On the need to use the median signal filtering method to improve the metrological characteristics of the rubidium frequency standard during processing and transmitting large data arrays

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***Abstract*—The article describes the construction of the rubidium – 87 quantum frequency standard for satellite infocommunication and navigation systems for various purposes. The necessity of improving the metrological characteristics of the quantum frequency standard for long-term transmission of large amounts of data is substantiated. A new algorithm is proposed for processing data of a large amount of data about the error signal using the median filtering method to improve the short-term and long-term stability of the frequency standard. The results of experimental studies of the metrological characteristics of the quantum frequency standard are presented. The improvement in long-term frequency stability was found to be 7%, which reduces the number of bit errors during long-term transmission of information by at least 3%.**

Keywords*—quantum frequency standard, signals processing, information transfer, data arrays, Allan's deviations, median filtering method

I. Introduction

In the modern world, accurate measurement of time and frequency is necessary to solve various problems in the fields of science and technology [1-7]. One of the most complex of them is ensuring the uninterrupted operation of satellite communication systems, navigation, Earth surface research and spacecraft control from orbit [1, 3, 8-17]. A special place among the devices for determining the frequency and time is occupied by quantum frequency standards (QFS) [8, 9, 18-22]. Currently, global satellite constellations for various purposes use only QFS [9.18-20, 23-25]. The main advantage of QFS over other devices is the use for stable operation of stabilization systems for the frequency of laser radiation and optical elements [3, 8, 19, 20, 25-29]. Other devices cannot provide the necessary accuracy in determining the frequency and long-term stability of its nominal value in conditions of large overloads. A slight deviation of the frequency from the nominal value leads to large errors, especially when transmitting large data streams.

One of the main problems of a satellite system is the mutual synchronization of satellite timelines to nanoseconds or less [9, 18-20, 30-32]. For example, the error of the navigation signals emitted by different satellites during a temporary mismatch of 10 ns causes an additional error in determining the location of an object of 10-15 meters.

The expanding of the tasks number for which the satellite navigation systems are used, the accuracy is required of increase of determining the object position to 0.5 m. On the other hand, a development of scientific and technological progress is changing the composition of the used electronic equipment. All this requires constant modernization of satellite navigation systems, including quantum frequency standards.

The development and commissioning of new QFS models is a very lengthy and expensive process. In most cases, there is no time and sufficient funds for its implementation. Therefore, in most cases, for the specific problems it is better to perform the modernization of the rubidium – 87 QFS and caesium - 133 QFS, which are in operation on satellite systems [18-20, 23-25, 32-35].

The process of modernizing frequency standards includes various directions: changing weight and dimensions, reducing energy consumption, improving metrological characteristics. The quantum frequency standards are characterized by the fact that modernization may not be for its entire structure, but only for individual nodes or blocks. In our work, we are considering one of such directions for improving the metrological characteristic of the rubidium-87 quantum frequency standard.

II. The control algorithm for frequency adjusting of the quantum standard

During the period of operation of rubidium – 87 QFS, the structural schemes of its various QFS models did not undergo fundamental changes in comparison with their classical representation [8, 9, 18-20, 30, 31]. In the design of the QFS, individual elements or blocks, as well as control systems for various parameters, are mainly changed to improve the metrological characteristics of the standard. On fig. 1 is shown the structural diagram of the rubidium – 87 QFS.

In this design the method developed by us for improving the microwave signal parameters to improve the metrological characteristics of the standard is implemented.

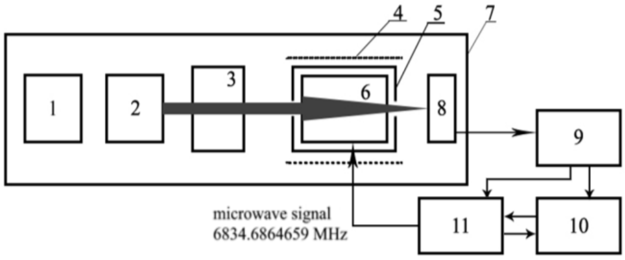

Fig. 1. The structural diagram of the rubidium QFS: 1 - reflector; 2 - a lamp with vapors of rubidium - 87; 3 - cell - filter; 4 - solenoid C - fields; 5 - radio frequency resonator; 6 - a cell with buffer gas; 8 - photodetector; 9 - automatic frequency control system; 10 - highly stable crystal oscillator;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

The operation of the rubidium – 87 QFS is based on the principle of tuning a highly stable voltage-controlled quartz oscillator 10 to the quantum-frequency transition of rubidium–87 atoms [8, 18, 23, 24, 35]. To implement the noted frequency adjustment of the quartz oscillator, a microwave signal from a frequency synthesizer (FS) 11 is supplied to a vacuum cell 6 filled with rubidium-87 atoms and a buffer gas 11. When the frequency of the microwave signal coincides with the quantum transition frequency of the excited rubidium – 87 atoms, the signal detected by the photodetector has maximum signal to noise ratio (S/N). If the frequency of the microwave signal f_{mw} leaves the value of 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 points in the operation of the QFS on rubidium atoms is 87, is the formation of a microwave signal taking into account its various features. The process of generating a microwave signal is carried out in the midrange 11. It is necessary that the output of the midrange provide high accuracy of the output frequency, high suppression of the side amplitude components in the spectrum of the output signal, low dependence of the frequency and amplitude of the output signal on temperature.

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

It should also be noted that the frequency of the microwave signal necessary for the operation of the QFS, which corresponds to the frequency difference between the two ultra-thin sublevels F = 2 and F = 1 [8], is formed at the output of the balanced midrange mixer 11. The BM operation can be described by the equation:

$$U_{out} = \frac{1}{2}cos(\omega_1 - \omega_2)t + \frac{1}{2}cos(\omega_1 + \omega_2)t, \qquad (1)$$

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

All side components, if they appear in the spectrum of signals with frequencies ω_1 and ω_2 (for example, due to temperature drift in a quartz filter), are converted to signals with combination frequencies. These signals will create additional errors. Therefore, during each communication session of the satellite with the ground station, when comparing the time scales in the QFS on the rubidium atoms, 87 adjust the frequency. If for some reason the communication session did not take place, then the satellite can be suspended in the navigation system.

Therefore, it is extremely important to develop a method that, on the one hand, provides high accuracy of the output frequency with its tuning in autonomous mode, regardless of communication with the ground station. In the methods for QFS considered in [8, 18, 30, 31], the frequency tuning step is more than 1 Hz using a voltage setting of the voltage-controlled crystal oscillator 10.

The frequency tuning of the crystal oscillator is controlled by the AFC system 9, which includes a crystal oscillator control unit (XOCU) and a control unit that converts the signal from the quantum discriminator and calculates the tuning code for further sending it to the XOCU.

In the previous version of the software for the QFS control device, simple accumulation of all received data at different frequencies was used with further calculation of the value of the error signal of the microwave signal. In the new version, it is proposed 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 equally spaced from the beginning and end of the ordered series of elements.

III. The results of experemental investigations and dicussion

During of the using of the optical light signals for recording of resonance conditions on a photodetector, the important characteristic is the spectral density S_φ [8]. The value of S_φ has a significant effect on the S/N ratio. In fig. 2 shows the spectral densities of phase noises for two designs of the QFS (the previously used design and a new). In new design was used the method of improving the parameters of the microwave signal.

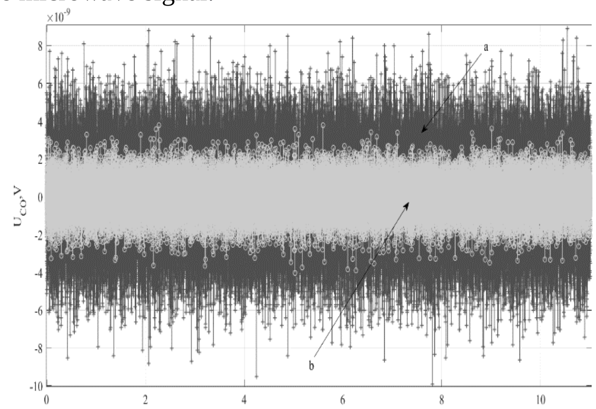

Fig. 2. The phase noise amplitude of error signal. (a) – corresponds to the earlier value of the error signal with simple accumulation, (б) – error signal using median filtration.

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

The spectral density of noise in the frequency range of the tuning of the resonant frequency of the quantum transition is presented on fig. 3.

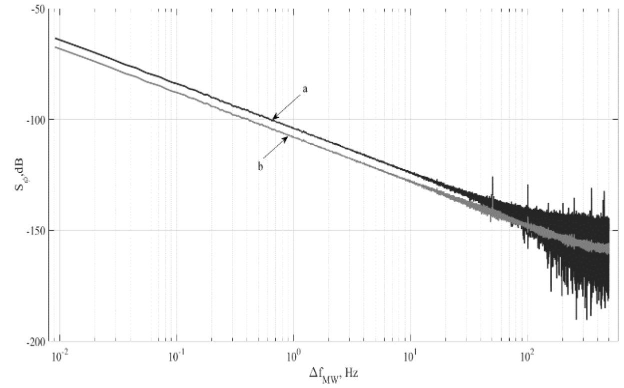

Fig. 3. The phase noise spectral power density of error signal: a - the previous version of the software; b - the new version.

An analysis of the obtained results of experimental investigations in fig. 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 fig. 4.

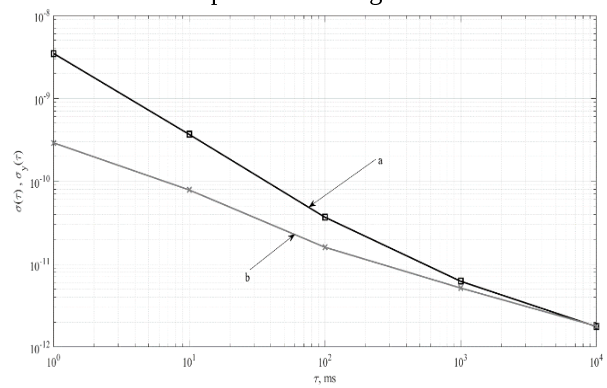

Fig. 4. The Allan deviation: (a) – previously used QFS construction, (b) – developed QFS construction.

The analysis of the obtained results (fig. 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 %.

IV. Conclusion

The obtained results have shown that the use of a new method of filtering data in the automatic frequency adjustment system of the microwave excitation signal reduces one of the most important disturbing factors (spectral noise density) that affects short-term frequency stability.

The experimental investigations of the metrological characteristics of the rubidium – 87 QFS are showed the improvement of the long-term frequency stability on 7 %. The resulting improvements in short-term and long-term frequency stability can improve the reliability of satellite transmission systems of large amounts of information.

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