New processing algorithm in quantum frequency standard on Hg-199 ions

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Abstract. In the paper the new processing algorithm for low mass-dimensional microwave frequency standards is developed. The newly constructed design for the driver system is presented. The comparisons of experimental Allan deviation data for the previously designed prototype are performed

1. Introduction
Currently, the successfully solving of the many tasks, 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 using 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 them are sources of highly stable, high-precision, spectrally pure signals [40-43].

The modernization process of standards’ design while lowering its mass-dimensional properties mostly leads to searching for new technical ideas leading to sufficient decreasing of mass and size for one of the main functional blocks as well as for developing new algorithms for automatic control and desired signal registration systems, signal that is used for determining the resonant frequency [28-32, 34, 35, 36, 39]. As it’s often occurring, there is not enough time and resources for holding a global fundemental research and developing brand new low mass-dimensional QFS models, that is why the majority of researches regarding QFS improvement are in fact a logical continuation of previously successfully implemented developments and methods in currently functioning devices.

2. Trap design
The core block of the microwave frequency standard on $^{199}$Hg+ ions is a magnetic trap which is also implemented in a plenty of other devices [35, 36, 39]. Magnetic trap is designed as n=4-pole with radius $r_o=0.7$ cm based on a design of Paul trap.

The alternating electro-magnetic field holds a required number of $^{199}$Hg+ ions in the magnetic trap in order to make them interact with $\lambda = 194.2$ nm radiation and emit a certain number of photons which then has to be registered by a PMT (Photomultiplier tube). Long-term and short-term stabilities are straight out connected a quality of ions’ trapping. Alongside with lowering mass and dimensions of the magnetic trap, electrode sizes for producing magnetic field are decreasing as well. That is why the requirements for
parameter stabilization of the operating signal, used for forming magnetic field, are increasing vastly. In order to solve such a task we developed a new block for controlling electromagnetic field that provides a proper trapping of charged particles.

We handled preliminary calculations before the design of this block. Charged particles in the trap are held with an effective potential:

\[ V_{\text{eff}} = \frac{n^2 V_0^2 q^2}{r_0^2 m^2 r'^2} \tag{1} \]

Trapping a particle with a single charge \( q \) shall be limited by mass \( m \): at the upper band – by a depth of effective potential and at the lower band – by a mean duration of an ion trapping. The requirements to voltage amplitude \( V_0 \) are performed when:

\[ \Omega \geq \Omega_{\text{min}} = \frac{n^{-1} \sqrt{E_m} \sqrt{m_{\text{max}}}}{3 r'} \frac{m_{\text{min}}}{r_0} \tag{2} \]

where \( E_m \) - kinetic energy of a single particle, \( \Omega \) - frequency of the operating signal, \( r' \) - normed radius value, \( m_{\text{max}} \) and \( m_{\text{min}} \) – maximum and minimum masses of trapped particles respectively.

3. Developing a new algorithm

In the current paper we present an algorithm for handling optical signal that is based on the handled research and calculations. The pattern for photon count and PEM (Photomultiplier tube) voltage output was taken into account while processing the received signal in microcontroller MCS-51. After final processing and calculations in the controller the operation signal is formed, the one used for driving power circuits which supply electrodes of the magnetic trap (core element in the device) through a coil system.

The photon counter determines time interval \( \tau \) that could be varied in a certain range depending on deployment conditions: from 1 to 10 seconds, the number of registered photons by PEM: from \( 10^4 \) to \( 5 \cdot 10^5 \). The driving system produces processing commands judging by the number of photons emitted with the help of the newly developed algorithm in order to drive the frequency of the main quartz generator and also the power circuits. Voltage output from these circuits passes transformer coils and corrects the magnetic field in the trap in order to ensure stable and precise maintenance of the device. The construction block scheme is presented on the fig. 1.

![Block scheme of the developed control system](image)

**Figure 1.** Block scheme of the developed control system
The whole correction cycle is represented as a feedback loop where the magnetic trap provides the controller with information regarding its resonance shift. The programmable part consists of CPU, counter and quartz generator driver (QGD), quartz generator itself receives the error signal information and shifts the produced frequency to resonance. The whole work is performed inside the counter and CPU-related parts, thus taking the most crucial tasks, digital and analog circuitry are also separated making it easier for developers to maintain the device as well as further reducing its size.

4. The results of the experimental research
The held research has shown that spectrums of the driving voltages in the new magnetic trap construction have no sufficient perturbations which may affect the stability of operation. The experiments show the slight short-term stability improvement by Allan deviation. On the fig. 2 the measurement results are presented.

![Figure 2. Allan deviation compared to the prototype. The red graph corresponds to the previously used standard design. The blue line corresponds to the standard design developed by us.](image)

The gained data has shown a stable work of the core physical block and low level of perturbations (negative 70 dB and less).

5. Conclusion
The experimental data provides the results that it was possible to ensure the magnetic trap stable maintenance while improving short term stability characteristics by 5% and long-term stability by 3% in comparison with previously designed Hg+ 199 prototype for navigational devices and communication systems in mobile flying vehicles.

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