Method of processing velocity increase of measuring results of quantum frequency standard parameters for information transfer velocity increase in satellite communication systems

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***Abstract*—The new method for frequency characteristics calculating of the quantum frequency standard on the rubidium atoms – 87 is considered. The implementation of this method in the developed software is presented. The processing of the experimental results with using a developed software is realized. The proposed method allows to adjust the standard frequency tuning on during its deviates to the nominal value over shorter interval of time than before. During this time interval, the information transfer rate does not deteriorate. The results of experimental investigations of the metrological characteristics are presented.**

Keywords—quantum frequency standard, velocity processing, information transfer, Allan deviation, root mean deviation, frequency drift

I. INTRODUCTION

Currently, one of the urgent tasks in modern communication and navigation systems is to increase the synchronization accuracy of the time scales between various devices [1-9]. This is necessary for obtaining of the reliable results during the investigations conducting of the Earth's surface, the upper atmosphere, the transmission and processing of large amounts of information at high speed [7-17]. Depending on the required accuracy of the synchronization of time scales, different models of frequency standards are used in the systems. The most optimal solution to this problem is the using of quantum frequency standards (QFS). Among the quantum frequency standards for various navigation systems the most popular were rubidium QFS, as them have small size and low cost compared to other types of QFS. These key advantages allow to use the rubidium standards in composed of the small-sized rubidium watches, which are widely used at base stations of the mobile communications and on board of the communication satellites [4, 18-21]. Such systems should are working the autonomously for a long time. Therefore, for information processing in them are used the various optical systems [20-26].

One of the most important characteristics of any standard is the stability of its operation. The stability is determined the quality of the QFS [1, 2, 4, 5, 19-21, 26-30]. To produce high-quality rubidium frequency standards (RFS), prototypes of the standard undergo various tests. The during implementation of these tests, it is necessary in real time to control the change in the frequency characteristics of the test sample, in order to identify instabilities in its work [4. 19, 26-28, 30 - 34]. And also to improve the frequency adjustment systems, since of the frequency drift in a satellite communication system will have a negative impact on the quality and speed of information transfer.

In real-time regime of the results tracking requires the increase of data processing velocity. The increasing of the large array processing velocity of the experimental data is one of the urgent tasks in this area. One of the possible solutions to this problem is presented in our work.

II. THE FREQUENCY CHARACTERISTICS OF THE STANDARD AND THE METHOD OF THEIR CALCULATION

The following methods are used to assess the stability of frequency standards: the standard deviation of the frequency (classical variance) is calculated and the Allan deviation is calculated [1, 5, 19, 27, 28, 30]. The standard deviation S of the group containing N measurement results is calculated by the formula:

$$S = \sqrt{\frac{\sum_{i=1}^{N}(x_i-\bar{x})^2}{\mathrm{N}-1}}, \qquad (1)$$

where x_i is result of frequency measurement on step i, $\bar{x}$ is the arithmetic mean value.

This characteristic is used to assess the stability of frequency standards, but its use can be difficult if there is a correlation between fluctuating values. In addition, as a result of various investigations, it was found that with many measurements, the use of standard deviation becomes ineffective in assessing the stability of frequency standards. Therefore, Allan proposed the original solution, the essence of which was as follows. The during a calculating the deviation, it is necessary to use the difference between two adjacent frequency measurements, and not the measurement of the frequency deviation from the mean value, as in the classical case. This method is called Allan deviation:

$$\sigma_y(\tau) = \sqrt{\frac{\sum_{i=1}^{N-1}\delta_{0i}^2}{2(N-1)}} \qquad (2)$$

where $\delta_{0i}$is relative frequency variation in the *i*-th measurement:

$$\delta_{0i} = \frac{f_{i+1}-f_i}{f_{rat}} \qquad (3)$$

f_i – value of frequency measure at *i*-th measurement, f_{rat} = 5 MHz – rated frequency value, N – number of measurements.

Currently, Allan deviation is the most convenient and more reliable measure to determine the stability of the frequency in the time domain. Its analogue in Russian standards is the mean square relative random variation σ (SRRV), which differs from the Allan deviation by a constant $\sigma_y(\tau) = \frac{\sigma}{\sqrt{2}}$.

For calculating of these frequency characteristics was been developed the following method. The total data stream which is coming from the measuring device is divided into time series. After that the corresponding characteristics are calculated. A time series is a sequence of observations of a parameter in successive equal time intervals t. Individual observations make up the level of the series and are denoted by x_t, where t = 1, ..., n. In the study of the time series, several components are distinguished:

$$x_t = u_t + y_t + c_t + e_t, t = 1, \dots, n, \tag{4}$$

where u_t is a smoothly changing component that describes the net influence of long-term factors (for example, linear frequency drift with time); y_t – seasonal component reflecting the frequency of processes over a not very long period (day, week, month, etc.); c_t is a cyclic component that reflects the recurrence of processes over long periods of time over one year; e_t is a random component that reflects the influence of random factors that cannot be taken into account and recorded (for example, the influence of external noise).

The first three components are deterministic components. The random component is formed as a result of a superposition of a large number of external factors that each individually have a minor effect on the change in the values of the investigated parameter.

Analysis and research of the time series allow us to build models for predicting parameter values for the future, if the sequence of observations in the past is known. Currently, time series are the most intensively developing, promising area of mathematical statistics. The using this approach, it is possible to reduce the time of the experiment and predict the behavior of the frequency characteristics of the standard based on the analysis of the data obtained. In our work during of the measurement results processing, we used the time series recommended by the state standard: 1, 2, 5, 10, 100 ... s. The value of the characteristic at each point in the time series is updated and filled in as data is received from the measuring device in real time. Thus, according to the data obtained, it is possible to investigate the standard stability and predict its future work.

III. CONDUCTING AN EXPERIMENT AND PROCESSING MEASUREMENT RESULTS

An experimental setup was used to assess the stability and quality of the standard. Its structural diagram is presented on fig. 1.

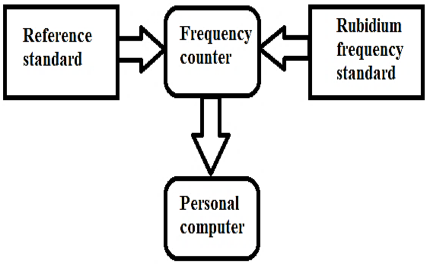
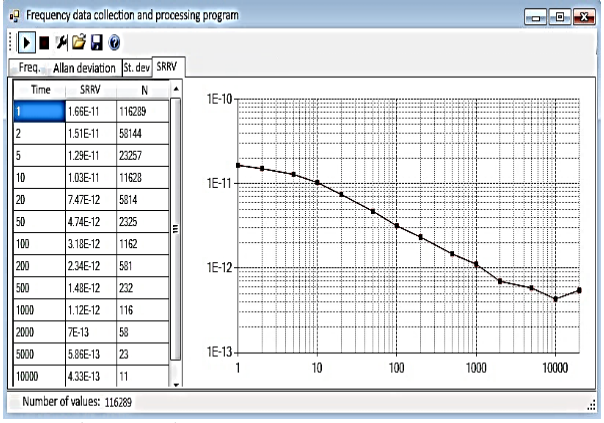


Fig. 1. Block diagram of the experimental setup.

One of the outputs of the test sample of the rubidium frequency standard is connected to the measuring device, which is used as a frequency counter Pendulum CNT-91. At the same time, a signal from the reference standard is sent to the frequency counter. The hydrogen standard is used as a reference in the experiment. The frequency counter in this case acts as a comparator, comparing the signal of the studied standard with a more stable signal of the reference standard. The obtained data from the frequency counter is fed to a computer, where they are analyzed and further processed.

To process the frequency values, special software was developed, which implemented the above calculation methods: standard deviation, Allan deviation and SRRV.

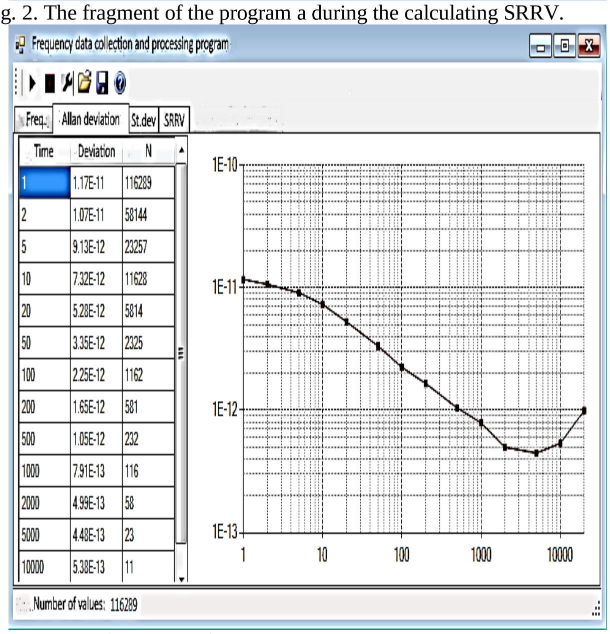
During the calculations, the interaction of two data streams was used: the first stream was used to obtain the primary frequency values from the device, and in the second stream, the required values were directly calculated. This processing algorithm proposed by us in the implementation of calculations using (1), (2) and (3) in the developed program allowed us to assess the stability of standards in real time and significantly accelerated the processing of experimental results. The calculation of standard deviation, Allan deviation and SRRV in the program during the experiment for two days is presented on fig. 2-4.



Time	SRRV	N
1	1.66E-11	116289
2	1.51E-11	58144
5	1.29E-11	23257
10	1.03E-11	11628
20	7.47E-12	5814
50	4.74E-12	2325
100	3.18E-12	1162
200	2.34E-12	581
500	1.48E-12	232
1000	1.12E-12	116
2000	7E-13	58
5000	5.86E-13	23
10000	4.33E-13	11

Number of values: 116289

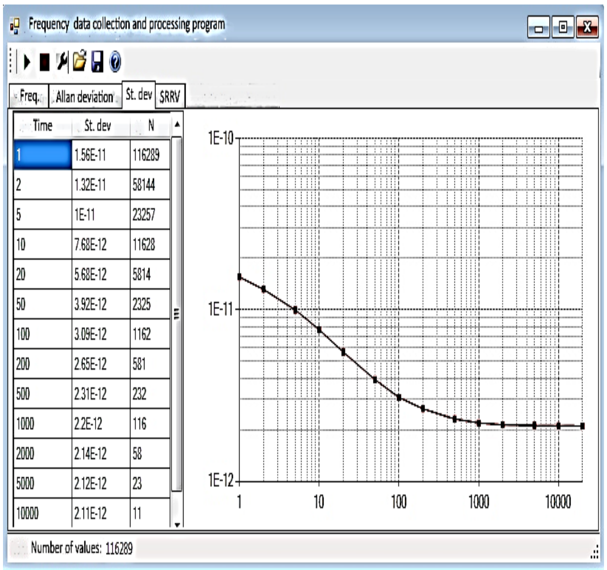
Fig. 2. The fragment of the program a during the calculating SRRV.



Time	Deviation	N
1	1.17E-11	116289
2	1.07E-11	58144
5	9.13E-12	23257
10	7.32E-12	11628
20	5.28E-12	5814
50	3.35E-12	2325
100	2.25E-12	1162
200	1.65E-12	581
500	1.05E-12	232
1000	7.91E-13	116
2000	4.99E-13	58
5000	4.48E-13	23
10000	5.38E-13	11

Number of values: 116289

Fig. 3. The fragment of the program a during the calculating Allan deviation.



Time	St. dev	N
1	1.56E-11	116289
2	1.32E-11	58144
5	1E-11	23257
10	7.68E-12	11628
20	5.68E-12	5814
50	3.92E-12	2325
100	3.09E-12	1162
200	2.65E-12	581
500	2.31E-12	232
1000	2.2E-12	116
2000	2.14E-12	58
5000	2.12E-12	23
10000	2.11E-12	11

Number of values: 116289

Fig. 4. The fragment of the program a during the calculating standard deviation.

The stability of the rubidium standard is influenced by various factors. One of them is frequency drift. Long-term frequency instability is determined by the drift and frequency drift of the reference transition. During the operation of the RFS, the composition and partial pressures of the filling components of the optical elements slowly change (diffusion inside the cell walls, gas leakage from the outside, etc.), which leads to a shift in the frequency of the reference transition. The values of these parameters can change under the influence of changes in ambient temperature and atmospheric pressure, which also leads to periodic departures of the frequency of the reference transition. Because of this, it is necessary to correctly evaluate the stability of the investigated standard.

Comparing the standard deviation and Allan deviation, we note that the use of standard deviation as a measure of frequency stability is not recommended. Since this value does not converge for some types of noise commonly found in frequency sources. The problem with standard deviation is associated with the use of deviations from the average value, which is not stationary for noise types with a large difference. This problem can be solved by using instead the first differences in the frequency values, as is done when calculating the Allan deviation.

We will analyze the data obtained, for this we compare the experimental results with the requirements for stability of the rubidium standard (table 1). To assess the stability of the frequency standard, we use SRRV. Since this value is recommended by the Russian state standard, it differs from the Allan deviation by a constant.

Comparing the values of the SRRV calculated during the experiment with the permissible values in the technical requirements, we can conclude that the tests of the rubidium standard are correct and that its stability is consistent with the required quality. The developed method made it possible to provide the necessary data processing speed for parallel computing of the standard deviation, deviation of Allan and SRRV. A small deviation of the SRRV value at $\tau = 1$ s can be explained by the influence of a random component (external noise). The analysis of the time series shows a decrease in stability at $\tau > 1000$ s; this can be explained by the influence of long-term factors, such as linear drift of the standard frequency, light shifts, and temperatures.

TABLE I. COMPARISON OF EXPERIMENTAL DATA WITH TECHNICAL REQUIREMENTS FOR THE STANDARD MODEL UNDER STUDY

Measurement time, τ, s	***SRRV(CNT-91)***	***SRRV (VCH-315)***	***SRRV (technical requirements), no more than***	***Stability***
1	$1.66*10^{-11}$	$1.08*10^{-11}$	$1.5 \cdot 10^{-11}$	Satisfactorily
100	$3.18*10^{-12}$	$3.73*10^{-12}$	$1.0 \cdot 10^{-11}$	Satisfactorily
1000	$1.12*10^{-12}$	$1.29*10^{-12}$	$5.0 \cdot 10^{-12}$	Satisfactorily

IV. CONCLUSION

The results of experimental investigations have shown that rubidium QFS is achieved the maximum stability of the measurement time $\tau \approx 1000$ s. The using of the method proposed by us and the developed software for its implementation allows to increase the processing velocity of measurement results in several times. This makes it possible to reduce the frequency adjustment time of during its deviates from the nominal value and maintain the quality and velocity of information transfer.

In addition, the using of the method of dividing data into time series allowed us to analyze the change in the characteristics of the standard in the long-term field. It is extremely important for implement of the reliable standard operation in the satellite information transmission systems.

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