conferences 140 02001
[10] Makolkina M, Pham V, Kirichek R, Gogol A and Koucheryavy A 2018 Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 11118 LNCS 547-559
[11] Andropov A V, Kuzmin S V and Korovin K O 2021 Springer Proceedings in Physics 255 675–681
[12] Raimzhanov T R, Kuzmin S V and Korovin K O 2021 Springer Proceedings in Physics 255 629–635
[13] Davydov R V, Saveliev I V, Lenets V A, Tarasenko M Yu and Yalunina T R 2017 Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 10531 LNCS 177-183
[14] Petrov A A and Myazin N S 2017 Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 10531 LNCS 561-568
[15] Podstrigaev A S, Smolyakov A V, Myazin N S, Grebenikova N M and Davydov R V 2019 Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial
Intelligence and Lecture Notes in Bioinformatics) 11660 LNCS 525-533

[16] Fadeenko V B and Pchelkin G A 2019 Journal of Physics: Conference Series 1400(4) 044010
[17] Moroz A V 2019 Journal of Physics: Conference Series 1410(1) 012212
[18] Moroz A V, Davydov V V, Malanin K Y, Krasnov A A and Rud V Yu 2019 Journal of Physics: Conference Series 1400(4) 044009
[19] Fadeenko V B, Pchelkin G A and Beloshapkina O O 2019 Journal of Physics: Conference Series 1410(1) 012238
[20] Fadeenko V B, Kuts V A and Vasiliev D A 2018 Journal of Physics: Conference Series 1135(1) 012053
[21] Sinicyna E A, Galichina A A, Lukyanov A S and Podstrigaev A S 2019 Journal of Physics: Conference Series 1236(1) 012075
[22] Grebenikova N, Moroz A, Bylina M and Kuzmin M 2019 IOP Conference Series: Materials Science and Engineering 497(1) 012109
[23] Kuzmin M S and Rogov S A 2019 Computer Optics 43(3) 391-396
[24] Fadeenko I, Fadeenko V, Reznik V, Moroz A, Popovskiy N and Nikolaev D 2019 IOP Conference Series: Earth and Environmental Science 390(1) 012022
[25] Ermolaev A N, Krishpents G P and Vysoczkiy M G 2016 Journal Physics: Conference Series 741(1) 012071
[26] Semenov V V, Nikiforov N F and Ermak S V 1991 Soviet journal of Communications Technology and Electronics 36(4) 59 – 63
[27] Petrov A A, Grebenikova N M, Lukashev N A, Ivanova N V, Rodygina N S and Moroz A V 2018 Journal of Physics: Conference Series 1038 (1) 012032
[28] Grebennikova A S, Davydov R V, Dudkin V I and Rud V Y 2019 Journal of Physics: Conference Series 1326(1) 012043
[29] Logunov S E, Rud V Y, Davydov R V, Moroz A V and Smirnov K J 2019 Journal of Physics: Conference Series 1326(1) 012024
[30] Lukashev N A, Glinushkin A P and Lukyantsev V S 2019 Journal of Physics: Conference Series 1410(1) 012211
[31] Lukashev N A, Davydov R V and Glinushkin A P 2019 Journal of Physics: Conference Series 1326(1) 012046
[32] Petrov A A, Shabanov V E, Zalyotov D V, Bulyanitsa A L and Shapovalov D V 2018 International Conference on Electrical Engineering and Photonics EExPolytech 2018 (Saint-Petersburg), vol. 8564389 (IEEE), p. 52-55
[33] Petrov A A, Vologdin V A and Zalyotov D V 2015 Journal of Physics: Conference Series 643(1) 012087
[34] Petrov A A and Grebennikova N M 2018 Journal of Communications Technology and Electronics 63(11) 1281–1285
[35] Lukashev N A and Moroz A V 2019 Journal of Physics: Conference Series 1236(1) 012068
[36] Petrov A A and Grebenikova N M 2018 Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 11118 LNCS 641-648
[37] Valov A P 2019 Journal of Physics: Conference Series 1410(1) 012246
[38] Petrov A A, Zaletov D V, Davydov V V and Shapovalov D V 2021 Journal of Communications Technology and Electronics 66(3) 295–299
[39] Petrov A A, Zalyotov D V, Shabanov V E and Shapovalov D V 2018 Journal Physics: Conference Series 1124(1) 041004
[40] Petrov A and Shapovalov D 2019 Journal of Physics: Conference Series 1400(4) 044008
[41] Valov A 2020 CEUR Workshop Proceedings 2667 102–105
[42] Riehle F 2004 Frequency standards. Basics and Applications (New Jersy: Wiley-VCH)