Method of improving the rubidium – 87 quantum frequency standard’s metrological characteristics

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Abstract. The need of using quantum frequency standard in satellite navigation systems is considered. The experimental results of improving the metrological characteristics of the standard using median filtering are presented.

1. Introduction
The operation of many systems, for example, to ensure flight safety or prompt delivery of goods, depends on the correct determination of the object coordinates [1-9]. In conditions of a large number of interference and reflected signals [8, 10-20] during a using of the terrestrial radio navigation systems (TRNS) are many problems. The presence of various obstacles in the area (mountains, high-rise buildings, lowlands, etc.) distort or reduce the power of radio navigation signals. These problems do not solve the using of the fiber optic communication lines and the optic processing methods [7, 9, 10, 21-28]. On the other hand of the high placement density of terrestrial stations is not economically profitable. The moving objects for navigation systems is one of the solutions to this problem. On the other hand of the requirements for such navigation systems are increasing [29-34]. The coordinates of the object must be determined with an accuracy of less than 1.5 m [29, 32, 35-39]. The use of quantum frequency standards (QFS) as reference generators in these objects is the only possible solution that allows these requirements to be met, because they are sources of highly stable, high-precision, spectrally pure signals [40-43]. The use of rubidium – 87 frequency standards is the most appropriate solution, because they have small dimensions in comparison with caesium – 133 QFSs, although they don’t have such high metrological characteristics as caesium QFSs do. An improvement in their accuracy characteristics is required to ensure the solution of these problems. Experience with these QFSs has shown that the most optimal solution is the modernization of devices in operation [32-43].

2. Principle of operation of the rubidium frequency standard
The operation of the rubidium – 87 QFS is based on the principle of tuning the less stable frequency of the voltage-controlled crystal oscillator (VCXO) to the highly stable frequency of the quantum transition of rubidium – 87 atoms. A microwave excitation signal is generated in the frequency multiplier block. The interaction of the microwave field with rubidium – 87 atoms causes their transitions to the corresponding unpopulated level. It is possible to determine the frequency of the microwave field at
which the transition probability is maximal by measuring the population of this level after interacting with the microwave field. The signal-to-noise ratio (S / N) of the recorded resonant signal from the emitted photons at the photodetector in this case will be maximum. The received signal is used to generate a highly stable frequency which equal to 6834.7 MHz [30, 32, 38, 40].

This frequency is corrected for effects that lead to frequency shifts of the central resonance. The main contribution to the frequency shift of the central resonance is made by the parameters of the microwave excitation signal. Therefore, the process of generating a microwave signal, which is fed into the interaction zone of rubidium-87 atoms with the field along the waveguide path, needs to be given increased attention when upgrading the design of the QFS. Figure 1 shows typical structure of rubidium – 87 QFS.

Figure 1. The structural diagram of the rubidium QFS: 1 - reflector; 2 - a lamp with vapors of rubidium - 87; 3 - cell - filter; 4 - solenoid C - fields; 5 - radio frequency resonator; 6 - a cell with buffer gas; 8 - photodetector; 9 - automatic frequency control system; 10 - highly stable crystal oscillator; 11 - frequency synthesizer.

In depending on the tasks to be solved, the nodes of the standard design are being modernized. The electronic circuits are manufactured using various components.

3. Experimental studies and discussion

Studies have shown that the accuracy of tuning to the resonant frequency f0 in the QFS will depend on the step of the microwave excitation signal frequency tuning Δf_{MW}. With this in mind, we proposed a new method for generating frequency adjustment codes for a microwave excitation signal in a frequency converter, which can significantly reduce the Δf_{MW} value compared to previously used QFS designs.

The principle of operation of the new technique is based on the use of median filtering of the QFS’s error signal (ES). Median filtering sorts and filters the digitized error signal values sent to the QFS control unit. After calculating the ES difference, the control unit generates codes for adjusting the frequency of the VCXO. This makes it possible to fine-tune the frequency of the microwave excitation signal to the central resonance frequency f0 (maximum S / N ratio in the photodetector). These changes are clearly visible on the phase noise spectral power density S_φ of the error signal shown by figure 2.
During the time of the using of the optical light signals for recording of resonance conditions on a photodetector, the important characteristic is the spectral density $S_\phi$. The value of $S_\phi$ has a significant effect on the S/N ratio. Figure 3 shows the phase noise amplitude of error signal for two designs of the QFS (the previously used design and a new). New design uses the method of improving the parameters of the microwave signal.

An analysis of the obtained results shows a significant decrease in phase noise amplitude when using the median filtering method.

An analysis of the obtained results of experimental investigations in figure 3 showed that the use of the method developed by us, as well as the use of a microcontroller for control in the QFS, reduces the power of phase noise in the output spectrum of the signal.

All this made it possible to improve the short-term frequency stability - Allan's deviation, as well as long-term frequency stability. The results of the investigations of Allan's deviation are presented on figure 4.
Figure 4. The Allan deviation: a – the previous version of the software; b – the new version.

The analysis of the obtained results (figure. 4) shows that the implemented technical solutions and the developed new method for improving the parameters of the microwave excitation signal during modernization of the standard design made it possible to improve Allan deviation by 7%.

4. Conclusion
The studies showed the universality of the proposed method for using the improvement of metrological characteristics, in particular, it can be used also for caesium – 133 QFS, because the principle of operation of the standard on caesium atoms is also based on the principle of tuning the frequency of the crystal oscillator according to the frequency of the caesium - 133 atomic transition. It was also found that the use of a new method for adjusting the frequency codes of the microwave excitation signal improved the Allan dispersion of the output signal of the QFS by more than 5% compared with previously used designs. This allows to solve the problem of determining the coordinates of the object with an accuracy of less than 1.5 m.

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References
[1] Rumyantsev N, Bondareva O, Makeev S and Krasnoshekov V 2019 IOP Conference Series: Earth and Environmental Science 390(1) 012037
[2] Kozar M, Sabliy L, Korenchuk M, Korshunov A and Kosolapov V 2019 IOP Conference Series: Earth and Environmental Science 390(1) 012002
[3] Artem’ev K, Kolik L, Podkovyrov L, Sevostyanov S, Kosolapov V, Meshalkin V and Diuldin M 2019 IOP Conference Series: Earth and Environmental Science 390(1) 012039
[4] Shafeev G, Barmina E, Valiullin L, Simakin A, Ovsyankina A, Demin D, Kosolapov V, Korshunov A and Roman Denisov 2019 IOP Conference Series: Earth and Environmental Science 390(1) 012041

[5] Krasnova E D, Matorin D N, Belevich T A, Voronov D A and Patsaeva S V 2018 Journal of Oceanology and Limnology 36(6) 1962-1977

[6] Kosolapov V, Rud' V, Korshunov A, Savchenko I, Switala F and Hogland W 2019 IOP Conference Series: Earth and Environmental Science 390(1) 012010

[7] Davydov R, Antonov V, Makeev S, Batov Y, Dudkin V and Myazin N 2019 E3S Web Conference 140 02001

[8] Podstreginae 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 LCNS 525-533

[9] Semenov V V, Nikiforov N F, Ermak S V and Davydov V V 1991 Soviet Journal of Communications Technology and Electronics 36 59 – 63

[10] Davydov V V, Dudkin V I, Petrov A A and Myazin N S 2016 Technical Physics Letters 42(7) 692-696

[11] Kuz'min S V 2004 Technical Physics Letters 30(11) 947-949

[12] Shannikov D V, Surikov V V and Kuz'min S V 2005 Technical Physics 50(11) 1531-1534

[13] Shannikov D V and Kuz'min S V 2003 Technical Physics Letters 29(11) 941-943

[14] 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

[15] Fokin G and Al-Odliari A H A 2018 Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 11118 LNCS 496–508

[16] Fokin G 2020 Proceedings of the 22nd International Conference on Advanced Communication Technology (ICACT-2020) Phoenix Park PyeongChang (South Korea) p. 1-5

[17] Fokin G 2019 Proceedings of the 2019 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom-2019) Sochi p. 1-3

[18] Fokin G 2019 Proceedings of the 21st International Conference on Advanced Communication Technology (ICACT-2019) PyeongChang Kwangwoon Do (South Korea) p. 360-365

[19] Fokin G, Kireev A and Al-odhari A H A 2018 Proceedings of the 2018 Systems of Signals Generating and Processing in the Field of on Board Communications (Moscow) p. 1-5

[20] Fokin G 2018 Proceedings of the 2018 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom-2018) Batumi, p. 1-5

[21] Davydov R, Antonov V and Moroz A 2019 Proceedings of the 2019 IEEE International Conference on Electrical Engineering and Photonics, EExPolytech 2019 (Saint-Petersburg) 8906791 p. 42-45

[22] Grebenikova N M, Davydov R V and Rud V Yu 2019 Journal of Physics: Conference Series 1326(1) 012012

[23] Logunov S E, Rud V Yu, Davydov R V, Moroz A V and Smirnov K J 2019 Journal of Physics: Conference Series 1326(1) 012024

[24] Logunov S E, Davydov R V, Vysotsky M G, Dudkin V I and Rud' V Yu 2019 Journal of Physics: Conference Series 1368(1) 022056

[25] Logunov S E, Koshkin A Yu and Petrov A A 2016 Journal of Physics: Conference Series 741(1) 012092

[26] Davydov V V, Dudkin V I and Karseev A Y 2015 Journal of Applied Spectroscopy 82(5) 794-800

[27] Davydov R, Antonov V and Kalinin N 2015 Journal of Physics: Conference Series 643(1) 012107
[28] Grebenikova N M, Myazin N S, Rud' V Yu and Davydov R V 2018 Proceedings of the 2018 IEEE International Conference on Electrical Engineering and Photonics, EExPolytech 2018 (Saint-Petersburg) 8564409 p. 295-297

[29] Petrov A A, Davydov V V 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

[30] Petrov A A and Davydov V V 2015 Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 9247 739-744

[31] Petrov A A, Davydov V V, Vologdin V A and Zalyotov D V 2015 Journal of Physics: Conference Series 643(1) 012087

[32] Valov A P, Davydov R V, Rud V Yu and Grevtseva A S 2019 Journal of Physics: Conference Series 1326(1) 012040

[33] Grevtseva A S, Davydov R V, Dudkin V I and Rud' V Yu 2019 Journal of Physics: Conference Series 1326(1) 012043

[34] Lukashev N A, Davydov R V, Glinushkin A P and Rud' V Yu 2019 Journal of Physics: Conference Series 1326(1) 012046

[35] 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

[36] Lukashev N A, Petrov A A, Davydov V V, Grebenikova N M and Valov A P 2018 Proceedings of 18th International conference of Laser Optics ICLO-2018 (Saint-Petersburg) 8435889 p. 271

[37] Petrov A A and Davydov V V 2016 Journal of Physics: Conference Series 769 (1) 012065

[38] Valov A P, Davydov V V and Rud V Y 2019 Journal of Physics: Conference Series 1410(1) 012246

[39] Lukashev N A, Davydov V V, Glinushkin A P, Rud V Yu and Lukyantsev V S 2019 Journal of Physics: Conference Series 1410(1) 012211

[40] Grebenikova N M, Davydov V V, Valov A P and Lukashev N A 2019 Proceedings of the 2019 IEEE International Conference on Electrical Engineering and Photonics, EExPolytech 2019 (Saint-Petersburg) 8906867 p. 17-20

[41] Petrov A A, Davydov V V, Shabanov V E, Zalyotov D V, Bulyanitsa A L and Shapovalov D V 2018 Proceedings of the 2018 IEEE International Conference on Electrical Engineering and Photonics, EExPolytech 2019 (Saint-Petersburg) 8564389 p. 52-55

[42] Petrov A A, Zalyotov D V, Davydov V V, Shabanov V E and Shapovalov D V 2018 Journal Physics: Conference Series 1124(1) 044004

[43] Petrov A A, Davydov V V and Shapovalov D V 2019 Journal of Physics: Conference Series 1400(4) 044008