The method of improving the parameters of the microwave excitation signal in the rubidium – 87 quantum frequency standard

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Abstract. This article discusses the design of the rubidium – 87 quantum frequency standard for satellite navigation systems. Also it is proposed a method for improving the parameters of the microwave excitation signal to improve the short-term and long-term stability of the frequency standard. The results of experimental research are presented.

1. Introduction

In the modern world, accurate measurement of time and frequency is necessary to conduct various experiments in many fields of science, for example, atomic physics (atomic-photon interactions, atomic collisions and atomic interactions with static and dynamic electromagnetic fields), the study of the earth's surface (geodesy) or outer space radio astronomy and pulsar astronomy [1-7]. It is impossible to use metrological services and communication equipment without highly stable sources of frequency and time [1, 3, 8-11]. Frequency standards occupy a special place in satellite navigation systems [1, 2, 6, 12-16]. Global navigation satellite constellations (for example, European Galileo, Russian GLONASS, or US Global Positioning Systems) use quantum frequency standards (atomic clocks) [1, 2, 5, 6, 10, 16-18].

One of the main problems of a satellite navigation system is the mutual synchronization of satellite time scales to nanoseconds and less [5, 7, 9, 10, 12]. The error of the navigation signals emitted by different satellites at a time error of 10 ns causes an additional error in determining the location of the object at 10-15 meters.

For expanding the range of tasks of satellite navigation systems demands an increase in the accuracy of determining the location of an object to 0.5 m. On the other side, the composition of the used electronic equipment changes with the development of scientific and technological progress. All of this demand continuing upgrades of satellite navigation systems, including quantum frequency standards. (QFS).
The development and entry-into-service of new QFS models is a very long and expensive process. There is no time and sufficient funds for its realization in most cases. Therefore, in order to solve specific problems, modernization of rubidium – 87 and caesium – 133 QFS which are in operation on satellite systems is carried out [4-10, 12-14, 17-19].

Process of modernizing frequency standards includes various directions: change of weight and dimensions, decrease in energy consumption, improvement of metrological characteristics. In this paper, we consider one of these directions to improve the metrological characteristics of the rubidium – 87 quantum frequency standard.

2. Principles of rubidium atomic clock operation

During the period of operation of the rubidium – 87 QFS, the structural diagrams of its various models did not fundamentally change compared with their classical representation [1, 2, 20]. It is characteristic for quantum frequency standards that modernization may not be for its entire structure, but only for individual nodes or blocks and also control systems of various parameters to improve the metrological characteristics of the standard. Figure 1 shows the block diagram of the rubidium atomic clock, which implements the method we have developed to improve the parameters of the microwave signal to improve the metrological characteristics of the standard.

![Figure 1. Block diagram of a rubidium atomic clock: 1 – reflector; 2 – rubidium – 87 lamp; 3 – filter cell; 4 – C – field solenoid; 5 – radio frequency resonator; 6 – glass gaseous cell; 8 – photodetector; 9 – automatic frequency control system; 10 – highly stable crystal oscillator; 11 – frequency synthesizer.](image)

The work of the rubidium atomic clock is based on the principle of tuning a highly stable voltage controlled crystal oscillator to a quantum-frequency transition of rubidium – 87 atoms [1, 2, 8, 17-20]. To implement the noted frequency tuning of the crystal oscillator, a microwave signal from the frequency synthesizer (FS) 11 is fed to the vacuum cell 6 filled with rubidium – 87 atoms and the buffer gas. When the frequency of the microwave signal matches with the frequency of the quantum transition of excited rubidium – 87, the signal recorded by the photo detector has the maximum value of the signal-to-noise ratio (S/N). If the frequency of the microwave signal $f_{mw}$ deviates from the frequency of the resonant transition, the S / N ratio decreases and an error signal is generated by the electronic circuit 9. This signal is used to adjust the frequency of the crystal oscillator 10. Therefore, one of the key moments of the work of the frequency standard on the rubidium - 87 atoms is the formation of a microwave signal taking into account various features. The process of generating a microwave signal is carried out in the FS 11. It is necessary that the FS output will be provided with
high accuracy of the output frequency, high suppression of the lateral amplitude components in the output signal spectrum, low dependence of the frequency variation and the amplitude of the output signal to temperature ratio.

The method of generating a microwave signal in a frequency synthesizer, described in detail in [1, 2, 20], has one major drawback. The spectrum of the output signal with a frequency of 5.3125 MHz, which is obtained at the output of one of the balanced mixers of FS 11 [20], contains side amplitude components. If one of the side amplitude components matches with the frequency of any Zeeman transition, this will lead to transitions of atoms at these levels and the occurrence of an error in establishing the actual value of the output frequency signal of the QFS. It is used crystal filter with a high temperature dependence to suppress the lateral components. For reliable operation of the crystal filter requires high temperature stabilization. This is extremely difficult to provide, especially in conditions of a long flight of a satellite.

It should also be noted that the required for QFS operation frequency of the microwave signal, which corresponds to the frequency difference between the two ultrathin sublevels F = 2 and F = 1 [1, 2, 20], is formed at the output of the balanced mixer (BM) FS 11. The BM can be described by the equation:

$$U_{\text{вых}} = \cos \omega_1 t \cdot \cos \omega_2 t = \frac{1}{2} \cos(\omega_1 - \omega_2) t + \frac{1}{2} \cos(\omega_1 + \omega_2),$$

where $\cos(\omega_1 - \omega_2) t$ - difference and $\cos(\omega_1 + \omega_2) t$ - total frequency.

All side components are converted into signals with combinational frequencies, if they appear in the spectra of signals with frequencies $\omega_1$ and $\omega_2$ (for example, due to temperature drift in a quartz filter). These signals will create additional errors. Therefore, when comparing time scales in the QFS the frequency is adjusted during each communication session of the satellite with the ground station. If for some reason the communication session did not take place, then the operation of the satellite in the navigation system may be suspended.

Therefore, it is extremely important to develop a method that would be ensuring high accuracy of the output frequency with its adjustment in an autonomous mode, regardless of the connection with the ground station, on the one hand. On the other hand, high suppression of the side amplitude components at the FS output, as well as the possibility of frequency tuning of the FS output signal in a wide frequency band with a small frequency tuning step. In the methods considered in [1, 2, 20] for QFS, the frequency tuning step is more than 1 Hz using the voltage setting of a voltage-controlled crystal oscillator 10. Changing the frequency of the crystal oscillator 10 leads to the appearance of additional side components in the signal spectrum due to the peculiarities of the construction of the fractional frequency 5.3125 MHz forming scheme.

In the microwave signal generation method developed by us, the direct digital synthesis (DDS - Direct Digital Synthesis) method is used. The microwave signal generated using DDS is synthesized with high accuracy, what is typical for digital systems. The frequency, amplitude and phase of the signal at any given time are precisely known and controlled. It is especially necessary to note that systems with DDS are practically not subjected to temperature drift [8, 10]. To implement DDS in FS 11, we developed its new design.

An important feature of the new FS design is the use of the algorithm for redirecting the input data of the transcoder table. To implement this algorithm, it is necessary to place the values of the argument of the function $\sin(x)$ and the corresponding values of the function $\sin(x)$ in the interval $[0; \frac{\pi}{2}]$ in the code table. Using the redirection algorithm of input data, we can fully determine the values of the $\sin(x)$ function on the interval $[0; 2\pi]$, using only $\frac{1}{4}$ of the values of the $\sin(x)$ function for a given argument. This will reduce the amount of data stored in the ROM on the one hand, and on the other hand, will provide an opportunity to increase the number of values of the argument of the function.
sin(x). This will allow us to determine the amplitude of the sin(x) function with greater accuracy (4 times), which ultimately affects the spectrum of the FS output signal.

It was established that the use of a 12-bit argument code of the sin(x) function, a 10-bit DAC in the new FS design, as well as the use of the redirection algorithm of input data, allows to obtain a higher signal-to-noise ratio in the output signal spectrum than in previously used designs of the FS.

According to the results of the research it was found that the frequency resolution of the FS output signal is thousandths of a Hz with an output frequency of about ten MHz. In the newly developed design, the step of tuning the FS output frequency is calculated by the following formula:

$$\Delta f_{out} = \frac{f_c}{2^N},$$  \hspace{1cm} (2)

where \(f_c\) - clock frequency, \(N\) - bit depth of phase accumulator

The developed design of the FS uses a phase accumulator with \(N = 40\). Such a construction of the formation of a fractional frequency signal of 5.3135341 MHz with high accuracy allowed to significantly reduce the influence of the side components in the microwave signal spectrum on the resonant frequency signal.

In addition, the use of the new FS design allowed us to implement a new scheme for adjusting the frequency of the microwave excitation signal. Information about the error signal is now also fed to FS 11 (figure 1) and the frequency is adjusted with high accuracy by changing the fractional frequency signal. Additional harmonics and side components in the microwave signal spectrum, as it was previously in the used FS constructions, are not formed. The balance mixer is used in the FS operation only once to obtain the difference frequency 6834686465.9 Hz. The summation modes of frequencies using BM, which, due to the peculiarities of its operation, lead to the appearance of additional harmonics close to the resonant frequency in the new FS design, do not apply.

3. Experimental research results and discussion

Figure 2 and figure 3 shows, as an example, the output spectrum of the fractional frequency of the previously used synthesizer design (a) and that developed by us (b). The spectrum is measured in the 3 kHz recording band (figure 2) and 300 kHz (figure 3).

![Figure 2. Suppression of the side amplitude components in the 3 kHz band: (a) – previously used FS design; (b) – the FS design developed by us.](image-url)
The obtained experimental results show that the suppression of combinational components in the spectrum of a fractional frequency signal in the 3 kHz recording band is improved by 18 dB, and in the 300 kHz recording band by 5 dB. This allowed to exclude from the composition of the new FS design a crystal, which, with good frequency selectivity, has a high temperature dependence. The exclusion of a crystal filter from the process of forming a microwave excitation signal having a high quality factor made it possible to expand the frequency tuning range of the microwave signal up to 300 kHz; in earlier designs it was at least an order of magnitude smaller.

This increase in the range allows in case of a sharp malfunction in the QFS (the departure of the resonant frequency of more than 100 kHz) to carry out its adjustment in the automatic mode. In the previously used structures, a communication session with ground stations was required.

Using optical light signals to register resonance conditions on photoreceivers, spectral density $S_\phi$ is an important characteristic [17-27]. The value of $S_\phi$ has a significant effect on the S/N ratio. Figure 4 shows the spectral densities of the phase noise of the previously used QFS and new design, which uses the method of improving the parameters of the microwave signal.

**Figure 3.** Suppression of the side amplitude components in the 300 kHz band: (a) – previously used FS design; (b) – the FS design developed by us.
Figure 4. Phase noise spectral density $S_\phi$. Graph 1 corresponds to the previously used QFS construction, graph 2 - the QFS construction with the method developed by us.

Analysis of the experimental results obtained in figure 4 showed that the use of the method developed by us, as well as the use of a microcontroller to control QFS, allows us to reduce the power of phase noise in the output signal spectrum.

All this has improved the short-term frequency stability — the Allan deviation, as well as the long-term frequency stability. Figure 5, as an example, presents the results of the Allan deviation study.

Figure 5. Allan’s deviation: Graph 1 corresponds to the previously used design of the microwave standard, Graph 2 - the compact design of the microwave frequency standard developed by us.
Analysis of the obtained results (figure 5) shows that the implemented technical solutions and the new developed method for improving the parameters of the microwave excitation signal during the modernization of the standard design improved the Allan deviation by 15%.

4. Conclusion

Studies have shown that the simultaneous use of a new method of forming a microwave excitation signal and a filtering system reduces one of the most important disturbing factors (spectral noise density) affecting the short-term frequency stability. Experimental studies of the metrological characteristics of rubidium – 87 QFS showed an improvement in the long-term frequency stability by 7%. The resulting improvements in short-term and long-term frequency stability can improve the reliability of satellite navigation systems.

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References

[1] Riehle F 2004 Frequency standards. Basics and Applications (New Jersey: Wiley-VCH)
[2] Oduan K and Gino B 2002 Chronometry and basics of GPS 400 (New Jersey: Wiley-VCH)
[3] Semenov V V, Nikiforov N F, Ermak S V and Davydov V V 1991 Soviet journal of Communications Technology and Electronics 36 59 – 63
[4] Glazov A I., Grigor’ev V V, Kravtsov V E, Mityurev A K, Svetlichnyi A B, Savkin K B and Tikhomirov S V 2008 Measurement Techniques 51 1064 – 1070
[5] Kolmogorov O V, Shchipunov A N, Prokhorov D V, Donchenko S S, Buev S G, Malimon A N, Balaev R I and Fedorova D M 2017 Measurement Techniques 60 901 – 905
[6] 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
[7] Pakhomov A A 2007 Journal of Communications Technology and Electronics 52 1114 – 1118
[8] 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
[9] Nazarov L E and Golovkin I V 2017 Journal of Communications Technology and Electronics 52 1125 – 1129
[10] Petrov A A and Davydov V V 2017 Journal of Communications Technology and Electronics 62 289 – 293
[11] Balaev R I, Malimon A N, Fedorova D M, Kurchanov A F and Troyan V I 2017 Measurement Techniques 60 806 – 812
[12] Petrov A A, Davydov V V and Grebenikova N M 2018 Journal of Communications Technology and Electronics 63 1281-1285
[13] Baryshev V N, Aleynikov M S, Osipenko G V and Blinov I Yu 2018 Quantum Electronic 48 443-447
[14] Petrov A A, Vologdin V A, Davydov V V and Zalyotov D V 2015 Journal of Physics: Conference Series 643(1) 012087
[15] Davydov V V, Ermak S V, Karseev A U, Nepomnyashchay H K, Petrov A A and Velichko E N 2014 Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 8638 LNCS 694-702
[16] Davydov V V, Sharova N V, Fedorova E N, Gilshteyn E P, Malanin K Y, Fedotov I V, Vologdin V A and Karseev A Yu 2015 Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 9247 712-721
[17] Baryshev V N, Kupalov D S, Novoselov A N, Alenikov M S, Boiko A I, Pal’chikov V G and Blinov I Y 2017 Measurement Techniques 59 1286-1290
[18] Blinov I Y, Boiko A I, Domnin Y S, Kostromin V P, Kupalova O V and Kupalov D S 2017 Measurement Techniques 60 30-36
[19] 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
[20] Reley W J 2010 Rubidium Frequency Standard Primer (Hamilton Technical Services Beaufort, SC 29907 USA)
[21] Petrov A A, Shabanov V E, Zalyotov D V, Davydov V V, Bulyanitsa A L and Shapovalov D V 2018 Proceedings of the 2018 IEEE International Conference on Electrical Engineering and Photonics, EExPolytech 2018 (Saint-Petersburg) 8564389 p. 52-55
[22] Davydov R V, Antonov V I and Moroz A V 2018 Proceedings of the 2018 IEEE International Conference on Electrical Engineering and Photonics, EExPolytech 2018 (Saint-Petersburg) 8564378 p. 236-239
[23] Rykin E V, Moroz A V, Smirnov K J, Davydov V V and Yushkova V V 2018 MATEC Web of Conference 245 12002
[24] Myazin N S, Smirnov K J, Davydov V V and Logunov S E 2017 Journal of Physics: Conference Series 929(1) 012080
[25] Logunov S E, Davydov V V, Vysocezky M G, Koshkin A Y and Rud’ V Yu 2017 Journal of Physics: Conference Series 917(5) 052058
[26] Davydov R V and Antonov V I 2017 Journal of Physics: Conference Series 929(4) 012040
[27] Petrov A A, Grebenikova N M, Lukashev N A, Davydov V V, Ivanova N V, Rodugina, N S and Moroz A V 2018 Journal of Physics: Conference Series 1038(1) 012032