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Towards an optical time scale at VNIIFTRI

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Abstract. **A frequency chain for converting the frequency of an optical clock based on ultracold ^{87}Sr atoms is updated for its comparison with the frequency of microwave standards from the State Primary Standard of time and frequency units and the national time scale, GET 1-2018. The results of the corresponding experiments are reported and analysed. An instrumental complex for reproducing and keeping the time and frequency units and the national time scale of the primary standard is described; this complex includes an optical clock based on strontium atoms and microwave standards of new generation. The order of the atomic time scale generation with application of optical clocks is also determined.**

Keywords: *optical clock, time scale, ultracold atoms.*

1. Introduction

The definition of the second in the International System of Units SI is expected to be changed in the foreseeable future. The Consultative Committee for Time and Frequency (CCTF) has recommended a series of practical steps, which are necessary to redefine the second in the SI system: from the current definition, based on the microwave hyperfine transition in ^{133}Cs atoms, to a new one, which will be based on measuring the optical clock frequency [1, 2]. One of the procedures that must be carried out before starting the transition to the new definition of the second is the analysis of the possibility of applying a highly stable optical clock (OC) in order to form the International Atomic Time Scale TAI in correspondence with the procedures established for microwave standards [3]. To implement this approach in practice, national time laboratories should perform a long-term (several years) high-accuracy comparison of optical clocks with the microwave standards including in the composition of national standards and form local TA (k) scales with allowance for the results of this comparison. Based on these data, transferred from national laboratories to the International Bureau of Weights and Measures (BIPM), the latter should establish and maintain the international time scale TAI.

A comparison of the time scales TA (k) generated with allowance for the contribution of a highly stable optical clock should demonstrate a better convergence of national time scales in the nearest decade and thus justify experimentally the expediency of accepting the new definition of the second. Therefore, the implementation of the contribution of OCs to the generation of the atomic time scale TAI (a step recommended by CCTF) is an urgent task of time and frequency metrology.

An optical clock based on ultracold (trapped in the optical lattice) ^{87}Sr atoms has been developed at the VNIIFTRI (Russia). In 2018 this standard was introduced into the State Primary Standard of time and frequency units and the national time scale, GET 1-2018.

The uncertainty budget for the reproduction of time and frequency units for modern optical clocks is about 10^{-17} [4 – 8]. However, the contribution to the generation of TAI and uncertainty in reproducing the second from the OC based on ^{87}Sr atoms is $\sim 4 \times 10^{-16}$, because the $^1S_0 - ^3P_0$ transition in this atom is used for secondary redefinition of the second in the SI system of units [9]. The absolute frequency of this optical transition is determined proceeding from the previous measurements relative to the reference hyperfine transition in ^{133}Cs atoms when comparing the frequencies of OCs based on strontium atoms and the primary caesium fountain frequency standards [10 – 13]. The order of magnitude of the uncertainty of the latter is several units per 10^{-16} [10 – 15].

Currently, there are about ten functioning primary caesium fountain frequency standards in metrological laboratories all over the world. Only six laboratories, including the laboratory of the VNIIFTRI, present regularly the results of their measurements to the BIPM, based on which the latter sets and maintains the time scale TAI.

After performing the first measurements of the ^{87}Sr OC frequency at the VNIIFTRI [16], we transformed the scheme of experiments aimed at comparing the frequency of the OC based on ultracold ^{87}Sr atoms with the frequency of an ensemble of hydrogen masers, which form the main part of GET 1-2018. In this paper we describe the composition of the instrumental complex GET 1-2018, order of the generation of the time scale, and an updated scheme for measuring the OC frequency [16, 17] relative to the frequency of an ensemble of hydrogen masers. The values of the Allan deviation (type-A statistical uncertainty) found when measuring the clock laser frequency stabilised by the

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${}^1S_0-{}^3P_0$ transition in ^{87}Sr atoms relative to the frequency of one of the hydrogen masers entering the primary standard are reported. The factors contributing to the statistical uncertainty u_A are as follows: uncertainty of the conversion from optical frequencies to the rf range, uncertainty of transferring the hydrogen maser frequency to the laboratory for comparing with the OC frequency, and the instrumental measurement error.

The OCs based on atoms trapped in an optical lattice, developed at different laboratories, have not yet achieved the reliability typical of microwave clocks. The reason is that an OC based on strontium atoms should contain several simultaneously operating ultra-stable laser sources. The time of continuous reliable operation of an OC on strontium atoms may range from several hours to several days [18, 19], which is much shorter than the working time of not only hydrogen masers but also caesium standards, including the fountain-type frequency standards. In this context, when comparing the OC frequencies with the frequencies of continuously operating keepers of frequency and time (hydrogen masers), one must minimise the uncertainty on time averaging intervals up to several hours. Therefore, the main purpose of the updating the scheme of comparing the optical clock frequency with a hydrogen maser ensemble was to reduce the statistical uncertainty u_A.

The measurements performed with the new configuration of the complex for reproducing and keeping the time and frequency GET 1-2018 and updated frequency chain for converting the frequency of an optical clock based on ^{87}Sr atoms into the rf range, which is necessary for functioning the scheme of comparison of the optical clock frequency with that of hydrogen masers, have an Allan deviation value of $6\times10^{-14}/\tau^{1/2}$ on averaging time intervals from 1 to 3600 s.

2. Instrumental complex of the State Primary Standard

The complex for reproducing and keeping the time and frequency of the State Primary Standard GET 1-2018 includes different frequency standards (see Fig. 1). Currently, they form a basis for the functioning of GET 1-2018, which reproduces and keeps the time and frequency units and the national time scale.

The main components of the complex are the OC and hydrogen maser H18, which are located at the optical laboratory, and an ensemble of hydrogen masers – time and frequency keepers. There are also primary caesium atomic fountains; keepers based on a fountain of ultracold rubidium atoms; fibre-optic links, which transfer RF reference signals between the optical laboratory and the building where the maser ensemble and the primary caesium fountain are located. A comparison of the frequencies of all these standards and caesium atomic fountains, included in the composition of the State Primary Standard, contributes to the generation and keeping of the national time scale TAI (SU) and UTC (SU).

2.1. Time scale generated at the VNIIFTRI

The national coordinated time scale of the Russian Federation, UTC (SU), is reproduced and maintained by the State

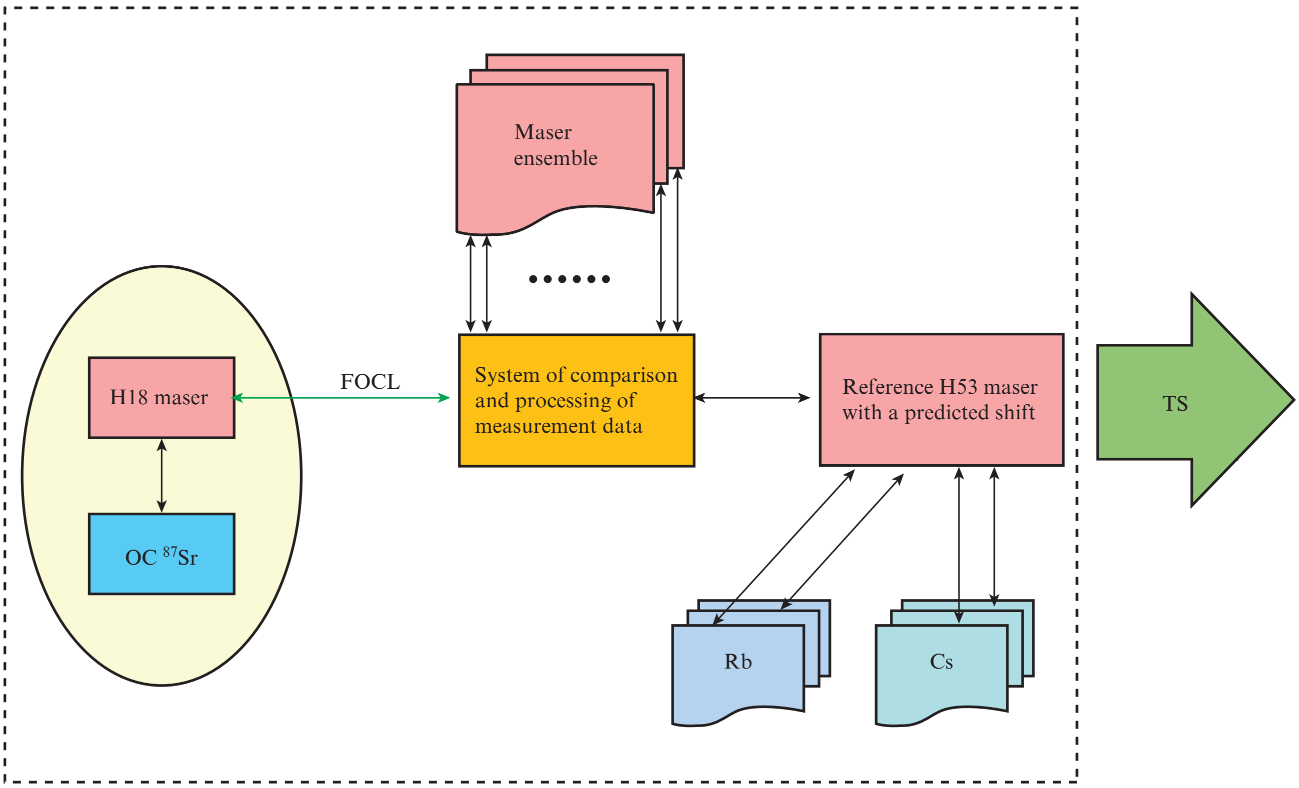

Figure 1. (Colour online) General composition of the complex of primary reference frequency standards: (OC) optical clock based on ultracold ^{87}Sr atoms; (FOCL) fibre-optic communication link; (Cs) primary frequency standard on a caesium fountain; (Rb) frequency keeper on a rubidium fountain; (TS) atomic time scale formed based on comparisons of an ensemble of hydrogen masers with microwave and optical clocks.

Primary Standard of time and frequency, which is operated on a facility situated in Mendeleevo (Moscow region, Russia). The main purpose of developing the system of primary frequency standards at the VNIIFTRI, including two caesium fountains, is to implement a regular contribution to the international time scale TAI/UTC with a high accuracy and provide a stable signal source for the generation of UTC (SU) (local UTC realisation in Russia).

Below we present the main results of the studies and developments aimed at improving the time and frequency standards, including the new generation of H masers and standards based on a fountain of rubidium atoms and neutral ^{87}Sr atoms in the optical lattice.

Fountain-type frequency references CsFO1 and CsFO2 have been operating at the VNIIFTRI for nearly nine years. Since 2014 CsFO2 has been officially involved in the calculations of the international scale TAI. The CsFO2 standard is used to increase the stability and accuracy of local UTC realisation. Figure 2 shows the results of comparing the time scales of Russia [UTC (SU)], Germany [UTC (PTB)], and the United States [UTC (USNO)] relative to the coordinated time scale UTC. Due to the use of fountain references based on caesium atoms and new-generation hydrogen keepers in the State Primary Standard, Russia has become one of the leading countries in the national realisation of coordinated time scale UTC (SU) [20].

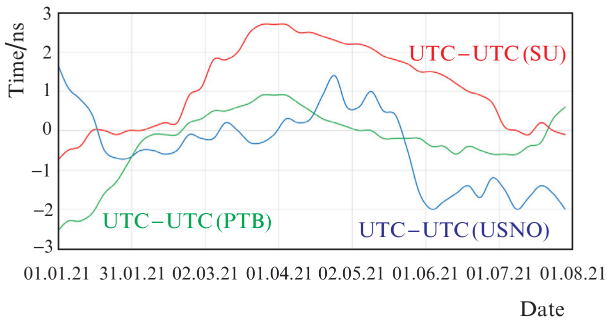

Figure 2. (Colour online) National local realisations UTC (k).

The time and frequency units are maintained independently using an updated complex of hydrogen (H) masers with a daily frequency instability of $(2-3)\times10^{-16}$ [21] for a month's period of time between the last official publication of UTC data and the next publication in the Circular T of the International Bureau of Weights and Measures (BIPM). Currently, the purpose of the complex is to keep the time and frequency units, provide both internal and external comparisons of standards, form operating time scales, and calculate the national atomic time scale TA (SU) and coordinated scale UTC (SU).

The results of comparing the time scale realisations are published in BIPM Circular T as the differences [UTC – UTC(k)], TAI – UTC, and [TAI – TA (k)] and in the bulletins of the Main Metrological Centre of the State Service of Time and Frequency (SSTF). Note that the scale of the world coordinated time UTC is maintained so that the difference UTC – TAI is equal to an integer number of seconds [22].

The ensemble of hydrogen keepers includes eight H masers CH-75A-01, four H masers CH1-1033, and six new-generation H masers.

The time scale UTC (SU) is calculated based on TA (SU); it is controlled and corrected with respect to UTC as soon as the next BIPM publication becomes available (monthly). According to this document, the displacement of the UTC (SU) time scale relative to UTC did not exceed 3 ns in 2021 (see Fig. 2) [23].

It is noteworthy that the VNIIFTRI is involved in the implementation of the Federal Target Programme GLONASS. Being the leading metrological institute of Russia, it is engaged in the development of reference instruments (and upgrade of the existing ones) for time and frequency measurements and provision of positioning and navigation in order to obtain the specified metrological characteristics of the GLONASS system. Currently, the UTC (SU) time scale is transferred to a ground-based control segment of GLONASS using navigation signal receivers; this scale is the national UTC realisation in correspondence with the BIPM requirements.

2.2. Frequency standard based on Sr atoms

An optical clock based on ultracold ^{87}Sr atoms was developed at the VNIIFTRI in 2020 [24] and included in GET 1-2018. The optical clock of this type uses a set of cooling and pumping diode lasers in order to implement two successive stages of laser cooling at the wavelengths $\lambda = 461$ and 689 nm, respectively. Due to this, one can prepare an ensemble of 10^5 atoms, captured at a temperature of $\sim$2.5 μK into a magneto-optical trap. Then the atomic ensemble is loaded into a vertical one-dimensional optical lattice, formed by a standing wave of radiation with $\lambda = 813$ nm from a diode laser with an optical amplifier tuned to the "magic" wavelength. As a result, the atomic ensemble can be kept with a negligible perturbation of clock transition frequency [25]. The clock transition spectroscopy is implemented using a laser system based on a Toptica DL Pro diode laser ($\lambda = 698$ nm), stabilised with respect to the external ultra-low expansion (ULE) glass cavity having a finess of 277 500. The characteristics of the clock laser system were found by studying the beat signal between two identical samples [17].

With the linear drift removed, the relative instability of laser frequency on measurement time intervals from 1 to 100 s decreases to $(2-3)\times10^{-15}$ at a spectral linewidth of $\sim$1 Hz. The frequencies of these laser systems have a linear relative drift at a level of 200 mHz/s. The clock laser is stabilised relative to the $^1S_0-{}^3P_0$ transition via successive spectroscopy of the components ($m_F = +9/2 - m_{F'} = +9/2$) and ($m_F = +9/2 - m_{F'} = -9/2$), after which the central transition frequency is determined. The measured relative transition probability $P \sim 0.4$ is obtained for each component at a spectral width 12 Hz at half maximum of the resonance [17]. The duration of one operating cycle, consisting of two laser cooling stages, loading atoms into the optical lattice, and determining the transition probability P, is about 1.3 s.

The long-term laser frequency stabilisation at $\lambda = 698$ nm by the clock transition is obtained using the following software algorithm. After obtaining the preliminary spectrum of the $^1S_0-{}^3P_0$ transition and determining its resonant frequency f_{res} and spectral linewidth, the frequency tuning step is chosen such as to make it possible to reconstruct the spectrum from the number of n points. An array consisting of frequencies related to points and the corresponding probabilities P of transition to the upper atomic level is formed in the first stage.

Then the frequency $f_{\text{res},n}$ (n is the number of working cycle), corresponding to the maximum probability P, is determined for the array. The previously found resonant frequency $f_{\text{res},n-1}$ is corrected by the value $f_{\text{res},n} = f_{\text{res},n-1} + \Delta f$, where $\Delta f = k\,(f_{\text{res},n} - f_{\text{res},n-1})$ and k is an experimentally chosen coefficient.

2.3. Fibre-optic links in the system for comparing frequency standards in GET 1-2018

The OC based on ultracold ^{87}Sr atoms is located in the optical laboratory at a distance of 1.3 km from the main instrumental complex of the State Primary Standard GET 1-2018. The main complex includes the following standards: caesium references and keepers based on rubidium fountains and an ensemble of hydrogen H masers, as well as phase comparators for comparing the frequencies of these microwave standards. The H53 maser is a reference oscillator in the ensemble of H masers, which provide storage of national time scale.

Among the entire ensemble of H masers, only the H18 maser is located directly in the optical laboratory, near the OC. In view of the remote location of the H18 maser, its comparison with the H53 maser is performed using a system of transferring their output RF signals through fibre-optic links. The measurement scheme providing comparison using multichannel comparators of the frequencies of the standards entering the main composition of the instrumental complex of primary standard GET 1-2018 is presented in Fig. 3.

The optical transmitters (OT1–OT3) and optical receivers (OR1–OR3) are connected to the ends of fibre-optic links linking the optical laboratory with the main instrumental complex of primary standard GET 1-2018. The output signals of H18 and H53 masers with frequencies of 5 and 10 MHz are transmitted by standard fibre (SMF-28) via amplitude modulation of the transmitter's optical carrier, having a wavelength of 1.3 μm. The H53 maser signal transmitted to the optical laboratory is also transmitted back to compare it with the initial H53 maser signal in order to estimate the influence of the fibre link on the uncertainty of its frequency transmission. Measurements showed that the contribution of the fibre transmission system to the uncertainty of comparisons of hydrogen maser frequencies does not exceed 2×10^{-16} for an averaging time of 10^5 s.

The frequencies of the H18 and H53 masers are compared using multichannel comparators K1–K6, positioned in the instrumental complex of the primary standard, and comparator K0, mounted in the optical laboratory.

The frequencies of the optical clock and H18 maser are compared by an optical frequency comb (OFC). The comparison results, which are processed and accumulated in a personal computer (PC), make it possible to determine the frequency drift of the H18 maser relative to the OC. A corrected H18 maser signal (with the frequency drift subtracted

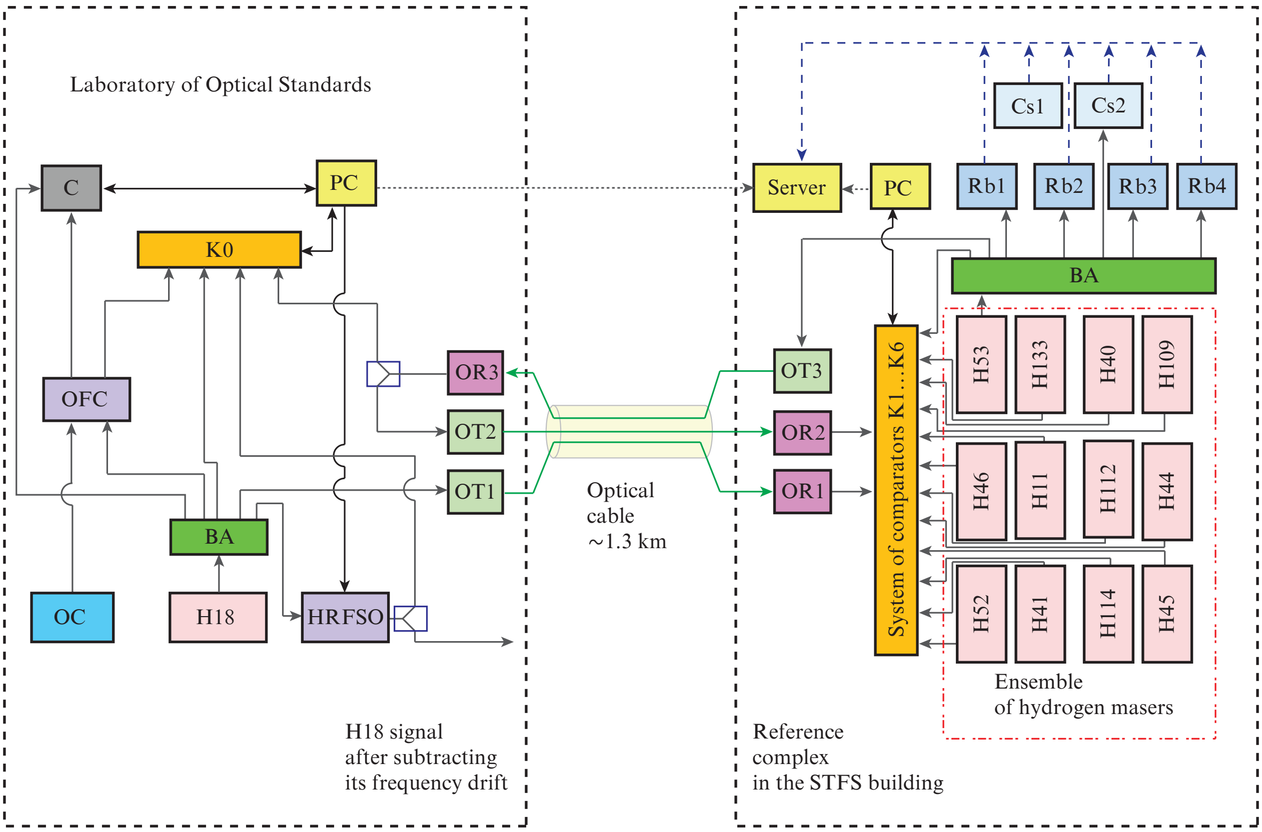

Figure 3. (Colour online) Measurement scheme providing comparison with the aid of multichannel comparators of the frequencies of standards entering the main composition of the instrumental complex of the primary standard GET 1-2018:
(BA) buffer amplifier; (K0, K1–K6) multichannel phase comparators; (OT) optical transmitters; (OR) optical receivers; (PC) personal computer; (C) counter of the OC frequency relative to the H18 hydrogen maser frequency (frequency counter); (OFC) optical frequency comb; (HRFSO) high-resolution frequency shift oscillator; (OC) optical clock based on ultracold ^{87}Sr atoms; (Cs) primary frequency standard based on a caesium fountain; (Rb) frequency keepers based on a rubidium fountain.

based on the results of its comparisons with the OC) is formed (under PC control) at the output of high-resolution frequency shift oscillator (HRFSO). The signal at the HRFSO output is the basis for the generation of the optical time scale.

2.4. System for measuring OC frequency

The operation of the OC based on Sr atoms implies conversion of the frequency of its clock laser at $\lambda = 698$ nm into the rf range using an optical frequency comb and its comparison with the frequency of a H maser output signal, which is equal to 5, 10, or 100 MHz.

A simplified schematic diagram, clarifying the conversion of the optical reference frequency into the rf range and subsequent frequency measurement is presented in Fig. 4. The clock laser radiation at $\lambda = 698$ nm, previously stabilised by a ULE cavity, is directed to Sr atoms to implement clock transition spectroscopy. After the detection of photons by an EMCCD camera with an electron multiplier, the obtained signal is analysed using the PC software. A control PC signal provides correction of the frequency of clock laser output radiation using an AOM. Some part of the clock laser beam is mixed with the corresponding mode of optical frequency comb. High-speed photodetector PD detects the repetition frequency $f_{\rm rep}$, carrier-envelope offset frequency $f_{\rm ceo}$, and the optical beat frequency $f_{\rm beat}$. At the OCF output the n-th harmonic of the comb frequency $f_{\rm rep}$ is recorded by a high-speed photodetector. Then the amplified signal $f_{\rm rep}$ is divided by splitters and filters into the first and fourth harmonics.

The signal with the first-harmonic frequency $f_{\rm rep}$ (~250 MHz) arrives at the multichannel frequency counter with zero dead time (K&K Messtechnik FXE) and is measured relative to the H18 maser frequency. This is an old part of the scheme for measuring the converted OC frequency at the OCF output. The frequency counter measures simultaneously the beatings of clock laser frequency from the nearest comb line and the comb offset frequency $f_{\rm ceo}$. To reduce the influence of temperature variations in the optical laboratory on the photodetector measurement error, the phase comparator, frequency counter, and RF synthesiser are placed in a constant climate chamber.

The signal with the fourth-harmonic frequency $f_{\rm rep}$ (~1 GHz) is used as a reference one for the low-noise RF synthesiser; this approach made it possible to implement a new scheme of more exact measurement of the converted OC frequency at the OCF output using a phase comparator (see Fig. 4). The frequency of the synthesised signal at the RF synthesiser output is bound to the OC and can be set very close to the values of 5, 10, or 100 MHz. Signals with these frequencies can be measured with a high accuracy by the phase comparator, which uses an H18 maser as a reference oscillator. However, measurements with a phase comparator can be performed only when the relative deviation of the frequency of synthesised signal at the RF synthesiser output from the frequency of the H18 maser output signal does not exceed 10^{-11}.

Using an RF synthesiser and a phase comparator in the updated measurement scheme, one can filter off the noise arising during the conversion of the OC signal into the rf range, as well as the noise generated in the measurement system, and avoid calculation errors when measuring the comb frequency $f_{\rm rep}$. Previously the $f_{\rm rep}$ value was measured by only a frequency counter with zero dead time [16]. In the updated scheme, an additional conversion and noise filtering circuit, based on a low-noise RF synthesiser and a phase comparator, was implemented to measure the fourth-harmonic frequency

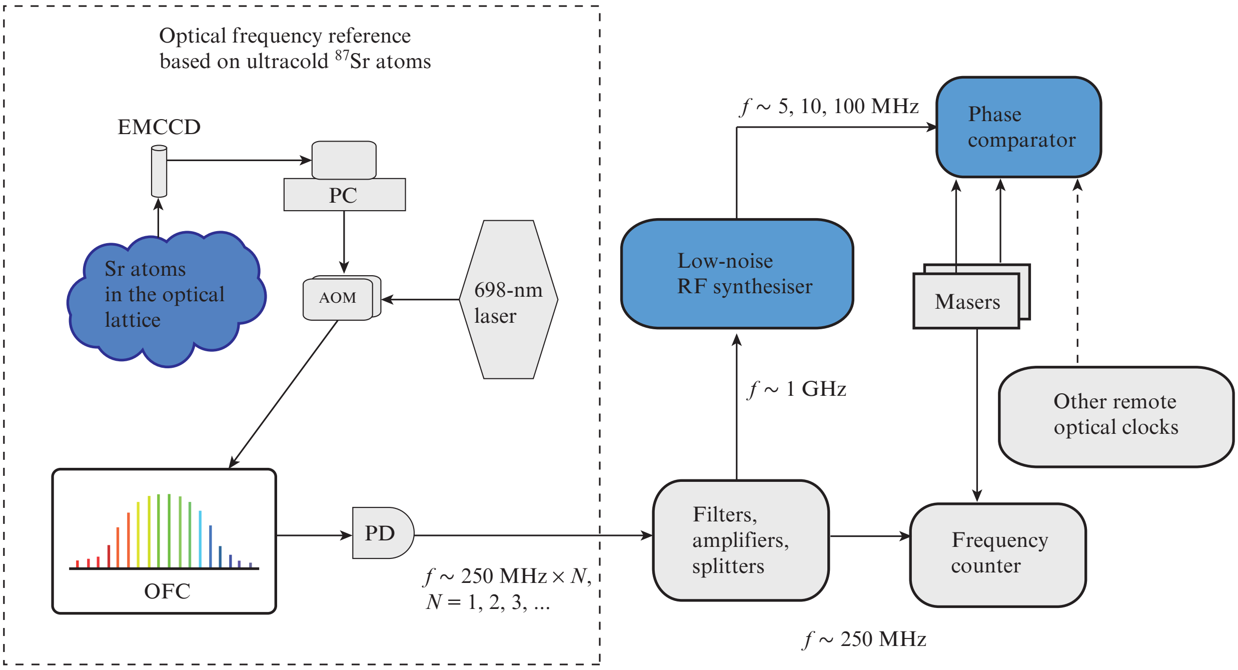

Figure 4. (Colour online) Schematic of conversion of an optical clock frequency into the rf range and updated circuit for measuring the converted frequency by a phase comparator:
(EMCCD) CCD camera with an electron multiplier; (PC) personal computer; (PD) high-speed photodetector; (AOM) acousto-optic modulator; (OFC) optical frequency comb.

f_{rep}. Note that we used a Vremya-Ch phase comparator with a narrow (about 3 Hz) transmission band.

The RF synthesiser generates frequencies with a step of 1 mHz. Due to this, the synthesiser frequency can be set so as to make it correspond to the H18 maser frequency with a relative deviation smaller than 10^{-11}. Specifically this circumstance allows one to use a Vremya-Ch phase comparator to compare the H maser frequency and the comb repetition frequency f_{rep}. The observed frequency instability when measuring f_{rep} on time intervals τ from 1 to 3600 s corresponds approximately to $\sigma_y = 6 \times 10^{-14}\,(1/\tau)^{1/2}$ and, therefore, is determined by the H maser noise. This conclusion is confirmed by the fact that specifically this frequency instability on measurement time intervals up to 1 h is characteristic of new-generation hydrogen masers, to which H18 belongs. This fact indicates that the noise level in the updated measurement scheme for comparing the OC and microwave keeper frequencies, in which a high-resolution synthesiser and a comparator with a narrow (~3 Hz) transmission band are used to convert the frequency f_{rep} and perform measurements, does not exceed the intrinsic maser noise.

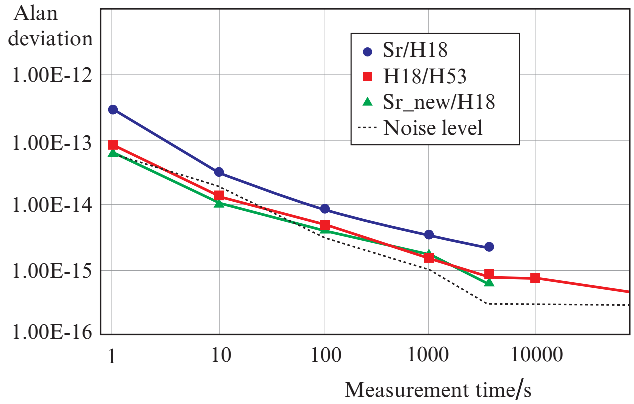

Figure 6. (Colour online) Allan deviation of the ^{87}Sr OC frequency, measured by a frequency counter (circles) and a phase comparator (triangles), comparison of the frequencies of two H masers using a 1.3-km-long fibre-optic link (squares) and the comparator noise level (dotted line). The frequency counter and phase comparator are placed in a constant climate chamber.

3. Results

Figures 5 and 6 present the Allan deviation values obtained in measurements of the OC frequency relative to the H18 maser frequency, which were carried out using a frequency counter and a phase comparator. There are several noise sources, which may affect the uncertainty in these frequency measurements. To demonstrate them, Fig. 5 shows the Allan deviation value (Sr/H18) obtained in the measurements of the ^{87}Sr OC frequency based on our previous measurement measuring system with application of a frequency counter. In the range of measurement times of 1 – 10 s, the Allan deviation (Sr/H18) starts with a value of $\sim 4 \times 10^{-13}$ (frequency counter noise) and decreases according to the law of $1/\tau$. The second noise source can be found in the range of measurement times of 200 – 1000 s, in which the Allan deviation (Sr/H18) falloff changes to a rise, caused by temperature variations in the optical laboratory. This noise is eliminated by placing all essential parts of the measurement system in a constant climate chamber. This is demonstrated in Fig. 6, which shows the Allan deviation (Sr/H18) obtained in measurements by a frequency counter using our new measurement system, with a frequency counter placed in the constant climate chamber.

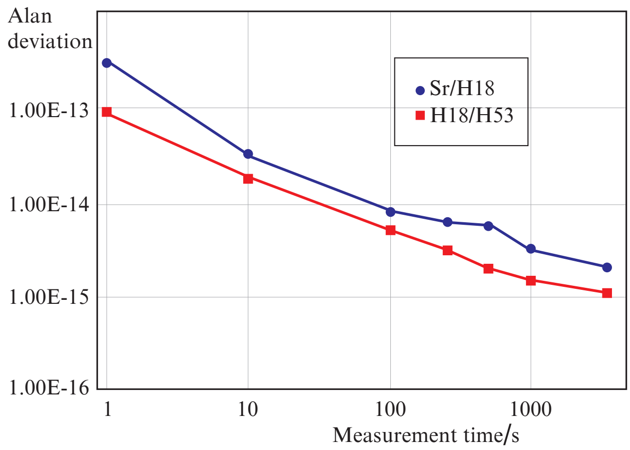

Figure 5. (Colour online) Allan deviation of the ^{87}Sr OC frequency measured by a frequency counter beyond a constant climate chamber (circles) and comparison of the frequencies of two H masers by a phase comparator using a 1.3-km-long fibre-optic link (squares).

It can also be seen in Fig. 6 that the uncertainty of the measurement results (Sr_new/H18) obtained using a phase comparator in the new measurement system for comparing the ^{87}Sr OC and H18 maser frequencies is determined by the H18 maser noise. This is confirmed by the fact that the uncertainty (H18/H53) for comparisons of the frequencies of H18 and H53 masers, presented in Fig. 6, and the uncertainty (Sr_new/H18) for comparisons of the OC and H18 maser frequencies almost coincide. The results of comparing the OC and H18 maser frequencies, obtained with a phase comparator in the new measurement system (Sr_new/H18), which are also shown in Fig. 6, have smaller (by a factor of 2 – 4) uncertainty than that of the results (Sr/H18) obtained in the old scheme using a frequency counter. Therefore, the new measurement system based on a phase comparator contributes less to the statistical uncertainty u_A when comparing the frequencies of OCs based on ^{87}Sr atoms and the hydrogen keepers entering the standard GET 1-2018.

4. Conclusions

We described the composition of the instrumental complex of the State Primary Standard GET 1-2018, updated order of the time scale generation, and a new scheme for measuring the OC frequency [16, 17], as well as the results of these measurements. A new scheme for comparing the frequencies of the optical clock based on ^{87}Sr atoms with the frequencies of microwave time and frequency keepers and primary caesium standards is implemented. The measurements performed within this scheme are characterised by an Allan deviation falling off as $1/\tau^{1/2}$ at measurement times of 1 – 3600 s and a level determined by not the optical clock but characteristic of the best hydrogen masers. A new State Time and Frequency standard of the Russian Federation must be approved in 2022. This standard will include three optical time and frequency standards based on ultracold strontium atoms, which will undoubtedly increase the level of the metrological characteristics of the atomic time scale formed on its basis.

References

1. Riehle F., Gill P., Arias F., Robertsson L. *Metrologia*, **55**, 188 (2018).
2. https://www.bipm.org/documents/20126/35554894/CCTF+Strategy/7cf0f648-2afe-d15c-0909-1f03406bbb8f; https://www.bipm.org/en/committees/cg/cgpm/26-2018/resolution-1.
3. Gu´ena J., Abgrall M., Clairon A., Bize S. *Metrologia*, **51**, 108 (2014).
4. Nemitz N., Gotoh T., Nakagawa F., Ito H., Hanado Y., Ido T., Hachisu H. *Metrologia*, **58** (2), 025006 (2021).
5. Tanabe T., Akamatsu D., Kobayashi T., Takamizawa A., Yanagimachi S., Ikegami T., SuzuyamaT., Inaba H., Okubo S., Yasuda M., Hong F.-L., Onae A., Hosaka K. *J. Phys. Soc. Japan*, **84**, 115002 (2015).
6. Lin Y.-G. et al. *Chin. Phys. Lett*., **32**, 090601 (2015).
7. Grebing C. et al. *Optica*, **3**, 563 (2016).
8. Hachisu H., Petit G., Nakagawa F., Hanado Y., Ido T. *Opt. Express*, **25**, 8511 (2017).
9. *Report of the 21st Meeting (8-9 June 2017) to the International Committee for Weights and Measures* (CCTF, 2017) p. 49.
10. Weyers S., Bauch A., Hubner U., Schroder R., Tamm Ch. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, **47**, 432 (2000).
11. Levi F., Lorini L., Calonico D., Godone A. *IEEE Trans. Instrum. Meas*., **52**, 267 (2003).
12. Fang F., Mingshou L., Pingwei L., Weiliang C., Nianfeng L., Yige L., Ping W., Kun L., Rui S., Tianchu Li. *Metrologia,* **52**, 454 (2015).
13. https://www.bipm.org/en/time-ftp/circular-t.
14. Donley E.A., Heavner T.P., Tataw M.O., Levi F., Jefferts S.R. *Proc. IEEE International Frequency Control Symposium and Exposition* (Montreal, Canada, 2004) pp 82 – 86.
15. Guena J., Abgrall M., Rovera D., Laurent P., Chupin B., Lours M., Santarelli G., Rosenbusch P., Tobar M.E., Li R., Gibble K., Clairon A., Bize S. *Progress in Atomic Fountains at LNE-SYRTE*; arXiv:1204.3621v1, 2012.99.
16. Sutyrin D.V., Berdasov O.I., Antropov S.Yu., Gribov A.Yu., Balaev R.I., Stel'mashenko E.F., Fedorova D.M., Malimon A.N., Slyusarev S.N. *Quantum Electron*., **49** (2), 199 (2019) [*Kvantovaya Elektron*., **49** (2), 199 (2019)].
17. Berdasov O.I., Gribov A.Yu., Belotelov G.S., Pal'chikov V.G., Strelkin S.A., Khabarova K.Yu. *Quantum Electron*., **47** (5), 400 (2017) [*Kvantovaya Elektron*., **47** (5), 400 (2017)]; https://doi.org/10.1070/QEL16346.
18. Berdasov O.I., Sutyrin D.V., Strelkin S.A., Gribov A.Yu., Belotelov G.S., Kostin A.S., Kolachevskii N.N., Slyusarev S.N. *Quantum Electron*., **48** (5), 431 (2018) [*Kvantovaya Elektron*., **48** (5), 431 (2018)].
19. Lodewyck J. et al. *Metrologia*, **53**, 1123 (2016).
20. Donchenko S.I. et al. *Izmer. Tekh*., (1), 35 (2020).
21. Belyaev A.A., Demidov N.A., Medvedev S.Yu., Pastukhov A.V., Sakharov B.A., Blinov I.Yu. *Vestn. Metrol.*, (2), 14 (2015).
22. GOST (State Standard) 8.567-2014: Gosudarstvennaya sistema obespecheniya edinstva izmerenii. Izmereniya vremeni i chastoty. Terminy i opredeleniya (State System Providing Uniformity of Measurements. Time and Frequency Measurements. Terms and Definitions) (1984).
23. https://webtai.bipm.org/ftp/pub/tai/Circular-T/.
24. Gribov A. et al. *2020 Proc. IEEE International Frequency Control Symposium and International Symposium on Applications of Ferroelectrics (IFCS-ISAF)* (Keystone, CO, USA, 2020) pp 1–4; https://doi.org/10.1109/IFCS-ISAF41089.2020.9234906.
25. Katori H., Takamoto M., Pal'chikov V.G., Ovsiannikov V.D. *Phys. Rev. Lett*., **91** (17), 173005 (2003); https://doi.org/10.1103/PhysRevLett.91.173005.