Quantum Electronics **48** (10) 967–972 (2018)

OPTICAL FREQUENCY STANDARDS

https://doi.org/10.1070/QEL16778

Creation of the first Russian time and frequency standard on a fountain of ultracold rubidium atoms

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Abstract. **Technical specific features of the first Russian rubidium frequency standard of a fountain type are described, which are distinct from those of abroad analogues. Test results of separate systems and the metrological characteristics of the standard are presented. The achievable output frequency instability is 4×10^{-16} per measurement interval of 24 hours and 1×10^{-16} per 16 days.**

Keywords: *frequency standard, ultracold atoms, high-vacuum pump, magnetic field formation system, thermostabilisation, long-term instability.*

1. Introduction

Modern technologies of laser cooling and atom motion control are powerful instruments for developing and producing new-generation ultra-high-precision stability references – time and frequency standards. The random error of modern frequency references on cold atoms operating in the microwave range is substantially below 1×10^{-15} [1]. The practical employment of such accuracy requires time and frequencyt stable references, that is, devices capable of keeping the frequency and time units for a long period with minimal accuracy degradation after the calibration by a primary standard.

Presently, active hydrogen masers are used as the most stable frequency references. However, their instability is fundamentally limited by uncontrolled variation of the atomic line frequency due to the ageing of the storage bulb coating. The limiting frequency instability of modern hydrogen oscillators may reach 3×10^{-16}, substracting a linear drift [2].

One more important field is synchronisation of the scales of promising onboard synchronising units in navigation systems with the instability of $(1-5)\times10^{-15}$ [3]. This approach requires creation of terrestrial time and frequency standards possessing an instability of about 1×10^{-16}. Presently, the most promising one is the rubidium frequency standard on cold atoms, that is a rubidium fountain frequency standard (RFFS). As compared to a caesium fountain, the rubidium fountain may provide a several times greater flow of active atoms. In addition, the density of active atoms may be maximally increased because the spin-exchange interaction that limits the accuracy in caesium standards is approximately 100 times less in a rubidium standard than in caesium [4].

Modern reliable and advanced synchronisation of the time scales for onboard synchronising devices requires terrestrial time and frequency standards placed in several distant territories [5]. It is important to develop a rubidium frequency standard based on a fountain of cold atoms, which, as opposed to traditional standards developed and operating in world observatories (SYRTE, USNO, etc.), might be preliminarily assembled and adjusted at the factory in the form of bulk units, delivered to a customer and put into operation after short-term final mounting and fine adjustment.

2. General operation principle of a frequency standard on a fountain of cold atoms

The RFFS is a pulsed frequency standard, which functions in continuously repeating cycles. At the end of each cycle, it presents a numerical value of the frequency difference between the interrogation signal (formed by the synthesiser from a reference signal) and ‘clock’ transition in rubidium atom (6834682610.9043126 Hz). A detailed energy level diagram for the Rb atom is given in [6], and a general RFFS appearance is presented in Fig. 1.

The operation cycle of the RFFS comprises the following main stages.

1. Formation of a cloud of cooled atoms and launching it along a ballistic trajectory through an atomic spectroscope.

The interaction of atoms with a microwave field in the Ramsey scheme yields a very narrow resonance peak, the width of which is inversely proportional to the time interval between the first and the second interaction. It is critically important that the field is phase-coherent between the two interactions, and the coherence of rubidium atoms is not lost, that is, the atoms should be in a free flight rather than interacting either with the field, or with reservoir walls. However, at room temperature, atoms chaotically move in space at a velocity of $\sim$4000 km h^{-1}. In order to keep them localised within a uniform field cavity domain ($\sim$10 mm) for a time of 0.5 s (such an interval between interactions provides a line width of 1 Hz) it is necessary to cool them to a temperature of $\sim$1 μK. This is realised through a multi-stage laser cooling in the so-called ‘optical molasses’ in chamber II (Fig. 1).

After a sufficient number of rubidium atoms are cooled down in the optical molasses, the formed cloud of cold atoms is launched upward vertically like water in a fountain (the

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Received 3 July 2018; revision received 1 August 2018
Kvantovaya Elektronika **48** (10) 967–972 (2018)
Translated by N.A. Raspopov

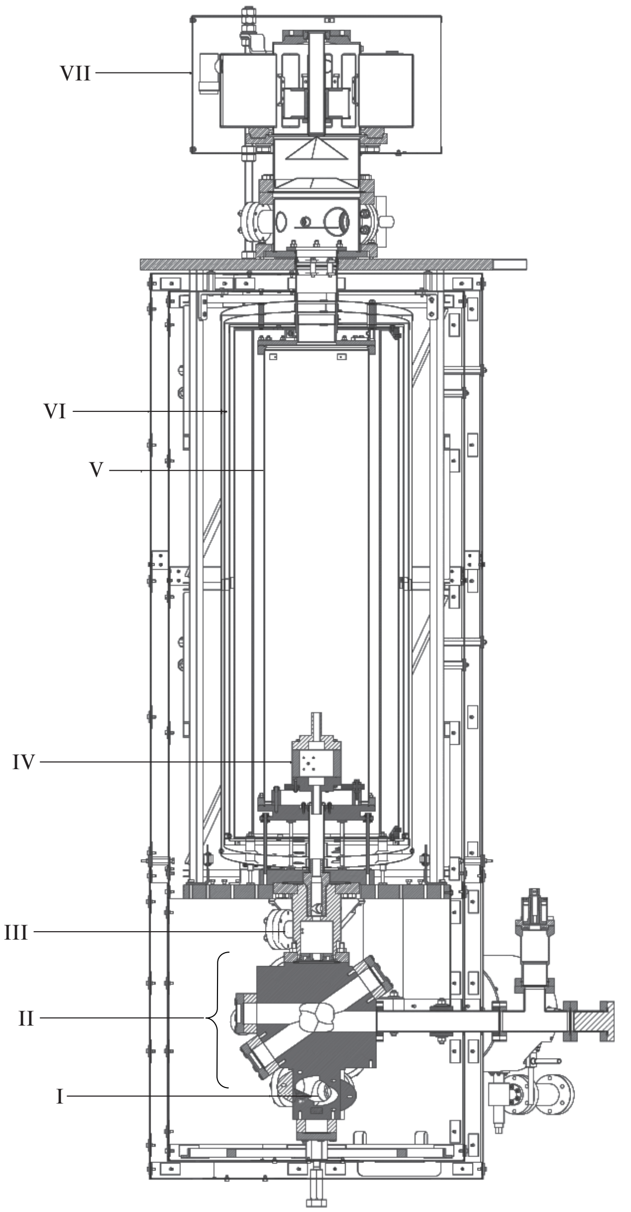

Figure 1. General appearance of the RFFS:
(I) detection zone; (II) molasses chamber; (III) state selection cavity; (IV) Ramsey cavity; (V) vacuum volume of the free flight zone; (VI) magnetic shield; (VII) high-vacuum pump.

name of this kind of devices originates from this analogy). Thus, the double successive interaction of the atomic cloud with the interrogation signal is realised in the cavity (so-called Ramsey cavity) during the upward and downward transits.

2. Selection of active atoms by means of the interaction with the microwave field and optical radiation.

Prior to the first interaction with the interrogation signal in the Ramsey cavity, the cloud of cold atoms passes through a so-called 'state selection' cavity III (Fig. 1). All atoms in states distinct from $5^2S_{1/2}$ ($F = 1$, $m_F = 0$) are removed from the coud in this resonator, because only this state participates in the following interaction in the Ramsey cavity and forms the 'clock' transition. The rest atoms do not participate in the interaction, but only make the resonance line wider due to the collision broadening and, moreover, reduce the signal-to-noise ratio because they additionally knock-out atoms from the cloud in the process of the free flight.

Atoms in the state $5^2S_{1/2}$ ($F = 1$, $m_F = 0$) are selected by means of their interaction with a microwave field and optical radiation. At the instant when the atomic cloud leaves the molasses, rubidium atoms are in states $5^2S_{1/2}$ ($F = 2$, $m_F = \pm 2, \pm 1, 0$). In the state selection cavity, the cloud interacts with the microwave field, which is in resonance with the transition $5^2S_{1/2}$ ($F = 2$, $m_F = 0$) $\leftrightarrow$ $5^2S_{1/2}$ ($F = 1$, $m_F = 0$). In this case, all the atoms at the sublevel $5^2S_{1/2}$ ($F = 2$, $m_F = 0$) execute the induced transition to the sublevel $5^2S_{1/2}$ ($F = 1$, $m_F = 0$), while the other atoms stay in the level $5^2S_{1/2}$ ($F = 2$). Immediately afterwards, the atomic cloud is hit by the laser beam, which is in resonance with the cyclic transition $5^2S_{1/2}$ ($F = 2$) $\leftrightarrow$ $5^2P_{3/2}$ ($F = 3$). This laser beam (let us call it the uncompensated beam) affects the atomic cloud from only one side; hence, it 'heats up' the atoms at the level $5^2S_{1/2}$ ($F = 2$) and pushes them out from the cloud. Thus, finally only the atoms at the sublevel $5^2S_{1/2}$ ($F = 1$, $m_F = 0$) remain in the cloud and participate later in the Ramsey interaction.

3. Double successive interaction with a microwave field of the interrogation signal in the cavity as the atomic cloud passes upwards and downwards (Ramsey interaction).

For obtaining the spectral pattern with a narrow central peak shown in Fig. 2 (Ramsey fringes), it is necessary to execute double successive interaction of the atomic cloud with a microwave field. In this case, the width of the central fringe used for stabilising the reference oscillator is inversely proportional to the time interval between the interactions. One of the main requirements to Ramsey interaction is free (unperturbed) evolution of the quantum state of atoms in the cloud and phase-continuity of the microwave signal between the interactions. The most efficient way to satisfy these requirements is launching the atomic cloud vertically upwards through the Ramsey cavity IV (see Fig. 1), in which the atomic cloud interacts with the interrogation signal. In this case, the atomic cloud in the cavity interacts twice with the field while passing upwards and downwards. Between the interactions, the quantum state of atoms in the cloud evolves freely, that is, the microwave field does not expand outside the cavity due to the employment of evanescent waveguides. In such a configuration, the time interval between the interactions and, consequently, the central fringe width are determined by an initial velocity or height of launch of the atomic cloud.

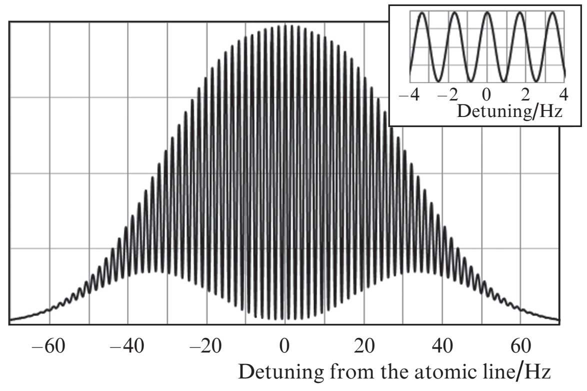

Figure 2. Ramsey fringes. The inset shows central fringes; the central fringe width is 0.8 Hz.

At the initial velocity of the atomic cloud (4.1 m s^{-1}), which provides the launch height of 87 cm, the central fringe width is less than 1 Hz (see Fig. 2).

4. Atom detection and calculation of the probability for the rubidium atom transition from the level $5^2S_{1/2}$ ($F = 1$, $m_F = 0$) to $5^2S_{1/2}$ ($F = 2$, $m_F = 0$).

For determining the probability of the Rb atom transition from the level $5^2S_{1/2}$ ($F = 1$, $m_F = 0$) to $5^2S_{1/2}$ ($F = 2$, $m_F = 0$) as a result of the microwave Ramsey interaction, which, as mentioned, depends on the frequency detuning between the interrogation signal and the 'clock' transition frequency it is necessary to measure the populations of levels $5^2S_{1/2}$ ($F = 1$, $m_F = 0$) and $5^2S_{1/2}$ ($F = 2$, $m_F = 0$).

For this purpose, at the final phase of the RFFS operation cycle, the atomic cloud passes to the detection zone I (see Fig. 1), where a system of prisms and mirrors forms an optical field of a special configuration. In the first zone, the laser radiation interacts with atoms occupying the level $5^2S_{1/2}$ ($F = 2$, $m_F = 0$), and a photodetector records the luminescence intensity proportional to the population of this level. Then in the second zone, the uncompensated laser beam, similarly to the beam in the state selection cavity 'heats' atoms at the level $5^2S_{1/2}$ ($F = 2$) and pushes them out from the cloud. In the third zone, the laser radiation resonant to the transition $5^2S_{1/2}$ ($F = 1$) ↔ $5^2P_{3/2}$ ($F = 2$), transfers all atoms from the state $5^2S_{1/2}$ ($F = 1$) to $5^2S_{1/2}$ ($F = 2$) with optical pumping and spontaneous relaxation. As a result, detection in the fourth zone is similar to that in the first zone; however, in the former case the luminescence signal is proportional to the number of atoms initially resided at the level $5^2S_{1/2}$ ($F = 1$, $m_F = 0$). Thus, the populations of both levels of the 'clock' transition are determined and, respectively, the transition probability in the result of microwave Ramsey interaction is found.

After detection, the atomic cloud is absorbed by a graphite-getter pump at the bottom part of the standard, and the RFFS operation cycle starts again.

3. Main construction differences of the atomic fountain produced by 'Vremya-CH' from world analogues

Outstanding metrological characteristics obtained required the knowledge and experience of leading companies and institutes in this field. In particular, the laser system, which provides an optical radiation for all components of the RFFS (the molasses chamber, state selection cavity, detection zone) is made completely of fibre-optical elements, which increases the reliability and robustness.

The main units of the RFFS were preliminarily assembled, tested, and adjusted in Nizhny Novgorod; then those were transported to All-Russian Scientific Research Institute of Physical-Technical and Radiotechnical Measurements (VNIIFTRI), where the complex was finally assembled and thoroughly adjusted. For a such complicated logistic scheme, substantial changes and improvements with respect to a conventional construction of the frequency standard based on a cold atom fountain have to be made:

– ruggedise the mechanical construction for providing the necessary stability during transportation to the customer;

– change the vacuum part of the spectroscope for increasing vibration robustness and mechanical reproducibility;

– apply a multisection temperature control system, which substantially reduces temperature stability requirements to the laboratory, where the RFFS is arranged;

– improve the system of the magnetic field formation and stabilisation in the atomic spectroscope (five layers of magnetic shields, a solenoid with compensation coils, an active stabilisation system for the magnetic field in the atom molasses), which may weaken the requirements to instability of the technogeneous magnetic field in the place of the RFFS arrangement.

All elaborated and applied improvements are described below.

Mechanical construction of the RFFS. Since the preliminarily assembling of the spectroscope and preparation of the vacuum unit were made at the JSC 'Vremya-CH' and then the preliminarily outgased spectroscope was transported to VNIIFTRI, substantial changes were made in the classical spectroscope construction for providing its vibration resistance during transportation.

First, vacuum joints were completely separated from the carrying structures. The vacuum part of the spectroscope is not structurally tied to carrying hexahedral supports and the upper platform on which a massive high-vacuum pump is arranged. This substantially unloaded (the total weight of the atomic spectroscope with a system of magnetic shields is more than 200 kg) the vacuum joints and made it possible to transfer the most of vibration loads arising during the transportation from vacuum parts of the spectroscope to rigid carrying supports.

In addition, the entire vacuum part of the atomic spectroscope is made of titanium, which noticeably improves its strength, reduces the weight, and provides a substantially higher degree of vacuum purity inside the spectroscope without additional polishing (in contrast to aluminium). The employment of titanium allows one to use high-vacuum flanges with metal gaskets (made of indium or copper) in the construction and, hence, avoid a complicated technology for welding heterogeneous materials.

Vacuum system of the RFFS. The level of residual vacuum in the atomic spectroscope is a key factor in obtaining high metrological characteristics of the standard, because it affects both the number of cooled atoms arriving at the detection zone (and, respectively, the signal-to-noise ratio) and the atomic line broadening due to collision effects.

A pressure of residual gases in the spectroscope mostly affects the number of cooled atoms passing to the detection zone, because collisions of residual gas molecules with cold rubidium atoms accelerate the latter and force them to leave the cloud before passing to the detection zone. It is established experimentally that at a pressure of residual gases in the spectroscope of about 1×10^{-8} mbar, the cloud of cold atoms completely dissipates while passing to the detection zone. Thus, the proper functioning of the standard on a fountain of cold atoms requires that the pressure in the vacuum part V of the spectroscope (see Fig. 1) be below 1×10^{-9} mbar.

In a classical scheme of a frequency standard on a fountain of cold atoms the needed vacuum in the spectroscope is provided by several powerful ion pumps. However, there are some drawbacks critical for the project. First, an ion pump comprises strong magnets, which produce a high-intensity magnetic field environment. Complicated systems of shield and magnetic field compensation are needed in order to reduce the influence of pump stray fields on the atoms residing in the molasses and free flight zones. In addition, ion pumps with a high pump rate, which is needed for maintaining the pressure of residual gases in the spectroscope below 1×10^{-9} mbar are rather massive. This is not a problem for laboratory equipment; however, it substantially complicates transportation from the place of assembly to a customer in the framework of the project.

For solving these problems, a combined high-vacuum pump was developed and employed by 'Vremya-CH' (Fig. 3). It comprises three kinds of pump elements. The main pump rate of more than 2000 L s^{-1} with respect to N_2 is provided by a section made of a non-evaporable TiV-getter. Such a pump has a high pump rate for most of atoms and molecules; however, it does not pump noble gases due to physical principles. Noble gases (mainly argon passing to the spectroscope from ambient atmosphere) are evacuated from the RFFS atomic spectroscope by using an ion pump section with a relatively low pump rate ($\sim$67 L s^{-1} with respect to N_2). In order to increase the pump rate for noble gases, some electrodes in the ion pump section are made of tantalum. In addition to the problems mentioned above, which are specific of any frequency standard with a vacuum unit, there are additional difficulties in the case of rubidium frequency standards related to evacuation of residual rubidium vapours. This chemical element belongs to alkaline group and possesses high chemical activity; hence, on open surfaces including plates of the ion pump and vacuum windows it reacts with a surface material and produces a persistent film. The film prevents further pumping in the ion pump and blocks the laser beam passing through the vacuum windows. To prevent these destructive consequences, the critical elements of the spectroscope are protected by elements made of high-purity graphite with a high pump rate with respect to Rb. For evacuating rubidium produced in a result of sputtering from a cold cloud, getter insertions from high-purity graphite are used in the RFFS combined pump.

RFFS thermostabilising system. The maintaining of stable preliminarily prescribed temperature in the atomic spectroscope and its constituting parts is very important for obtaining the required metrological characteristics of the RFFS. First, the copper thermal expansion due to a temperature change affects the Ramsey cavity frequency: the temperature coefficient for the cavity frequency is 110 kHz °C^{-1}. Due to the pulling effect, a change in the Ramsey cavity frequency results in a change in the RFFS output frequency. The coefficient of temperature influence on the RFFS output frequency depends on the cavity and atomic line Q-factors. The latter, in turn, depends on the number of cold atoms in the cloud. At the cavity Q-factor of 10000 and the number of cold atoms 1×10^7 (the parameters reached in the RFFS), the coefficient of temperature influence on the RFFS output frequency due to cavity frequency variation is s, in the worst case, 7×10^{-16}/°C.

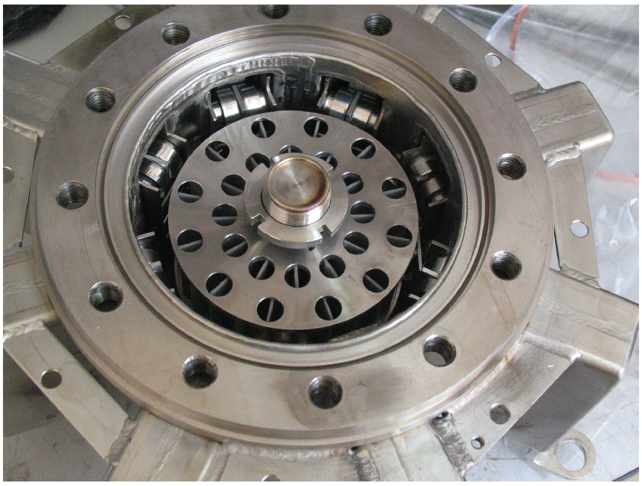

Figure 3. Main combined high-vacuum pump.

Thus, in order to exclude the influence of a cavity temperature variation on the instability of the RFRFT output frequency and reach the instability of less than 4×10^{-16} per 24 hours it is necessary to maintain the cavity temperature with an accuracy of ±0.2 °C.

The RFFS output frequency is also affected by a temperature of atomic cloud 'environment' (walls of the vacuum chamber and cavity, and so on), because the thermal radiation of the 'environment' shifts the atomic line due to blackbody radiation. The coefficient of the sensitivity of clock transition frequency due to this shift is 1.7×10^{-16}/°C, linearided for small temperature changes around the room temperature. Thus, at the temperature stability specified above, the frequency shift of the atomic line due to the influence of blackbody radiation contributes to the RFFS frequency instability budget at most 1×10^{-16} at the measurement interval of 24 hours.

In addition, if an RFFS is used as both a stability and an accuracy reference, then not only the stabilities of temperature shifts are critical, but also their absolute values. These values are determined as integrals of the frequency shifts at each trajectory point with a complicated weight function, because the velocity of flight of the atomic cloud inside the atomic spectroscope is not constant, and the transit time is different in each trajectory section. Thus, in order to most accurately calculate the resulting temperature shift of the atomic line frequency not taking into account the weight function, it is necessary to provide the maximal spatial homogeneity of temperature of the atomic cloud 'environment' along the flight trajectory in the atomic spectroscope.

In the most of world metrology laboratories, this problem is solved through temperature stabilisation in a room where the standard of the fountain type is arranged. However, this applies severe limitations on the room thermo-stabilisation system and, thus, makes it noticeably more complicated and expensive. 'Vremya-CH' provides RFFS operation in laboratories without precision thermostabilising systems by using its own system for temperature stabilisation.

This system is based on a multi-section heater and the control block, which obtains information from temperature sensors arranged on a spectroscope surface. The multi-section (10 completely independent sections) heater eliminates 'ambient' temperature gradients along the trajectory of the atomic cloud flight. Parasitic magnetic fields are excluded by using the bifilar winding in the heaters and pseudorandom noise sequence for powering them. Additionally, four precise calibrated PT100 sensors are included in the system to measure the absolute temperature of vacuum volume walls with an accuracy of less than 0.3 °C for further calculations of the RFFS output frequency shift due to blackbody radiation.

System of the magnetic field formation and stabilisation in the RFFS. One of the main sources of the RFFS output frequency instability is a magnetic field in the free flight zone, which affects the clock transition through the quadratic Zeeman effect:

$$\Delta\nu_{00} = K_Z^{(2)} B^2,$$

$$K_Z^{(2)\mathrm{Rb}} = 575.14\times10^8\ \mathrm{Hz\ T^{-2}},$$

where $\Delta\nu_{00}$ is the 'clock' transition frequency variation; B is the magnetic field induction; and $K_Z^{(2)}$ is the second-order Zeeman coefficient.

Hence, for obtaining high metrological characteristics it is necessary to maintain a high accuracy and stability of the magnetic field in the free flight zone. First, the transit zone should be shielded against the Earth's magnetic field and its variations. Since the frequency of the atomic transition depends quadratically on the magnetic field induction, at an equal absolute change in the magnetic induction ΔB, the value of atomic line frequency variation $\Delta\nu_{00}$ will be greater for a stronger induction B. Thus, for reducing the influence of external magnetic field variations on the atomic line frequency it is necessary to minimise the magnetic field in the flight zone. For this purpose, the RFFS construction employs the system of magnetic shields VI (see Fig. 1), which comprises five layers of a magnetically soft material and has the total coefficient of external magnetic field shielding of more than 10^5.

However, at the exactly zero magnetic field induction, sublevels with different magnetic quantum numbers m_F degenerate and so-called Majorana transitions arise. In this case, some atoms leave the sublevels with the magnetic quantum number $m_F = 0$ and do not participate in the Ramsey interaction, thus, reducing the signal-to-noise ratio and stability of the RFFS output frequency. For excluding this effect, a special non-zero magnetic bias is produced in the flight zone. Similarly to the effect of temperature influence on the RFFS output frequency, the magnetic field also has the accumulation effect along the trajectory of atomic cloud motion. Hence, for accurate calculation of the value of the atomic line shift due to the Zeeman effect, it is necessary to produce a maximally homogeneous magnetic field along the atomic cloud flight trajectory. A solenoid is used for this purpose. Since its length is finite, compensating coils are wound over the main solenoid in order to compensate for the side effects and eliminate local inhomogeneities. There are four such coils in the RFFS construction.

Thus, the employment of a complicated system for screening external magnetic fields and forming the bias field in the flight zone allows one to use RFFS in laboratories with a complicated magnetic environment of both geological and technogenic nature.

4. Results of the employed technical approaches

As a result of this work, two rubidium frequency standards of the fountain type were produced, mounted, and put in operation. A series of investigations were performed in the process of adjusting these standards, which proved appropriateness of the technological solutions.

1. The number of cold atoms in the cloud was above 10^7 in both standards. The number of atoms arrived at the detection zone was 10^6. These two parameters along with the atomic cloud lifetime in the optical molasses (more than 1 sec) testify that the pressure of residual gases did not exceed 1×10^{-9} mbar both in the molasses and in the free flight zones. Such a level of residual vacuum was reached due to the thorough preparation of constituting parts, employment of high-vacuum in-house-design flanges, and by using the combined high-vacuum pump.

2. The employment of the specially constructed solenoid and thorough adjustment of the compensating coils resulted in obtaining the magnetic field inhomogeneity along the atomic cloud flight trajectory of ±2 nT. This is not the limiting value for the developed system of the magnetic field formation in the flight zone. However, at the present stage, it is limited by the sensitivity of the magnetic field sensor employed in preliminary adjustment. In the future, measurements of the frequency of magneto-sensitive transition $5^2\mathrm{S}_{1/2}$ ($F = 1$, $m_F = 1$) $\leftrightarrow$ $5^2\mathrm{S}_{1/2}$ ($F = 2$, $m_F = 1$) will give a possibility to additionally adjust the compensation coils and obtain the magnetic field inhomogeneity of 1 nT.

5. Conclusions

After installing two rubidium fountain frequency standards at the VNIIFTRI and their final adjustment, these devices were put in operation in the State Time and Frequency Service of the Russian Federation and are presently used for keeping the state unit of time. Instability characteristics of the difference signal from two RFFS's demonstrate outstanding results for the output signal (Fig. 4): the instability of less than 4×10^{-16} at the interval of 24 hours and less than 1×10^{-16} at the interval of 16 days. These values correspond to world analogues and even surpass them.

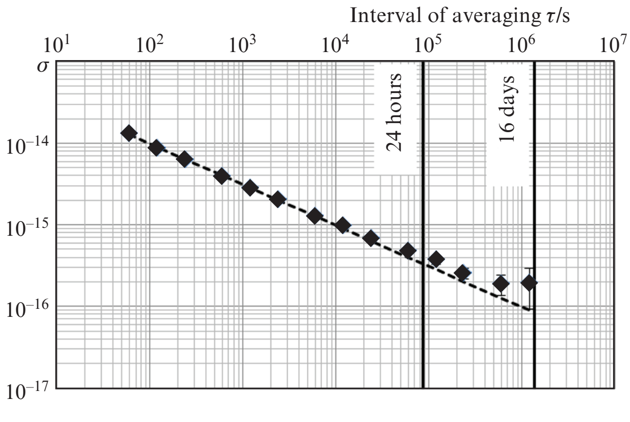

Figure 4. Two-sample deviation σ of the difference signal for two RFFS's (points refer to measured data, dashed curve is approximation at $\sigma = 9.22\times10^{-14}\sqrt{\tau}$).

Note that the mutual drift of the two RFFS's is smaller than the measurement uncertainty for presently available measurement intervals and does not exceed 3×10^{-17} for 24 hours. In addition, the absolute frequency difference of the output signals from two RFFS's is less than 1×10^{-14}, which completely agrees with the uncertainty of the bias field in the flight zone of the RFFS (±2 nT). This value of the field uncertainty related to Zeeman effect yields the uncertainty of the RFFS output frequency of 1.1×10^{-14}.

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