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CURRENT STATUS AND PROSPECTS FOR THE DEVELOPMENT OF THE STANDARDS BASE OF THE NATIONAL SERVICE FOR TIME, FREQUENCY, AND THE DETERMINATION OF THE PARAMETERS OF THE EARTH'S ROTATION

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The current status and prospects for the development of the standards base of the National Service for Time, Frequency, and Determination of the Parameters of the Earth's Rotation (GSVCh) are examined. The basic metrological characteristics of the National Primary Standard for the Units of Time and Frequency and the National Time Scale (GET 1-2012) and the secondary standards of the GSVCh are presented. Areas for further development and improvement of the standards are discussed.
Keywords: *standards base, National service for time, frequency, and determination of the parameters of the Earth's rotation, primary and secondary standards.*

Data on the national time scale of the Russian Federation UTC(SU) are widely used in all spheres of government activity and ensure highly precise synchronization of many technical systems used in astronautics, navigation, communication, and transport, as well as in banking, customs and logistical operations, and also in national defense and security. Information on the exact time, calendar date, and the earth's rotation parameters distributed by the National Service for Time, Frequency, and Determination of the Parameters of the Earth's Rotation (GSVCh) is essential for users in the Russian Federation.

The GSVCh is managed by the Federal Agency for Technical Regulation and Metrology (Rosstandart), and the activity of the Service is regulated by the Decree on the National Service for Time, Frequency, and Determination of the Parameters of the Earth's Rotation [1]. The GSVCh carries out its scientific-technical and metrological activities using various technical means and systems. One of these basic technical systems is its standards base. The standards for the units of time and frequency are supplied by the Main Metrological Center (GMTs), Metrological Control Points (PMK), and the means for transfer of standard time and frequency signals (ESChV).

The standards base of the GSVCh is intended to ensure the uniformity of measurements of time and frequency in the country and to meet domestic demand for information on exact time, standard frequencies, and the UTC(SU) scale. The foundation of the standards base of the GSVCh is the National Primary Standard for the Units of Time, Frequency, and the National Time Scale GET 1-2012 and the Rosstandart secondary standards for the units of time and frequency. The standards base also includes the standards for the units of time and frequency of the Ministry of Defense of the Russian Federation and other federal executive agencies. The scientific, methodological, and operational work for ensuring continuous functioning and development of the equipment in the standards base is carried out by the main metrological center (GMTs) of GSVCh, which calculates UTC(SU) on the basis of GET 1-2012. The information published by the GMTs is official and generally available to all users.

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The standards base is used to solve the major problems of the GSVCh: independent reproduction of the units of time and frequency in accord with the definition of the second in the International System of Units (SI); storage of the units of time, frequency, and the UTC(SU) scale; transfer of the units of time, frequency, and the UTC(SU) scale in accordance with the requirements of the national verification scheme for means of measurement of time and frequency [2].

The standards base of the GSVCh includes the following Rosstandart standards: the National Primary Standard for the Units of Time and Frequency and the National Time Scale GET 1-2012 (GMTs GSVCh, VNIIFTRI); the National secondary standards for the units of time and frequency VET 1-5, VET 1-7, and VET 1-19 (at, respectively, GSVCh metrological control point (PMK) of the Eastern-Siberian and Far-Eastern branches of VNIIFTRI, and the Siberian State Research Institute of Metrology (SNIIM)); the National Working Standard for the Units of Time and Frequency RET1-1 (at the PMK GSVCh of the Kamchatka branch of VNIIFTRI).

The constantly increasing demand for operational and exact frequency-time information requires continuous improvement and development of the standards base of the GSVCh. These efforts are based on leading technologies and the latest advances in the science and engineering of precision quartz oscillators, hydrogen frequency and time standards, cesium frequency standards, optical frequency standards, equipment for internal comparisons, and means for comparing the time scales of standards that are located far apart.

In recent years, the Federal Targeted Program on Global Navigation System (GLONASS) has had a significant effect on the development of the standards base of the GSVCh [3, 4]. GLONASS is intended for determining the position, velocity, and exact time of users [5]. GLONASS is a system with a double purpose, as the central link in coordinate-time and navigation support for the Russian Federation and as a component of the government's strategic infrastructure for national security. The system operates with its own time and the UTC(SU) scale is a reference for it. The GLONASS spacecraft are functionally a part of the subsystem of equipment for transfer of the standard time and frequency signals (ESChV) of the GSVCh. GLONASS is one of the basic and most exacting consumers of information on the UTC(SU) scale, since in order to attain maximum accuracy in determining coordinates and time the GLONASS time scale and the on-board scales of the spacecraft must be synchronized with high accuracy among themselves and with the UTC(SU) scale.

Because of their territorial distribution, the Rosstandart standards for the units of time and frequency included in the standards base of the GSVCh are a unique technical basis, in terms of their functional capability, for monitoring the parameters and characteristics of the navigation field created by GLONASS.

Work on the GLONASS program during 2007–2011 led to considerable progress in creating and improving the means and methods for time and frequency measurements. The following technical means were introduced to equip the standards base of the GSVCh:

1) means for reproducing the units of time and frequency – fountain-type metrological cesium frequency standards (MTsR Fontan) using laser cooling of atoms [6] with an unexcluded systematic error in the reproduction of the units of time and frequency of no more than $5.0 \cdot 10^{-16}$;

2) the means for storage of the units of time and frequency are Ch1-75A hydrogen frequency and time standards, Ch1-76A hydrogen frequency and time standards, and Symmetricom 5071A cesium frequency standards;

3) the complex for formation and transmission of the UTC(SU) scale in the earthbound control complex for GLONASS on real time scale with an error of no more than ±2 nsec;

4) modernized PKChV-M portable hydrogen quantum clocks which provide an error of no more than ±2 nsec in storing the time scale during a transportation time of 24 h;

5) equipment for internal comparisons based on Stanford Research Systems SR-620 time interval measurement units, and #10265 (TimeTech) and VCH-315 (Vremya-Ch company) phase comparators; equipment for formation of working time scales based on HROG-5 (Spectradynamics) digital phase converters; and

6) equipment for time scale comparisons of spatially remote objects based on a apparatus for duplex comparisons of time scales (TimeTech), and also based on specialized two-frequency multichannel GLONASS/GPS TTS-3 and TTS-4 signal receivers (PikTime Systems).

The standards of Rosstandart were equipped with new auxiliary equipment, their technical infrastructure was modernized, and the electrical supply, precision air-conditioning, and environmental parameter monitoring systems were rebuilt.

TABLE 1. Comparative Characteristics of the Standards GET 1-98 and GET 1-2012

Metrological characteristics	GET 1-98	GET 1-2012
Relative unexcluded systematic error in reproducing the units of time and frequency, no more than	$3.0 \cdot 10^{-14}$	$5.0 \cdot 10^{-16}$
Mean square deviation in the results of measurements for reproduction of the units of time and frequency for a measurement time interval of 1 day, no more than	$1.0 \cdot 10^{-14}$	$5.0 \cdot 10^{-15}$
Relative instability of the units of time and frequency for measurement time intervals of 10–30 days, no more than	$5.0 \cdot 10^{-15}$	$1.0 \cdot 10^{-15}$
Limits of permissible deviations in UTC(SU), relative to UTC, nsec	±100	±10
Range of measured time intervals, sec	$1.0 \cdot 10^{-9}$–$1.0 \cdot 10^{8}$	$1.0 \cdot 10^{-9}$–$1.0 \cdot 10^{8}$
Range of measured frequencies, Hz	1.0–$1.0 \cdot 10^{14}$	1.0–$5.0 \cdot 10^{14}$

TABLE 2. Comparative Characteristics of Rosstandart Standards Before and After Steps Were Taken to Improve Them

Standard	Improvement	Combined error $S_{\Sigma 0}$, no more than	Relative instability in frequency ν_0, (τ_m=10–30 days), no more than	Limits of permissible deviations in time scale ΔT[UTC(SU)-UTC(k)], nsec	Range of Measured	
					time intervals, sec	frequencies, Hz
VET 1-5	before	$2.0 \cdot 10^{-14}$	$2.0 \cdot 10^{-14}$	±100.0	$1.0 \cdot 10^{-9}$–$1.0 \cdot 10^{8}$	1.0–$1.0 \cdot 10^{8}$
VET 1-7	after	$1.0 \cdot 10^{-14}$	$5.0 \cdot 10^{-15}$	±30.0	$1.0 \cdot 10^{-9}$–$1.0 \cdot 10^{8}$	1.0–$4.0 \cdot 10^{10}$
VET 1-19	before	$3.0 \cdot 10^{-12}$	$5.0 \cdot 10^{-13}$	±300	$1.0 \cdot 10^{-6}$–$1.0 \cdot 10^{8}$	1.0–$1.0 \cdot 10^{8}$
RET 1-1	after	$1.0 \cdot 10^{-13}$	$5.0 \cdot 10^{-14}$	±100	$1.0 \cdot 10^{-9}$–$1.0 \cdot 10^{8}$	1.0– $4.0 \cdot 10^{10}$

Besides updating technical equipment, work was done to improve the standards documents – sets of builder and user documents for standards were developed and their methodological documentation was improved and unified. In 2012, the standard of [2] was developed; it was accepted by the Intergovernmental Council on Standardization, Metrology, and Certification and was enacted as the national standard of the Russian Federation beginning on July 1, 2014.

Equipping the standard GET 1-2012 with metrological cesium reference standards for frequency and the set of duplex comparisons of time scales has made it possible to proceed to a new strategy for realizing the UTC(SU) scale [7]. Based on a systemic approach to the development of means and methods for the reproduction, storage, and transfer of the units of time and frequency and aimed at meeting the government's needs for accuracy and availability of frequency-time information, this new strategy for realization of the UTC(SU) scale has provided the following:

1) independent formation of the national atomic time scale TA(SU) based on the units of time and frequency reproduced by the Fontan metrological cesium frequency standards in accordance with the SI definition of the second;

2) formation and transfer of the UTC(SU) scale to users with specified characteristics in real time; and

3) increased certainty and reliability of information on the UTC(SU) scale through automation of the technological processes by which it is formed, stored, and transferred.

In 2012, GET 1-2012 and in 2014 secondary and working standards with new compositions and improved metrological characteristics were adopted in the decrees of Refs. 8 and 9 and entered into the corresponding branches of the federal data bank for support of the uniformity of measurements.

As a result of these steps, GET 1-2012 has become one of the leading standards for the units of time and frequency and the metrological characteristics of the secondary and working standards from the GSVCh standards base have been significantly improved. Tables 1 and 2 list the basic metrological characteristics of the standards before and after steps were taken to improve them.

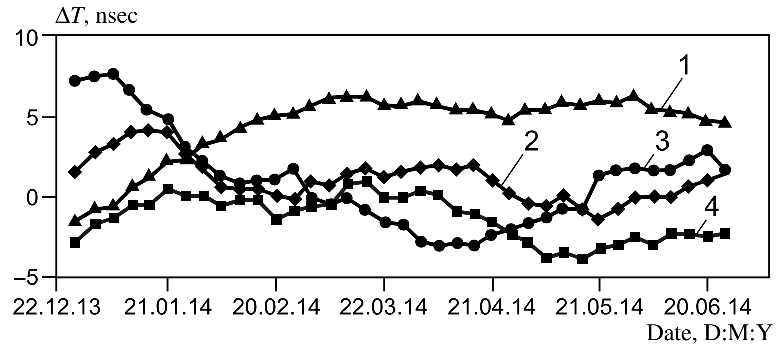

Fig. 1. Comparative evaluations of the shifts ΔT [UTC–UTC(k)] in the coordinated time scales UTC(k) relative to the UTC scale in 2014: *1*, *2*, *3*, *4*) UTC(NIST), UTC(USNO), UTC (SU), and UTC (PTB), respectively.

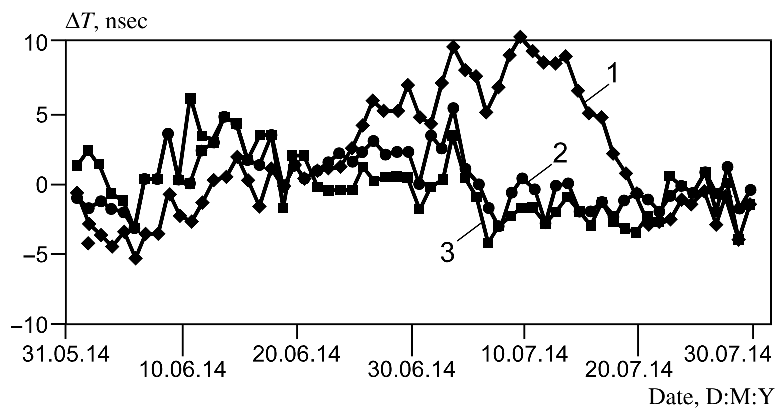

Fig. 2. The shifts ΔT [UTC(SU)–UTC(k)] in the scales of coordinated time UTC(k) relative to UTC(SU) during June–July, 2014: *1*, *2*, *3*) UTC(Nm), UTC(Im), UTC(Km) scales for the secondary standards of the units of time and frequency located in Novosibirsk, Irkutsk, and Khabarovsk, respectively.

These characteristics of the GSVCh standards base are at the world level of development for means of measuring time and frequency and can now support GLONASS with standard values of time and frequency, UTC(SU), and data on the parameters of the Earth's rotation in accordance with the specifications of the GLONASS federal targeted program.

At present, the shift of the UTC(SU) scale relative to the international universal coordinated time scale UTC is within ±10 nsec. Official estimates by the BIPM [10] confirm that UTC(SU) is among the best realizations of UTC (Fig. 1). The shifts in the coordinated time scales for secondary Rosstandart scales relative to the UTC(SU) scale are within ±30 nsec, so that they meet the relevant specifications (Fig. 2).

Further development of GLONASS is being undertaken in accordance with the Federal Targeted Program on Support, Development, and Utilization of the GLONASS System for 2012–2020 [11]. The goals of this program are the introduction and utilization of domestic satellite navigation technologies and the services of GLONASS in the interests of specialized and civilian users and the international utilization of Russian satellite navigation technologies through the support and development of GLONASS. Here it is assumed that the formation accuracy for UTC(SU) will be increased by at least a factor of 3 and the transfer accuracy, by at least a factor of 8. The specifications and characteristics for the formation and transfer of UTC(SU) through 2020 are listed in Table 3.

TABLE 3. Targets for the Federal Targeted Program GLONASS

Year	Matching error	
	UTC(SU) with UTC, nsec	GLONASS time scales with UTC(SU), nsec
2012	±10	±120
2013	±10	±50
2014	±10	±35
2015	±7	±25
2016	±7	±20
2017	±7	±15
2018	±5	±10
2019	±4	±7
2020	±3	±4

In order to ensure competitiveness in the development and achievement of the specified tactical and technical characteristics of the system through 2020, it is proposed that the standards base of the GSVCh be further developed in the framework of steps to be taken in the GLONASS targeted program in the following areas:

1) modernization of the complexes for storage of the UTC(SU) scale to ensure its consistency with the UTC with an error of no more than ±3 nsec;

2) creation of high accuracy means of comparing UTC(SU) with the GLONASS time scale and other time and frequency standards;

3) creation of storage for the units of time and frequency based on a rubidium atom fountain with an instability of $(1.0–2.0)\cdot 10^{-16}$ to equip the standards for the units of time and frequency;

4) creation of optical frequency standards with an unexcluded systematic error of $1.0\cdot 10^{-16}–1.0\cdot 10^{-17}$ in reproducing the units;

5) creation of a new generation of portable quantum clocks with an error in the storage of the time unit of no more than ±1 nsec, and a set of apparatus for duplex comparisons of the time scales with an error of no more than ±1.5 nsec; and

6) studies for the creation of a high-accuracy channel for transfer of the standard time and frequency signals by fiber-optic cables.

These steps to improve the means of reproducing, storing, and transfer of the units of time, frequency, and the UTC(SU) scale in the GSVCh standards base will provide a technical foundation for further competitive development of GLONASS as a whole, of means for its metrological support, and of means for monitoring the characteristics of the formed system of the navigation field. Improvements in the standards base of the GSVCh will help Rosstandart meet its goals [1, 12]. Users will be provided with high-accuracy operational data on the national time scale, standard frequencies, and parameters of the Earth's rotation.

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