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Possibility of using atomic clocks on mercury-199 ions in satellite navigation systems

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Abstract. The necessity of developing atomic clocks with high long-term stability for space exploration and improving the operation of satellite systems is substantiated. The photon detection system for the design of atomic clocks on mercury-199 ions for space applications is developed. A comparison is made of various data on the Allan deviation for various models of atomic clocks based on mercury-199 ions. For comparison, we used the results obtained by us and other scientists. The directions for further research are determined.

Keywords: satellite navigation system, atomic clock, atomic clock on mercury-199 ions, Paul ion trap, Allan deviation

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Возможность использования атомных часов на ионах ртути-199 в спутниковых навигационных системах

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Аннотация. Обоснована необходимость разработки атомных часов с высокой долговременной стабильностью для исследования космического пространства и улучшения работы спутниковых систем. Разработана система регистрации фотонов для конструкции атомных часов на ионах ртути-199 для космического применения. Проведено сравнение различных данных по девиации Аллана для различных моделей атомных часов на ионах ртути-199. Для сравнения использовались результаты, полученные нами и другими учеными. Определены направления для дальнейших исследований.

Ключевые слова: спутниковая навигационная система, атомные часы, атомные часы на ионах ртути-199, ионная ловушка Паули, девиация Аллана

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Introduction

Modern society in the age of advanced technologies cannot function without the exact time [1–7]. Especially in such areas as information transmission and navigation [1, 3, 8–12]. Atomic clocks or quantum frequency standards as high-precision devices provide a time reference for solving problems of information transfer and determination of object coordinates at any time [10–14]. The accuracy of positioning and synchronization of satellite navigation and positioning in outer space depends on the reliable operation of atomic clocks [15–20]. According to the positioning principle of navigation systems, and small deviation in time can lead to huge deviations, for example, if the time shift is 1 μs, the positioning accuracy will be shifted by 300 m, so to reduce the positioning deviation caused by time shift, increased requirements are imposed on the accuracy of atomic clocks [15–23].

At present, there are three types of modern space atomic clocks that are relatively well developed and widely used in global navigation satellite systems: cesium atomic clocks, rubidium atomic clocks, and passive hydrogen masers, these atomic clocks use the spectral lines of transitions of hyperfine energy levels of the ground states of atomic systems, to distinguish appropriate excitation signals and receive error signals, and then adjust the output frequency of the crystal oscillator to output a stable and accurate time-frequency signal [20–26]. There are problems when using these standards. In cesium atomic clocks the frequency instability is mainly influenced by the second-order Doppler effect and magnetic field, in rubidium atomic clocks it is mainly influenced by external environments such as optical shifts and buffer gases, and passive hydrogen masers it is mainly influenced by collisions with the vessel walls [16–29]. Therefore, it is necessary to adjust the frequency standards during the communication session with the Earth. With the development of satellite navigation system technology and deep space exploration technology, the characteristics of these space satellite atomic clocks no longer meet the requirements, and atomic clocks with better characteristics are needed as time standards, we have noticed that atomic clocks on mercury-199 ions can be the best solution.

Atomic clocks on mercury-199 ions are microwave atomic clocks, which entered the space after cesium atomic clocks, rubidium atomic clocks, and passive hydrogen masers, compared to them this new generation of atomic clocks uses the Paul ion trap to trap mercury ions, this device effectively reduces the collisions of ions with the wall and reduces interference from the external environment, eliminates the second-order Doppler effect [30–33]. The main problem in the development of atomic clocks on mercury-199 ions is associated with reducing the size and weight of the Paul ion trap, as well as reducing power consumption while maintaining the metrological characteristics that have been obtained for atomic clocks on mercury-199 ions ground application.

Principles of trapped mercury-199 ions to provide the necessary precision performance

The working principles of capturing mercury ions using the Paul ion traps have been described in detail in several papers [13–15, 19, 30–33]. Mercury-199 ions captured by the Paul ion trap interact with a wavelength $\lambda = 194$ nm (this can be provided by a laser, but the simplest option is to use a lamp with mercury-202 ions) and a microwave field, whose frequency is formed by the transition with a frequency equal to c/λ. When the frequencies match exactly, the maximum fluorescence signal is formed, which is registered by the photodetector. If the frequencies do not match, an error signal is generated and the frequency of the crystal oscillator is adjusted to the transition frequency. In this case, an important element is the photo counter. We proposed a new design for the photo counter (the block diagram is shown in Fig. 1).

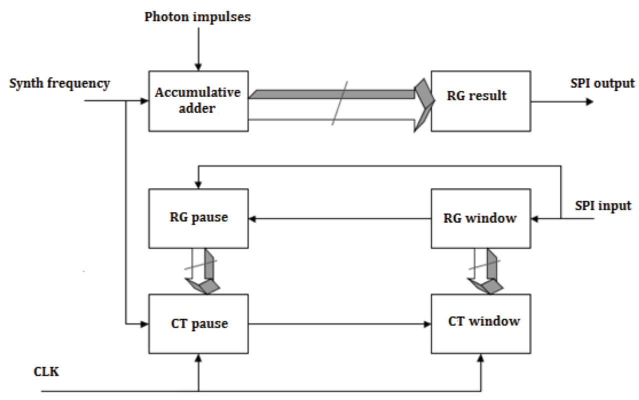

Fig. 1. Block diagram of the photon counting functional block

The input to the counter has three components: the modulation frequency, the signal of the clock frequency and the input data received from the microcontroller, which were sent to the input of counter, which generated a signal with variable counting and pause windows, and the counting of photon pulses at the corresponding time interval.

The sign of the pulse count is positive or negative due to the difference in the half-period of the signal of the frequency synthesizer signal, where the photons were recorded. The count result of the counter characterizes the frequency detuning of the crystal oscillator, on which basis the microcontroller forms a control voltage to change the output frequency of the crystal oscillator.

It is used to count photons by transferring signal parameters through the serial peripheral interface SPI. The data transfer standard of this interface allows the microcontroller and the peripheral to work in full duplex mode (receiving and transmitting information), where the data transfer is performed bit by bit.

On the one hand, using this design allowed to improve the signal-to-noise ratio, which depends on the number of photons and determines the accuracy of frequency tuning. On the other hand, it allowed reducing the weight and size of the frequency standard design.

Frequency stability analysis of quantum frequency standards

The following experimental setup (Fig. 2) was assembled for experimental studies of the output characteristics of the quantum frequency standard on cesium-133 and rubidium-87 atoms and the laboratory model of the standard on mercury-199 ions.

The signals from the reference and studied quantum frequency standards are fed to the VCH-308A comparator (Fig. 2). In the comparator, the phase-time method is implemented. Information about the signals is converted into time intervals, which are measured using a digital time interval meter. Then the signal is transmitted to a personal computer, where the information is archived and processed.

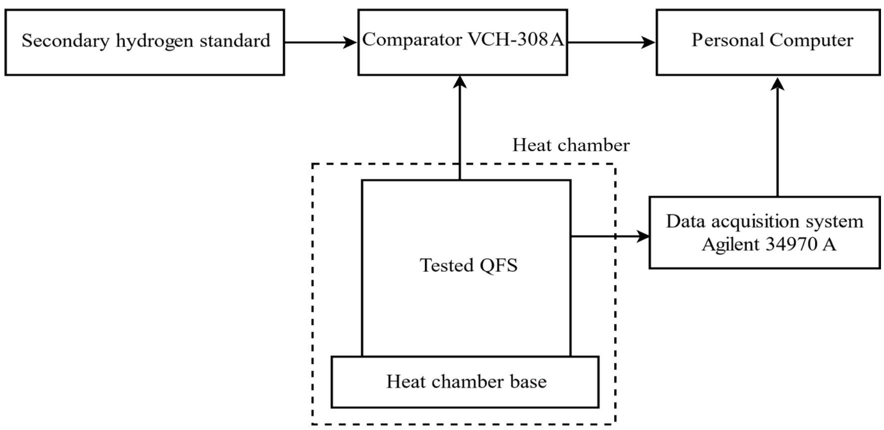

Fig. 2. Block diagram of the installation for the study of metrological characteristics

The measured parameters were controlled and monitored through a control circuit using the Agilent 34970A data acquisition system. The data acquisition system is connected to the same computer as the comparator. Every 100 seconds the frequency of the studied standards was measured. The obtained frequency values were recorded in the computer memory and then used to calculate the parameters that make it possible to estimate the frequency instability.

The Allan variance was chosen as a parameter to estimate the frequency instability and was calculated by using the following equation:

$$\sigma_y^2 = \frac{\sum_i^n \sigma_{0i}^2}{2(n-1)}, \tag{1}$$

where $\sigma_{0i} = \frac{f_{i+1} - f_i}{f}$ is the relative *i*th variation of the measured value of the frequency measure, n is the number of variations.

After processing the obtained data, graphs of the dependence of the values of the Allan deviation on time were plotted (Fig. 3). For comparison, Fig. 3 shows the results of the Allan deviation for other types of atomic clocks, which are placed on satellites. These data are obtained by other scientists.

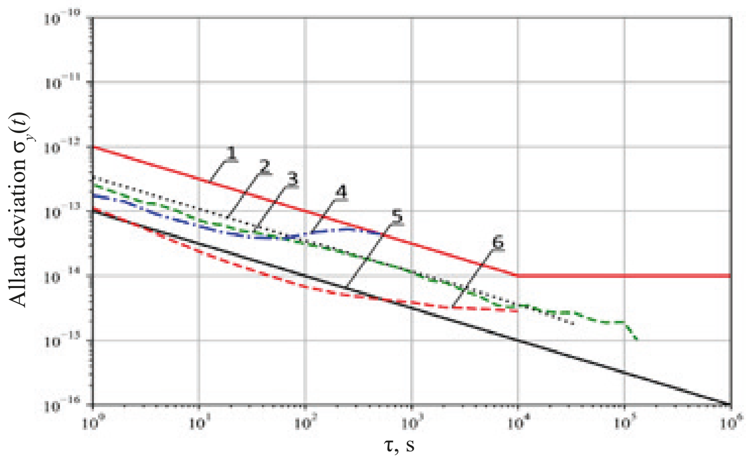

Fig. 3. Allan deviation of different current space atomic clocks and station communication on Earth. Curves *1*, *2*, *3*, *4*, *5*, and *6* correspond to the following atomic clock: Cs-133; Rb-87; ^{199}Hg ion – experimental layout; Leonardo RAFS – Galileo; PHM – ship communication station; PHM – communication station on Earth

Analysis of the Allan deviation data for various model atomic clocks shows that the atomic clocks on mercury-199 ions have better characteristics than others in some cases.

Conclusion

The obtained results showed that the atomic clocks on mercury-199 ions, compared with other types of atomic clocks, have higher stability of the output characteristics. This allows their use in spacecraft during flights to other planets, as well as in situations where the space orbit is already overloaded by other satellites.

The main problem of atomic clocks on mercury-199 ions is related to keeping the necessary number of charged ions in a fixed zone while reducing the size of the trap is now being addressed by groups of other scientists, to expand the possibilities for their use in various space systems.

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