CCTF/17-09

VNIIFTRI, RUSSIA

Time and Frequency activity at the VNIIFTRI

Introduction

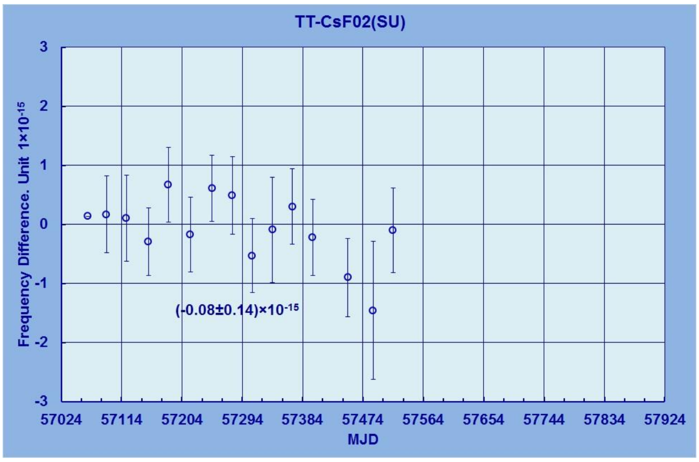
This report contains main results obtained during last two years in Time and Frequency division of the VNIIFTRI. The emphasis is paid mainly to three items:

– VNIIFTRI Time and Frequency department operational activity, that is first of all maintenance national time scales TA(SU) and UTC(SU). Apart from this, some results of just finished investigation and developing projects will be presented as well;

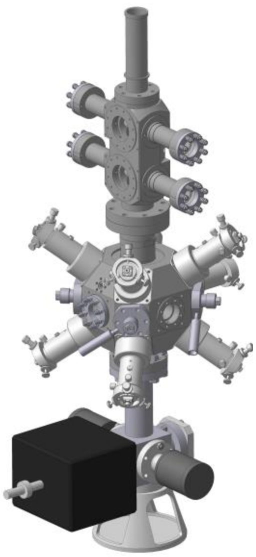
– VNIIFTRI suggestions to “Recommendation on the definition of time-scales“, prepared by Task Group on Time Scales Definition;

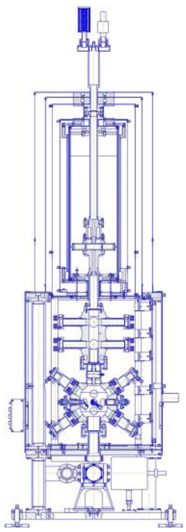
– and according to Resolution 1 24th meeting of the General Conference on Weights and Measures (2011) “On the possible future revision of the International System of Units, the SI”, VNIIFTRI opinion on proposed linguistic redefinition of SI base units.

Operational activity



During reported period CSF02(SU) standard contributed to TAI more or less regularly about one and a half years starting 2015 up to middle 2016. Then due to some technical problems, it was under investigations and started its contribution on beginning February 2017. Within operational period mean frequency difference TT – CSF02(SU) was less than 1×10^{-16} with standard deviation of the mean difference about 1.4×10^{-16}. Reported values confirm stated accuracy of the standard 2.5×10^{-16} [1].

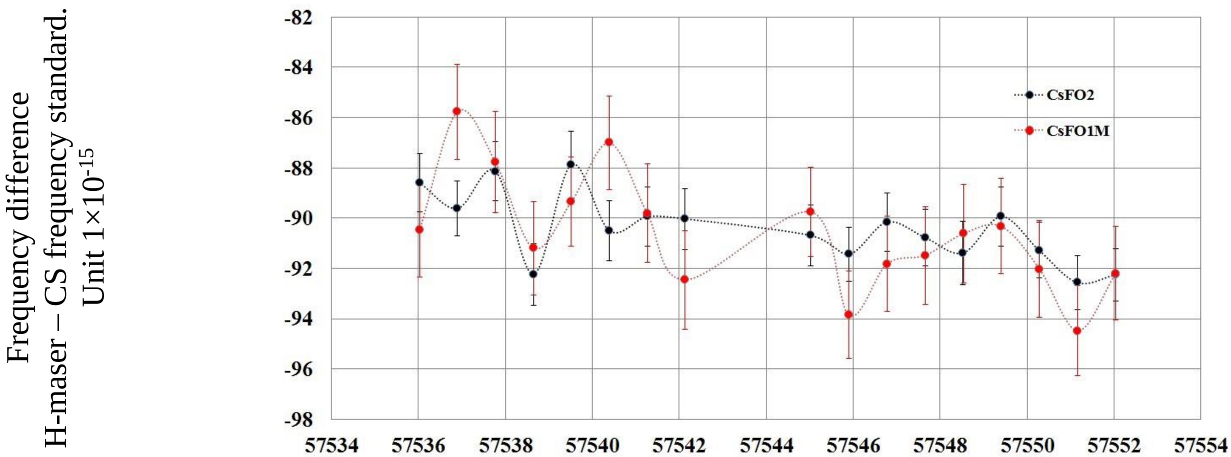




CSF01(SU) fountain standard during last two years has been considerably updated up to CSF01M(SU) [2]. The main feature of the instrument is laser beam geometry in laser cooling and caesium atom trapping zone. Such a geometry is quite different to any operational caesium fountains in the world, including CSF02(SU). In CSF01M(SU) eight laser beams form tetrahedron optical molasses where Cs atoms cools below 1 μK. The laser beams locates in two mutually orthogonal planes with beams angle relative to vertical axe about 1 radian. The main aim of such beams configuration is a desire to get more spherical shape of Cs cold atom cloud.

The other features are different design of detection zone, design of auxiliary cavity, the main μ-wave cavity feeding system, magnetic shielding design and vacuum system.

Accuracy estimation of the CSF01M(SU) gives somewhat $\leq 5\times10^{-16}$. This is 6 times better than original CSF01(SU). Accuracy estimation have been confirmed by simultaneous H-maser frequency measurements relative to both CSF02(SU) and CSF01M(SU) standards depicted below. This comparison gives mean frequency difference value about $(3.5 \pm 4.7)\times10^{-16}$. Normalized frequency stability of CSF01M(SU) $\sigma_y(\tau) \leq 4\times10^{-13}/\ \tau^{½}$.

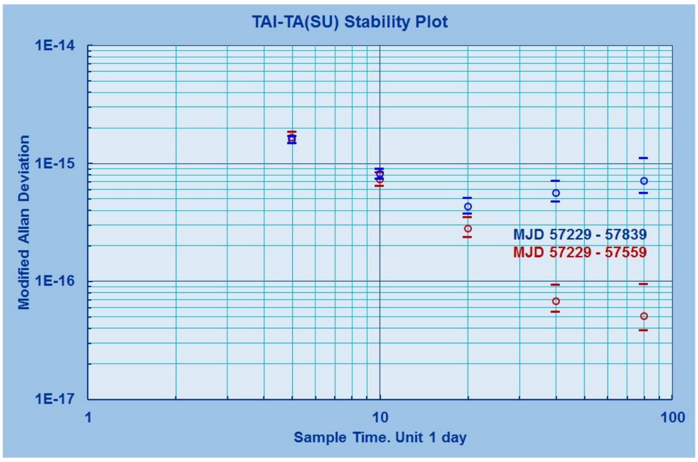


Because of there were no changes in time keeping instrumentation we focused our efforts on time algorithm improvements, TA(SU) particularly. The time unit in TA(SU) is matched to that reproduced by national the second SI realization. Time algorithm defines how basing on the ensemble of independent clocks with essentially different frequencies and time scales one generates the National Atomic Time Scale TA(SU) which in turn continuously keeps time unit SI(SU) matched to that reproduced independently by primary CSF01M(SU) and CSF02(SU) in accordance to the second definition in SI.

The main features of the algorithm are the same as in previous period [3]. The most significant difference – the whole clock ensemble is involved in the TA(SU) forecast to full extend by means of weighting procedure:

- particular clock contribution to TA(SU) depends on clock's statistical weight;
- clock's statistical weight is composition of a few components:
- the proximity of successive clock's frequency prediction relative to primary fountain standards (the main contribution);
- clock's frequency prediction uncertainty relative to primary standards;
- clock's frequency prediction uncertainty relative to TA(SU);

These changes have been introduced into algorithm at August 2015. During the period of CS fountain standard reliable and correct operation up to July 2016 we got very impressive figures of TA(SU) time stability relative to TAI. For the whole period of estimations 2015 up to beginning 2017 TA(SU) stability level looks much more moderate, first of all due to bad CSF02(SU) operation.



An excellent stability level for MJD 57229 – 57559 does not mean that TA(SU) was steering time scale. That means only that both time scales TAI and TA(SU) steered the same physical phenomena – frequency of caesium transition: TAI to weighted PFS and TA(SU) to CSF02(SU). In turn that means also CSF02(SU) high stability level.

To complete “Operational activity” paragraph it worth to mention one important issue – absolute delay calibration BIPM TTS4 receiver for GLONASS signals. That task was completed at the second half 2015 by issuing proper Calibration Certificate when BIPM TTS4 BP1K #136 was delivered back to the BIPM. Then AOS reference GNSS receiver was calibrated relative to BIPM TTS4 BP1K #136 and starting March 2017 Circular T began issuing correct data of relations of UTC and TAI with predictions of UTC(k) disseminated by GLONASS.

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BUREAU INTERNATIONAL DES POIDS ET MESURES

ORGANISATION INTERGOUVERNEMENTALE DE LA CONVENTION DU METRE

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4 - Relations of UTC and TAI with predictions of UTC(k) disseminated by GNSS.

[UTC-UTC(USNO)_GPS] = C0', [TAI-UTC(USNO)_GPS] = 37 s + C0'
[UTC-UTC(SU)_GLONASS]= C1', [TAI-UTC(SU)_GLONASS]= 37 s + C1'

For this edition of Circular T, S0'= 1.0 ns, S1'= 6.9 ns

2017	0h UTC	MJD	C0'/ns	N0'	C1'/ns	N1'
	FEB 25	57809	3.2	90	210.5	82
	FEB 26	57810	2.3	88	215.3	66
	FEB 27	57811	0.8	89	216.8	86
	FEB 28	57812	2.7	89	218.0	42
	MAR 1	57813	3.4	90	13.5	85
	MAR 2	57814	1.1	72	12.0	79
	MAR 3	57815	2.7	89	8.8	87
	MAR 4	57816	3.5	89	7.1	87
	MAR 5	57817	4.2	90	8.5	90
	MAR 6	57818	3.0	89	10.1	87
	MAR 7	57819	3.1	89	11.6	89
	MAR 8	57820	3.4	89	12.7	89
	MAR 9	57821	1.8	87	10.3	80
	MAR 10	57822	3.2	89	8.1	82
	MAR 11	57823	3.8	89	5.4	88
	MAR 12	57824	3.3	89	2.2	88
	MAR 13	57825	3.4	90	1.6	88
	MAR 14	57826	1.4	89	4.1	85

Note: Time step of C1' on MJD 57813 due to calibration of the GLONASS receiver at AOS.

Some results of just finished investigation and developing projects

At the fall, 2016 VNIIFTRI had finished several investigation and developing projects:

– prototype of the new clock ensemble and T&F transfer instruments;
– Rb fountain frequency standards;
– ^{87}Sr neutral atoms in an optical lattice frequency standard;
– time and frequency transfer techniques based on different technologies
    - TWSTFT links based on traditional and novel technologies;
    - new modem for TWSTFT and TWFTFT;
    - TW optical fiber time and frequency transfer experiments using SATRE modems;
    - T2L2 experiments using GLONASS satellite.

Prototype of the new clock ensemble and T&F transfer instruments

At the second half, 2016 VNIIFTRI has got base set of time keeping instrument from Vremya-Ch company [4]. That include ensemble of high quality H-masers (each in temperature/humidity control housing), distributing T&F amplifiers and time and frequency inter comparison system. Preliminary performance tests based yielded following results:

• H-maser frequency stability (frequency drift removed)

$\sigma_y(\tau) \leq 3\times10^{-16}$ τ = 1 day;

$\sigma_y(\tau) \leq 1\times10^{-16}$ τ = 10 days;

Frequency drift $\leq 1\times10^{-16}$ / day

• Time and frequency internal measuring system

Time $u_A \leq 20$ ps / single shot

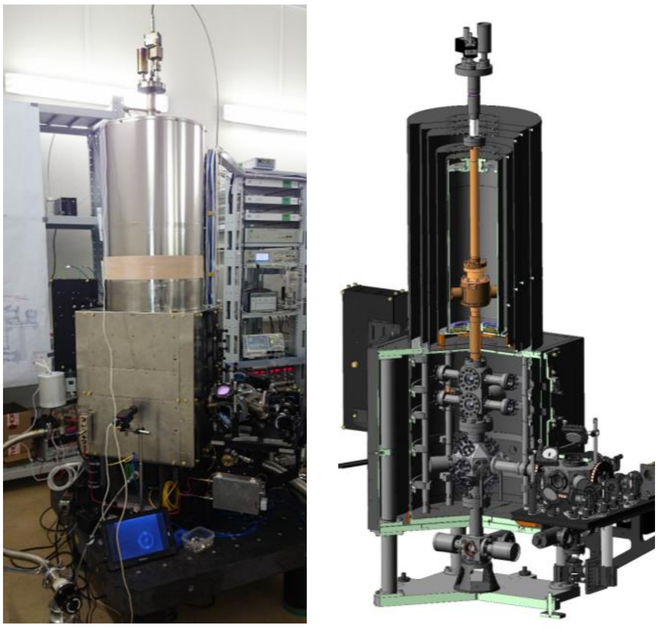
Frequency $u_A \leq 1\times10^{-18}$ / day

Till now this H-maser ensemble is not operational – clocks contribute neither to TA(SU) nor to UTC(SU). We are going to continue further investigations first regarding time u_B and frequency u_B uncertainties of measuring system and H-maser drifts. First two issues are very important because of systematic uncertainties in many aspects affects the whole H-maser ensemble performances.

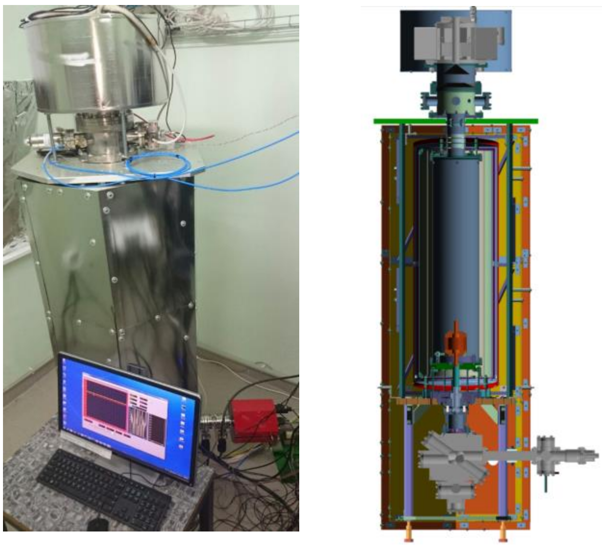
The above-mentioned base time keeping set was supplemented by time and frequency transfer equipment, GNSS and TWSTFT. The existence of three GNSS GTR 51 type receivers enables monitoring receiver's internal delay changes in individual instruments.

All these instruments are intended for re-equipping during coming 3-4 years primary (Mendeleevo) and secondary (Novosibirsk, Irkutsk, Khabarovsk, and Petropavlovsk Kamchatsky) time laboratories. As a result, we hope to be able, maintain time scale basing on ensemble of 20 to 30 H-masers.

Rb fountain frequency standards



VNIIFTRI1 Rb fountain
general view and vertical section



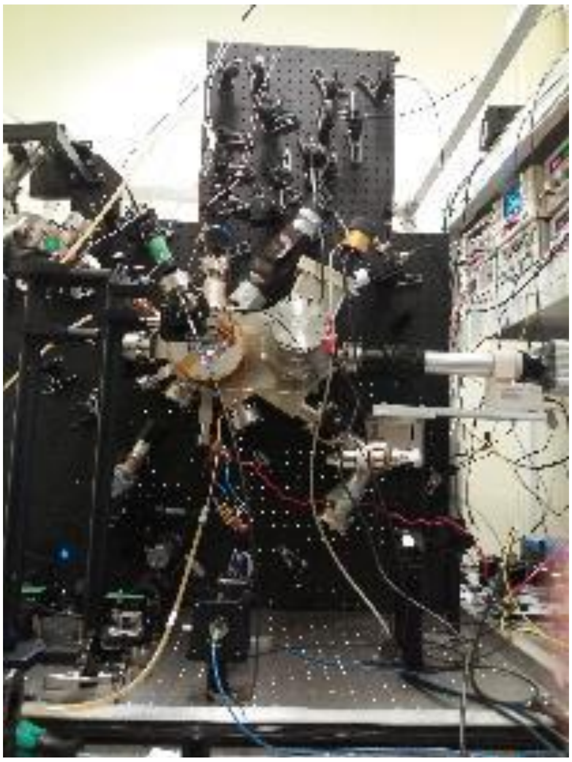
VNIIFTRI2 Rb fountain
general view and vertical section

In the second half 2016 VNIIFTRI time division has got two pairs of Rb fountain frequency standards. These pairs of standards VNIIFTRI$1_{1,2}$ and VNIIFTRI$2_{1,2}$ have somewhat different design. The main design difference is that VNIIFTRI2 has a completely fiber laser system developed and made by μQuanS company and based on industrial laser sources (λ=1560 nm) and industrial erbium fiber optical amplifiers. In contrast to VNIIFTRI2 VNIIFTRI1 has open laser system. Both type of instruments have a comparable central Ramsey fringe width about 1 Hz. First experiments within 2-3 months yielded comparable frequency stability estimation about $\sigma_y(\tau) \leq 1\times10^{-15}$ τ = 1 day and WFM noise dependence on time.

Till now further researches are in progress. Our nearest goal is to get more or less permanent measuring data stream. As a fist step this will be frequency difference VNIIFTRI Rb fountain standards and reference H-maser. Then may be continuous operation as a clock.

^{87}Sr neutral atoms in an optical lattice frequency standard

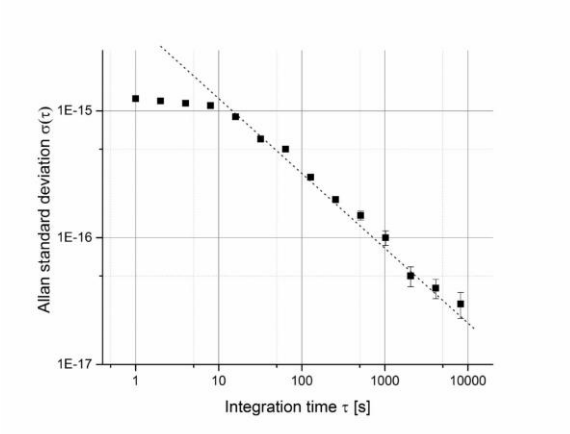
In fall, 2016 have been finished first stage of ^{87}Sr neutral atoms in an optical lattice frequency standard research program. As a result two standard prototypes have been developed.



The vertical wall at attached picture hosts optical spectroscope chamber with optical lattice system and clock transition laser detection system.

Partial uncertainty budget ^{87}Sr standard

Physical phenomena	**Uncertainty Unit 1×10^{-17}**
Black body radiation	2.1
Second order Zeeman shift	3.1
Optical lattice light shift	5.8
Detecting beam light shift	not detected
Cold atom collision	not detected
Total	**6.9**



Preliminary study of metrology performances yielded following approximate figures of u_B uncertainty and stability estimations.

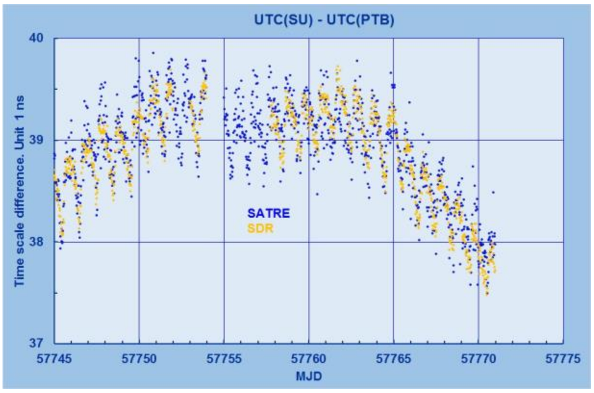
The above figures looks quite promising and are competitive to best results in world leading laboratories for ^{87}Sr standards. Stability level is considerably better than that for existing frequency standards in μ-wave band. Accuracy estimations, not including gravitation corrections, also exceed analogous for best existing μ-wave standards. Therefore, ^{87}Sr standard may be treated in future as a potential candidate to replace Cs primary time unit standard.

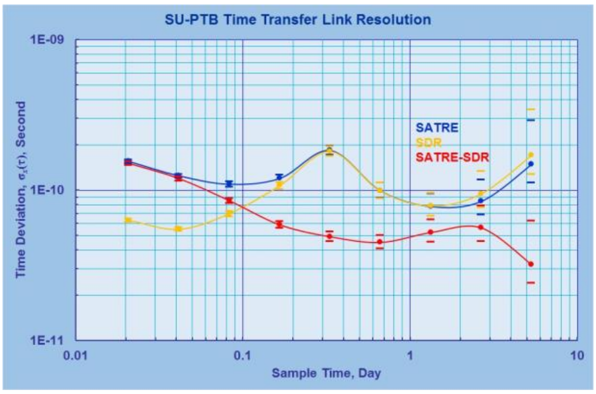
Time and frequency transfer techniques based on different technologies

TWSTFT links based on traditional and novel technologies

Due to many internal reasons and some limitations of Russian broadcasting regulation VNIIFTRI was able to get air license only in December 2016. VNIIFTRI immediately joined to the TWSTFT link via AM-22 and reset time scales comparisons with PTB, NIM and NTSC.

During beginning of 2016 VNIIFTRI time and frequency transfer laboratory purchased necessary equipment and has joined to the experiments with Software Defined Receiver (SDR). Presented below remote time scale comparison data obviously demonstrates considerable decreasing short time

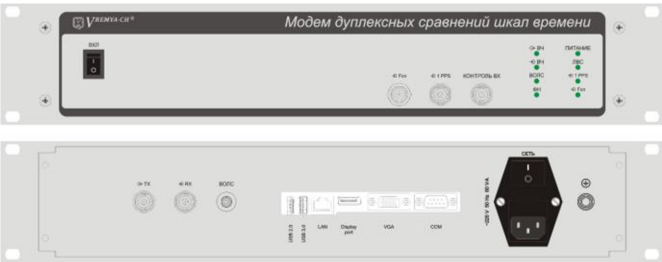




noise component for SDR. Diurnal component still presents both in SATRE and SDR data. Red curve at the right figure demonstrates random residuals in SATRE-SDR links. If one will succeed in suppression diurnal component SDR link performance will be considerably better than 1×10^{-10} s for any sample time starting from session repetition up to a few days.

New modem for TWSTFT and TWFTFT

Under VNIIFTRI contract, VREMYA-CH company is developing modem prototype for TW time and frequency transfer. This modem may be used for traditional TWSTFT as well as for TW time

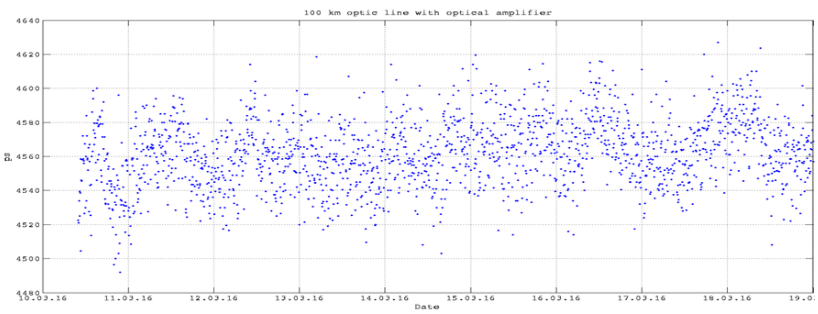


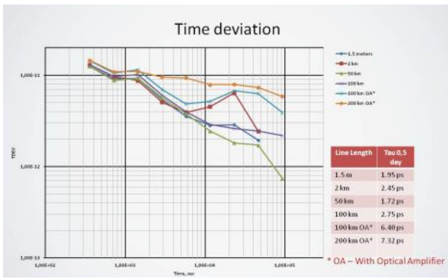
and frequency transfer using optical fiber (TWFTFT). To enable TWFTFT modem contains Tx and Rx optical modules, optical insulator and circulator.

This work is not finished yet, but preliminary theoretical estimations look very encourage. First experimental results are expected at the end of 2017.

TW optical fiber time and frequency transfer experiments using SATRE modems

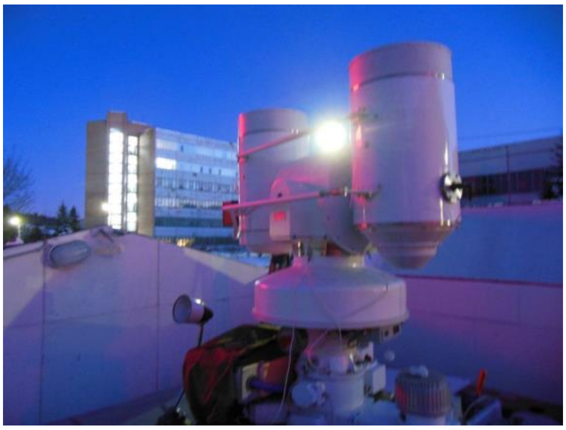
At the beginning 2017 when TWSTFT link in VNIIFTRI was not operated and we had two spare SATRE modems there was arranged TWFTFT laboratory experiment. Within experiment there were used a set of optical fiber length from 1.5 m to 200 km wounded on the spools.





The experiment demonstrated ability to get time resolution ~10^{-12} s for sample time about 1 day.

T2L2 experiments using GLONASS satellite.



Despite VNIIFTRI does not participate in Jason-2 Time Transfer by Laser Link (T2L2) campaign we started domestic analogous experiments using GLONASS # 747. Three laboratories are involved in this activity: VNIIFTRI (*Mendeleevo-1874*), VNIIFTRI ES branch (*Irkutsk-1891*), and GLONASS master station.

Using laser-ranging instruments for the first time in history GNSS time scale has been transferred from one remote laboratory to the other one. Until now, the main source of uncertainty is lime link between on land local time scale and laser station itself.

VNIIFTRI suggestions to the
“Recommendation on the definition of time-scales“,
prepared by Task Group on Time Scales Definition

VNIIFTRI would like to express gratitude to Task Group on Time Scales Definition for Draft 1.5.3 “Recommendation on the definition of time-scales”. That looks as well balanced paper based on fundamental resolutions of the IAU.

On the one hand Recommendation stresses that up to date there is no complete self-contained definition of TAI. Despite worldwide usage of the Coordinated Universal Time (UTC) as the basis of civil time UTC is not adopted as the unique international time reference system for all metrological applications. (Please look through, for example, Resolution 9 of the 24th CGPM (2011) (“On the adoption of a common terrestrial reference system”). Moreover, strictly speaking UTC cannot be used to disseminate the standard of frequency over any time interval.

On the other hand Recommendation in a gentle way reminds time and frequency community of necessity in future to waive the present limitation on the maximum magnitude of DUT1 so as to meet the needs of the current and future user communities.

On redefinition of the SI Units

To our understanding the main intentions of the CGPM, and CIPM particularly, reflected in Resolution 1 of the 24 meeting CGPM (2011) and Resolution 1 of the 25 meeting CGPM (2014) are very positive. Fifty years of nonstop progress since adoption by 13 CGPM in 1967 of the new definition of the SI time unit – the second [5], and about thirty five years since adoption by 17 CGPM in 1983 of the new definition of the SI length unit – the meter [6], successfully demonstrate beneficial of SI base units defined in terms of the invariants of nature − the fundamental physical constants or properties of atoms.

These changes in definition of two SI base units outlines beneficial aspects not only physical basement of new definition but also presents very clear and well understandable for general users linguistic definition of the time and length base units of the SI. The existing definitions of the SI time and length base units have to stimulate metrology community to follow these positive examples.

Within format 24 meeting CGPM (2011) Dr Inglis, president CIPM, presented report [7] in paragraph 9.7 of which entitled "Consultative Committees and the redefinition of some base units of the SI" particularly stated that "As a result of intensive discussions over the past few years, there is now firm consensus in favour of a redefinition of the kilogram, the ampere, the kelvin and the mole based on fixed numerical values of the Planck constant, h, the elementary charge, e, the Boltzmann constant, k, and the Avogadro constant, N_A, respectively."

In adopted then Resolution 1 of the 24 meeting CGPM (2011) [8] contains list of new definition of the kilogram, the ampere, the kelvin and the mole. The General Conference on Weights and Measures noted that the new definitions of the kilogram, ampere, kelvin and mole are intended to be of the explicit-constant type, that is, a definition in which the unit is defined indirectly by specifying explicitly an exact value for a wellrecognized fundamental constant. In addition to that, the International Committee for Weights and Measures also proposed the reformulation of the existing definitions of the second, metre and candela in completely equivalent forms, which might be the following:

• the second, symbol s, is the unit of time; its magnitude is set by fixing the numerical value of the ground state hyperfine splitting frequency of the caesium 133 atom, at rest and at a temperature of 0 K, to be equal to exactly 9 192 631 770 when it is expressed in the SI unit s^{-1}, which is equal to Hz,

• the metre, symbol m, is the unit of length; its magnitude is set by fixing the numerical value of the speed of light in vacuum to be equal to exactly 299 792 458 when it is expressed in the SI unit $m\ s^{-1}$.

Proposed by Resolution 1 of the 24 meeting CGPM (2011) the reformulation of the existing definitions of the second and the meter are in a formal conflict with section **invites** of the Resolution 1 "**the CIPM to continue its work towards improved formulations for the definitions of the SI base units** in terms of fundamental constants, **having as far as possible a more easily understandable description for users in general**, consistent with scientific rigour and clarity".

Let us compare the definition currently in force of the SI unit of time (the second):

“The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom”. At its 1997 meeting CIPM affirmed that: **“This definition refers to a caesium atom at rest at a temperature of 0 K”** [9].

and proposed by Resolution 1 of the 24 meeting of the General Conference on Weight and Measures (2011):

“The second, symbol s, is the unit of time; its magnitude is set by fixing the numerical value of the ground state hyperfine splitting frequency of the caesium 133 atom, at rest and at a temperature of 0 K, to be equal to exactly 9 192 631 770 when it is expressed in the SI unit s^{-1}, which is equal to Hz”.

The definition currently in force is a more easily understandable for users in general and representative – it explains how to realize the second and appeals to counting of time intervals (duration). On the other hand, definition indirectly specifies explicitly an exact value for a wellrecognized fundamental constant.

The proposed new one does not explain how to realize the second and appeals to the derivative unit – Hz. It looks quite strange: since the time unit is not defined there is no derivative unit – Hz.

Quite the same situation is regarding the SI unit of length (the metre).

The definition currently in force of the SI unit of length (the metre):

“The metre is the length of the pass travelled by light in vacuum during a time interval of 1/299 792 458 of a second”

and proposed by Resolution 1 of the 24 meeting of the General Conference on Weight and Measures (2011):

“The metre, symbol m, is the unit of length; its magnitude is set by fixing the numerical value of the speed of light in vacuum to be equal to exactly 299 792 458 when it is expressed in the SI unit ms^{-1}”

And quite the same comments.

Current definition is much more clear and representative – it explains how to realize the metre and appeals to a length.

The proposed new one doesn’t explain how to realize the metre. And too difficult to explain users in general tie between the unit of length and the speed of light. Let’s try to voice this new definition of the unit of length to your teenagers children or grandchildren and then ask them what is the link between length and the speed of light.

To our understanding there is no need to change definitions of the second and the metre, which proved their successful justifiability based on invariants of nature and clear understandable linguistic definition during ten years.

Moreover, following extraction from Resolution 1 of the 24th CGPM (2011), “it would enhance the understandability of the International System if all of its base units were of similar wording”, we may propose draft formulations for the definitions of the SI units the ampere, the unit of electric current, and the mole, the unit of amount of substance, “in terms of fundamental constants, having as far as possible a more easily understandable description for users in general, consistent with scientific rigour and clarity”:

The ampere, the unit of electric current, symbol A, is that constant current which is maintained in conductor by 10^{19}/1.602 17X electron per second flow.

The mole, the unit of amount of substance, symbol mol, the amount of substance of a system which contains 6.022 14X×10^{23} specified elementary entity, which may be an atom, molecule, ion, electron, any other particle or a specified group of such particles.

VNIIFTRI time division supports Resolutions of 23-25 CGPM regarding the SI base unit definition in terms of the invariants of nature. Along with it VNIIFTRI is not in favour of reformulations of existing SI base units of the time and length which proved their successful justifiability based on invariants of nature and clear understandable linguistic definition during ten years.

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[6] Resolution 1 of the 17th CGPM (1983), Comptes Rendus de la 17e CGPM (1983), 1984, p.97, Metrologia, 1984, **20**(1), 25-30.

[7] Report of the President of the CIPM on the work accomplished since the 23rd meeting of the General Conference, Proceedings of the 24th meeting of the General Conference on Weights and Measures (October 2011), 9.7 Consultative Committees and the redefinition of some base units of the SI, p.391.

[8] Resolution 1 of the 24th CGPM (2011), On the possible future revision of the International System of Units, the SI, Comptes Rendus de la 24[e] CGPM (2011), 2013, p.532

[9] Comité International des Poids et Mesures (CIPM), Procès verbaux de la 86e session (Septembre 1997), Bureau International des Poids et Mesures, Organisation Intergouvernementale de la Convention du Mètre