ОРИГИНАЛЬНАЯ СТАТЬЯ

ORIGINAL ARTICLE

Известия вузов России. Радиоэлектроника. 2019. Т. 22, № 4
Journal of the Russian Universities. Radioelectronics. 2019, vol. 22, no. 4

Метрология и информационно-измерительные приборы и системы
Metrology, Information and Measuring Devices and Systems

UDC 53.089.68 https://doi.org/10.32603/1993-8985-2019-22-4-109-114

Improvement of the Russian National Secondary Standard of the Unit of Length Using Latest Ultra-Stable Laser Equipment

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Abstract

Introduction. Increasing demands of precise geometry measurements by science and industry cause the necessity of improvement in an associated branch of legal and practical metrology. One of the most significant fields is the measurement of internal dimensions and so the issues with the unit of meter transfer. Now we face the situation when the current accuracies of National standards of different levels in corresponding traceability chain (reference rings measurements) get close to each other. This means that we have to make the standard of upper level more precise. One of the obvious ways is to apply the latest ultra-stable laser locked to a frequency comb.

Objective. The objective is to propose possibilities for improvement of the National secondary standard of the unit of length by researching its measuring capabilities to minimize measurement uncertainty.

Materials and methods. The calculation of expanded uncertainty of internal diameter measurements by the National secondary standard of the unit of length is performed according to the international document «Guide to the Expression of Uncertainty in Measurement» JCGM 100:2008 approved by BIPM. The secondary standard research results represented in previous reports and publications are also taken into consideration.

Results. Detailed uncertainty budget for the proposed measuring system is given as well as graphical data representing the accuracy improvement.

Conclusion. Actions for minimization of measurement uncertainty components of the National secondary standard of the unit of length in the field of reference ring internal diameter measurements in combination with state-of-the-art laser interferometer system improve it to the next frontiers of accuracy and precision.

Key words: national standard, the unit of length, reference ring, internal diameter, uncertainty, laser

For citation: Mosckalev A. A., Rahman A. Improvement of the Russian National Secondary Standard of the Unit of Length Using Latest Ultra-Stable Laser Equipment. Journal of the Russian Universities. Radioelectronics. 2019, vol. 22, no. 4, pp. 109–114. doi: 10.32603/1993-8985-2019-22-4-109-114

Conflict of interest. The authors declares no conflict of interest.

Submitted 03.07.2019; accepted 10.09.2019; published online 27.09.2019

Introduction. Units and systems which proper work depends on precise measurements of internal dimensions for the finest assembling and performance can be found in any branch of science or industry. A constant build-up of aircraft, ship construction, oil industry, etc. leads to requirements revision in production and control precision. So the level of accuracy in measurements of any kind of gauges and reference standards gets higher and higher in response to increasing demands of modern industry and science.

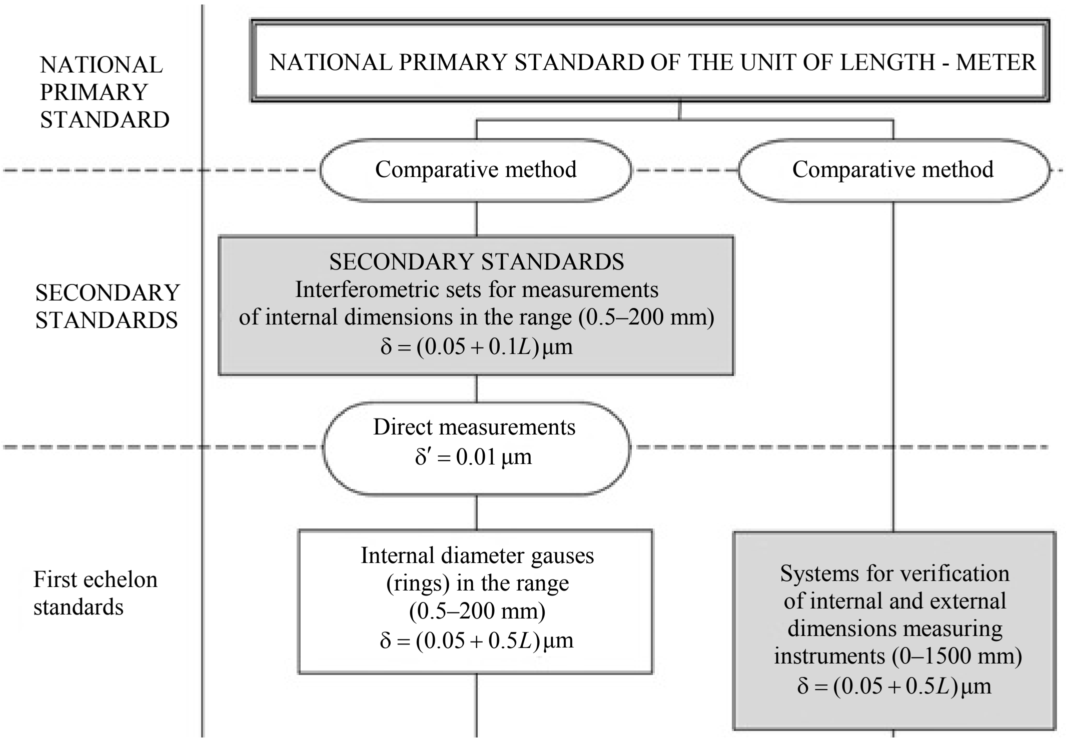

Fig. 1. Extract from the National Traceability Chain

As it concerns the legal metrology, uniformity of measurements and unit transfer regulations for this area in the Russian Federation are given in the latest edition of the National traceability chain [1]. Measuring rings are used as reference gauges for unit of length storing and reproduction. In dependence of its level in the chain rings can transfer unit to high-accurate measuring systems (horizontal instruments for example) as well as down to shop measuring instruments such as bore gauges. It's necessary to mention that according to the new revision of the traceability chain the unit of length – meter has to be transferred from the reference standard to the secondary standard, then to internal diameter gauges (rings) of the first echelon and then down the chain. But the highest accuracy level for this type of standards was the second in the previous version of the document [2]. So, we clearly see the upward trend in the accuracy level in this thread.

The secondary standard used here is the laser interferometer system developed by VNIIM and designed for internal measurements. Again, this system was added into the chain as well as the rings of the first echelon due to demands from the industry mentioned above.

The extract from the traceability chain that covers corresponding unit transfer is given in Fig. 1.

The systems to be discussed in this paper are shaded gray. Accuracy characteristics are given in terms of tolerances (instead of uncertainties, but the correlation will be represented in the following sections). As you see, confident tolerances according to the Formulas are close to each other, and the smaller the measuring range the closer they get. But there should be at least triple gap between the accuracy values of standards at nearest levels in the chain according to general theory [3]. So, the chain is still imperfect, and unfortunately, it cannot be upgraded as fast as the practical demands. And again, the most significant thread covers the unit transfer in the field of internal measurements and reference rings. The same issues appear not only in Russian Federation but in every country with CMCs declared in corresponding area. Only 20 % of countries represented in BIPM database have values of measuring uncertainty for reference rings less than 100 nm [4].

The detailed description of the laser ring measuring system used in VNIIM at the level of the secondary standard as well as its uncertainty components are given below.

Internal measurements laser system. The object of research is the system used in VNIIM for measurements of internal dimensions which consists

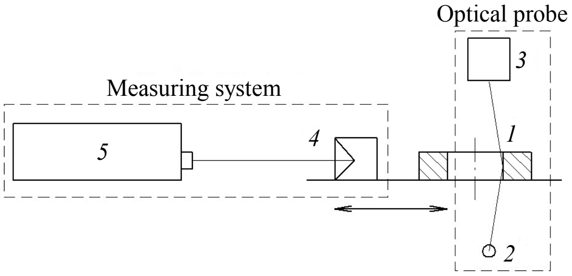

Fig. 2. Measuring setup: *1* – measuring item; *2* – the light source of the optical probe; *3* – photodetector of the optical probe; *4* – movable reflector of the measuring system; *5* – laser

of a horizontal comparator and a laser interferometer. The main feature of the system is the optical probe (also called ‘perflectometer’) for non-contact pointing at the gauge surface [4]. It is well-known that using the tactile probe for the same purpose causes contact deformation, which may affect the results, and the measuring range limitation depending on the probe size [5]. So, the non-contact probe is such an advantage for the entire system.

The general setup of the measuring system in combination with the optical probe is given in Fig. 2 [6]. The measuring item (reference ring) *1* is placed and fixed on the movable table on the axis of the optical probe. The light mark from the source *2* reflects from the gauge surface and the image produced is captured by the detector *3*. The measuring system in the setup consists of a stabilized He–Ne laser *5* with the wavelength $\lambda = 633$ nm that is the part of a Michelson’s interferometer scheme which movable reflector *4* is attached to the table. So the horizontal displacement of the table is the distance between two points on the opposite side of the gauge surface, that is an equivalent of the internal diameter.

The setup has some more parts not mentioned in Fig. 2, such as electronic counters and digital devices for interference pattern processing, temperature stabilization system, etc. Each one will be unfolded along with the uncertainty calculation approach.

Uncertainty calculation. The internal diameter of the reference ring can be evaluated as the function of interferometer readout, laser wavelength, temperature effects including the thermal expansion of ring material, corrections based on optical probe performance and correction on the instrumental error of interferometer system.

The mathematical model of internal diameter measurements can be represented as the Equation [6, 7].

$$d = N\lambda/(2n) + \Delta t_m \,\alpha D + \Delta_\text{p} + \Delta_i, \qquad (1)$$

where d – diameter of the gauge at the temperature of 20 ºC in mm; N – interferometer readout; λ – wavelength of the laser source, mm; n – air refractive index; $\Delta t_m = (20 - t_m)$ – deviation of the gauge temperature t_m from normal, ºC; α – thermal expansion coefficient of the gauge material, K^{-1}; D – nominal diameter of the ring, mm; Δ_p – correction depending on the uncertainty of the optical probe performance, mm; Δ_i – correction depending on the instrumental error of the interferometer system, mm.

This model gave as a result of the expanded uncertainty of measurements with the coverage factor $k = 2$ [7]:

$$U(D) = \sqrt{0.1^2 + 0.92^2 D^2}.$$

This was represented by VNIIM as the results of international comparisons of internal diameter gauges in the COOMET project 181/RU/99. The Formula was corrected after further research and then published in the BIPM CMC database as given (updated on December 28th, 2012) and can be represented as

$$U(D) = \sqrt{0.1^2 + 0.016^2 D^2}.$$

The goal now is to describe each component in details to find out any possibilities for its minimization.

Laser. Laser wavelength error depends on the frequency stabilization system a lot. The corresponding uncertainty has the distribution along the measured length (the distance of mirror displacement) as shown by

$$U_\lambda(D) = U(\lambda)D.$$

This value corresponds to the wavelength in vacuum. To accept it into real air it’s necessary to know air refraction coefficient, which can be calculated by Edlen Formula [8]. Through this, we can take into account combined impact to refraction coefficient by environment temperature, humidity, and pressure. Air refraction coefficient (n) can be derived this way with the error less than $1.8 \cdot 10^{-7}$. The uncertainty of n distributed along the measured length and can be represented as

$$U_n(D) = U(n)D.$$

In the measuring system operation mode the uncertainty of the interferometer readout occurs. The length measured by the interferometer is actually the number of the interference lines *N*. The main source of the error corresponds to the fractional lines counting, that can be obtained only via experiments. It's also a kind of combination of readout error, interferometer resolution, and photodetector sensitivity. Currently used laser LGN-302 gives the resolution error of 20 nm at the wavelength $\lambda = 633$ nm [7]. We can easily reduce this component by choosing the laser system with higher frequency stability, different wavelength and so lower resolution. So this part of the entire system seems to be the first one to be highly improved with the newest frequency stabilization technologies.

In 2017 the frequency comb system was placed in service at VNIIM as the part of the brand-new high-precision hardware complex for the reproduction and transfer of the unit of length [9, 10]. The complex in general consists of frequency measurement equipment (optical frequency comb) and two stabilized lasers with wavelengths of 633 and 532 nm. So, by applying the laser with $\lambda = 532$ nm wavelength to the reference rings measurement system we'll reduce the resolution error to 16 nm.

Temperature. In (1) Δt_m – is the temperature deviation from the normal conditions. This value can be estimated practically by using thermal sensors by "Trimos S. A." and the special software "WinComp" taken from the thermal compensation system of the first echelon standard of the unit of length in the range 10^{-6}–1100 mm [11]. The system consists of platinum temperature sensors by "Almemo" with the measurement uncertainty less than 0.01 K and traceability to the national primary standard of the unit of temperature.

The value contributes into the length measurement with the thermal expansion coefficient (CTE) of the gauge as shown in

$$U_{\Delta t_m}(D) = U(\Delta t_m)\alpha D.$$

The CTE value (α) is also known with error about $0.5 \cdot 10^{-6}\,\mathrm{K}^{-1}$ [12].

The CTE evaluation error affects to the length measurement uncertainty by $\Delta t_m D$.

Individual long-term tests to ensure the temperature stability in the laboratory were performed along one year using the temperature measurement system mentioned above. They represented small temperature excursions around the average value which are negligible for the practical time frame of a single measurement [5].

Instrumental error. The component Δ_i (1) corresponds to the instrumental error of the measuring system. This error is mostly caused by misalignment of the laser beam and movable carriage displacement direction. The basics of the error appearance are shown in Fig. 3.

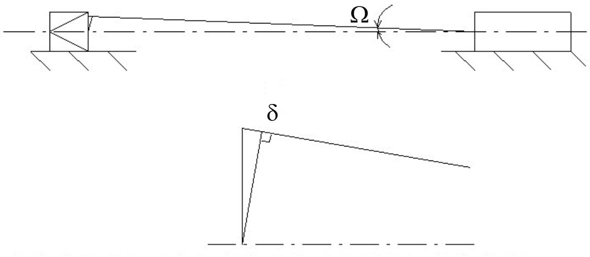

Fig. 3. Instrumental error general description

As seen from the picture, in this case we take as the measurement result not the horizontal displacement but the length increased by additional δ.

The angle Ω can be determined using autocollimator. The high-precise autocollimator by "Trioptics" used successfully in such situations (e.g. in the research of 30-meter interferometer comparator from the National primary standard of the unit of length – meter [13]) in combination with an accurate adjustment of the laser set may easily provide the value of $\Omega = 90''$.

The value δ can be calculated using geometrical formulas with the assumption that trigonometric functions of small angles can be replaced with the values of the angle and can be represented by

$$U(\delta) = \Omega^2/2.$$

The following formula shows the contribution at the measured length for $\Omega = 90''$:

$$U_{\Delta_i}(D) = \frac{\Omega^2}{2} D \approx 0.05 \cdot 10^{-6} D.$$

Optical probe performance. The component Δ_P covers optical probe performance and it means a combination of factors which gives the pointing operation error of the perflectometer system. In another word, it's the uncertainty that appears each time the gauge surface is acquired. It highly depends on the quality of the image we see in the perflectometer projective system and on the signal level of the image mark reflected from the gauge surface. To achieve higher performances, it is necessary to have good reflection and so good item roughness less than the optical probe light source wavelength. In the exact system we use the halogen source of $\lambda \approx 500$ nm. The typical roughness characteristics of reference ring $\mathrm{Ra} \le 40$ nm is the perfect fit according to [14].

The Δ_p component value can be obtained experimentally. Typical value of the VNIIM measuring system represented by

$$U\left(\Delta_\mathrm{p}\right) = 1.23 \cdot 10^{-8}\,\mathrm{m}.$$

This uncertainty appears twice as well as the readout error mentioned above, so the ultimate contribution shown by

$$U_{\Delta_\mathrm{p}}(D) = \sqrt{2} \cdot 1.23 \cdot 10^{-8} = 17\ \mathrm{nm}.$$

Results. Uncertainty components with the values mentioned above are represented in Table. Coefficient of $\sqrt{2}$ is applied for readout and probe components because corresponding uncertainties appear twice at opposite sides of the reference ring.

The following formula shows the calculation of the expanded uncertainty from Table by using coverage factor $k = 2$ according to the GUM [15]:

$$U(D) = \sqrt{0.055^2 + 0.44^2 D}. \tag{2}$$

To compare this result with the previous researches we drawn the following graphic of uncertainty in dependence of measured reference ring diameter in the range of (5…200) mm that corresponds to the measuring range of the National Secondary standard.

The uncertainty of the VNIIM set after improvements applied as they are given above and calculated from (2) is shown by diamonds. Traceability chain requirements for the secondary standards (Fig. 1) are given in terms of uncertainty and shown by triangles. The previous secondary standard research results obtained via international comparisons of internal diameter gauges in 2006 are also shown on the same picture (squares). It means that the methods for the measuring system improvement described in this paper may provide better performance and lower uncertainty to fit the requirements of uncertainty ratio between the secondary standard and the substandard (Fig. 1). The corresponding line (diamonds) also has more theoretically correct slope instead of previous data (squares).

Uncertainty Budget of Reference Ring Measurement

Input quantity, x_i	Standard deviation, $u(x_i)$	Sensitivity coefficient, $c_i = \delta d / \delta x_i$	Standard uncertainty $u_i(d)$, μm
N	$16 \cdot 10^{-9}$	$\sqrt{2}$	0.022
Δ_p	$1.23 \cdot 10^{-8}$	$\sqrt{2}$	0.017
λ	$3 \cdot 10^{-8}$	D	$0.03 \cdot 10^{-3} D$
n	$1.8 \cdot 10^{-7}$	D	$0.18 \cdot 10^{-3} D$
Δ_i	$0.05 \cdot 10^{-6}$	D	$0.05 \cdot 10^{-3} D$
Δ_{t_m}	0.01 K	$\alpha \times D$	$0.12 \cdot 10^{-3} D$
α	$0.05 \cdot 10^{-6}\ \mathrm{K}^{-1}$	$\Delta_{t_m} \times D$	$0.005 \cdot 10^{-3} D$

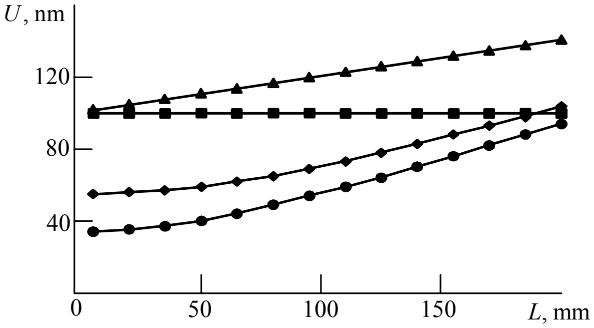

Fig. 4. Expected performance of the improved VNIIM measuring set

By using laser source with a frequency locked to the comb mentioned above we will make all the components related to the laser negligible. For example, relative frequency instability of the currently used LGN laser is $4 \cdot 10^{-9}$ while the same parameter of laser set from the higher precision comb complex is about $9 \cdot 10^{-12}$. So, connecting displacement measuring system of the secondary standard directly with the comb will reduce the resulting expanded uncertainty more. The expected performance is also shown in Fig. 4 by circles.

Conclusion. Here we declared the general setup of the laser interference system made by VNIIM for internal measurements of reference rings as well as some possible methods to be applied for minimization of the uncertainty components.

Along with the laser system improvement, some further steps will be taken to optimize the entire system to make its performance even better.

At first, the real-time thermal compensation system will be applied to have a clear view of temperature gradients in the volume of the measuring set. The system of 2 up to 6 thermal sensors with the special software by "Trimos S. A." is going to be used. The similar one is already launched successfully at the first echelon standard of the unit of length [16].

Then the photodetector of the optical probe will be replaced with the CCD camera and the software for digital image processing. At the same time the measuring table will be equipped with servo drives with the active feedback from the optical probe to make the system acquire diameter points automatically or by remote control. This will make the optical probe performance more accurate and also it will reduce human factor effects as well as the temperature deviations caused by human presence in the laboratory. The steps described will lead to the automation of the entire measurement procedure and the highest accuracy.

On the other hand, some legal procedures should take place to renew the National traceability chain according to the latest accuracy data obtained from the improved Secondary standard unit.

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