COOMET Supplementary Comparison

COOMET.L-S14

COOMET

Project № 569/UA/12

Comparison of length standards in the range of 0.001 to 1 mm

Supplementary comparison

Final Report

Content

1 Introduction

This supplementary comparison is carried out with the purpose of confirming calibration and measurement capabilities of the corresponding national metrology institutes (NMI).

Standard measuring instruments are taking part in comparison with the aim of providing validity of linear dimensions of measurements, of CMCs in the field of measurements of length.

2 Organization of comparisons

2.1 Participants

List of participants is presented in table 1.

Table 1 – Participants of comparisons

National Scientific Center "Institute of Metrology" Address: Mironositskaya str., 42, 61002, Kharkov, Ukraine. Tel.: +38 057 700 34 09 Fax: +38 057 700 34 47 e-mail: info@metrology.kharkov.ua	Kupko Vladimir Semenovich	Tel: +38 057 758 73 03 e-mail: volodymyr.kupko@metrology.kharkov.ua
The D.I. Mendeleev All-Russian Institute for Metrology VNIIM, Address: Russian Federation 19005, St.Peterburg, Moskovkiy avenue 19. Tel.: 7 (812) 251 76 01 Fax: 7 (812) 213 01 14 e-mail: info@vniim.ru http://www.vniim.ru	Chekirda Konstantin Vladimirovich	Tel: 7 (812) 323 96 64 e-mail: K.V.Chekirda@vniim.ru
The Republican state Enterprise "The Kazakhstan institute of Metrology " Address: Kazakhstan 010000, Astana, Levy Bereg, 35 street, Building 11 Tel: (3172)24 09 15	Dulat Moldybayev	Tel: +7 7172 75 07 57 e-mail: dulat_83@mail.ru

2.2 Schedule of comparison:

NSC "Institute of Metrology", Kharkov	July 2015
"KazInMetr", Astana	August 2015
VNIIM, St.Petersburg	January 2016
NSC "Institute of Metrology", Kharkov	August 2016

2.3 Scheme of performing comparison

The reference line gauge of comparison with a length of 1 mm scale is measured in the NSC "Institute of Metrology", thereafter it is successively delivered to all participants of comparison. After the measurement by the last participant, the reference line gauge is measured at the NSC "Institute of Metrology" for checking its stability.

By the end of comparison, the reference line gauge is not used for any other purposes except comparisons.

2.4 Reference line gauge of comparison

The reference line gauge of comparison is a line gauge of length of type OMO plant No. 0707. The nominal length of the gauge scale is 1 mm, the length of the scale gauge intervals is 0.005 mm.

Temperature coefficient of linear expansion of the gauge $\alpha = 10.0 \cdot 10^{-6} K^{-1}$.

The general view and geometric dimensions of the comparison measure of the type OMOs are presented in Fig. 1

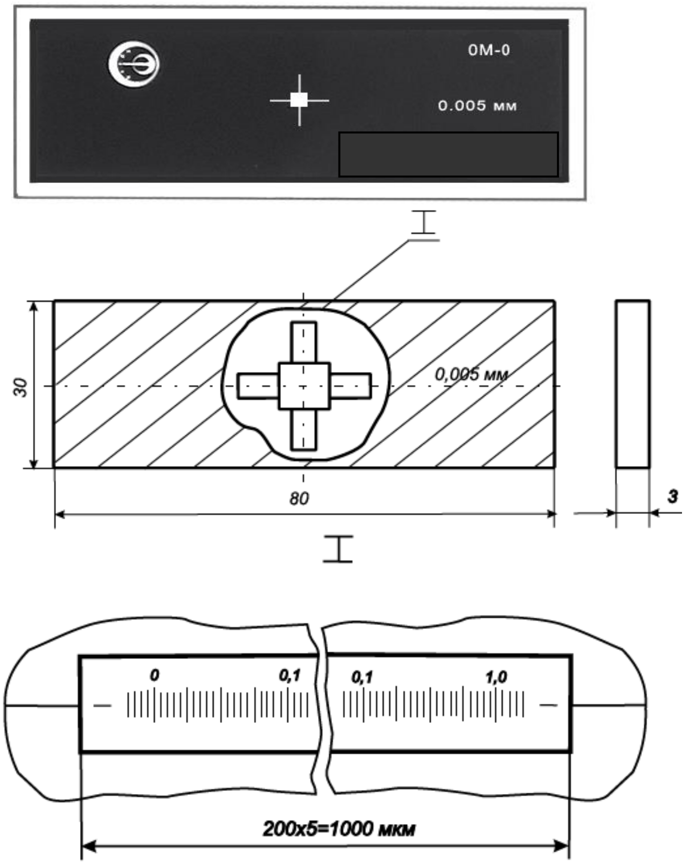

Fig. 1 – General view and geometric dimensions of the comparison measure of the type OMOs.

3 Methods of performing measurements

The measured value is the distance between the axis (center) "0" of the gauge line and the axis (center) of the line of the measured interval.

Nominal lengths of intervals, which are measured, are the following:

Nominal length of intervals, mm	
0 – 0.1	0 – 0.6
0 – 0.2	0 – 0.7
0 – 0.3	0 – 0.8
0 – 0.4	0 – 0.9
0 – 0.5	0 – 1.0

Determination and accurate adjustment (center) of the line is carried out using a photoelectric microscope. The length of the measured intervals is determined by an interference method.

Measurements of the temperature of the gauge and the refractive index of air are made by each participant of the comparisons according to their methodology.

The measurement uncertainties are calculated in accordance with [1]. Participants use the model adapted to their reference tools and measurement methodology.

4 Results of comparison

4.1 Kazakhstan Institute of Metrology

Measurements are carried out at the state secondary standard of the unit of length in the range from 0.001 to 200 mm.

Comparator consists of two following main parts:

– laser displacement interferometer equipped with a frequency-stabilized He-Ne laser of type LGS-311;

– optical-mechanical system;

– system of temperature measurements, humidity and pressure.

Measurements of interval length and general length of the band are carried out by absolute interference method at laser interference comparator.

The refractive index of air was calculated with the help of the Edlen formula on the measured physical parameters of air: humidity, pressure and temperature.

Temperature of the gauge (T_g) is determined using a platinum resistance thermometer. During the calculation of the length of gauge intervals, the arithmetic mean of the measure temperature measured before and after measurement is used. The uncertainty in measuring the temperature of the gauge is 0.029 °C.

Humidity was measured by the temperature and humidity transducer IPTV-206. The uncertainty in measuring the relative humidity of air is $u\ (e)$ = 26.7 Pa.

The air pressure was measured with a sample barometer of the model BRS-1M-2 with an absolute error 20 Pa, which, in terms of uncertainty is 12 Pa.

Conditions of performing measurements:

– air temperature (20 ± 0.3) °C;

– relative humidity (30 ± 5) %;

– air pressure (970 ± 10) hPa.

The protocol of deviation of lengths of the measured intervals from their nominal value is shown in Table 2.

Table 2

Nominal length of intervals, mm	Deviation, mm	Nominal length of intervals, mm	Deviation, mm
0 – 0.1	0.000022	0 – 0.6	0.000039
0 – 0.2	0.000030	0 – 0.7	0.000039
0 – 0.3	0.000010	0 – 0.8	0.000084
0 – 0.4	0.000038	0 – 0.9	0.000067
0 – 0.5	0.000041	0 – 1.0	0.000100

The results of measurements are given for 20 ºC.

The length of intervals of comparison, given for 20 ºC, is calculated on the base of comparison equation

$$L_{20} = (\lambda_0 \cdot \varphi_{int}) / n_a + (\alpha\, (\lambda_0 \cdot \varphi_{int}) / n_a\,) \cdot (20 - T_g)$$

L_{20} – length of the measured interval, given for 20 °C;

λ_o – wavelength of laser radiation in vacuum;

φ_{int} – phase shift of interference fringes in the interferometer during the movement of the carriage with a microscope;

n_a – refractive index of wavelength in air;

α – temperature coefficient of linear expansion of gauge;

T_g – gauge temperature.

Budget of uncertainty:

Table 3

Components of uncertainty	Type of uncertainty. Distribution	Standard uncertainty (nm)	Influence coefficient	Contribution to total uncertainty (nm)
Independent from length				
Nonideality of optics	On type A normal	10	1	10
Determination of line center	On type B uniform	10	1	10
Variation of the edge of the line	On type B uniform	10	1	10
Nonlinearity of interferometer	On type B uniform	7	1	7
Dependent from length				
Uncertainty on Type A	On type A normal			$50 \times L$
Wavelength of laser	On type B uniform	$2 \cdot 10^{-8}$	$L \times 10^{9}$	$20 \times L$
Air temperature $u\ (t)$	On type B uniform	0.029 °C	$0.947 \cdot 10^{3} \times L$	$27.5 \times L$
Air pressure $u\ (p)$	On type B uniform	12.0 Pa	$0.364 \cdot 10^{3} \times L$	$32.8 \times L$
Air humidity $u\ (e)$	On type B uniform	26.7 Pa	$0.056 \cdot 10^{3} \times L$	$11.2 \times L$
Refractive index of air $u\ (n)$	On type B uniform	$\sqrt{u(t)^2 + u(p)^2} + u(e)^2$		$44.2 \times L$
Edlen formula	On type B uniform	$5 \cdot 10^{-8}$	$L \times 10^{9}$	$50 \times L$
Gauge temperature	On type B uniform	0.029 °C	$10.0 \cdot 10^{3} \times L$	$290 \times L$
Temperature gradient of gauge	On type B uniform	0.029 °C	$10.0 \cdot 10^{3} \times L$	$290 \times L$
Gauge uncertainty of TCLE at $(20 – T_g = 0.1)$ ºC	On type B uniform	$1 \cdot 10^{-7}$	$0.1 \cdot 10^{2} \times L$	$10 \times L$

The total standard uncertainty of the length of the interval, taking into account the estimates given in Table 3, consists:

– of the total standard uncertainty, which not depends on the length of the interval

$u_{cn} = \sqrt{10^2 + 10^2 + 10^2 + 7^2} = 18.7$ nm

– of the total standard uncertainty, which depends on the length of the interval $u_{cd} = \left(\sqrt{50^2 + 20^2 + 44.2^2 + 50^2 + 290^2 + 209^2 + 10^2}\right) = 419 \times L$ nm.

The total standard uncertainty of the length of the interval, taking into account the dependent and length-independent components, will have the form

$$u_c = \sqrt{u_{cn}^2 + u_{cd}^2} = \sqrt{18.7^2 + (419L)^2} \text{ nm}$$

The expanded uncertainty U with a confidence probability of 0.95 is calculated by the formula $U_{0.95} = k \cdot u_c$ at $k = 2$.

$$U_{0.95} = 2 \cdot \sqrt{18.7^2 + (419L)^2} \text{ nm},$$

where L – length of the measured interval in metres.

4.2 The D.I. Mendeleev All-Russian Institute for Metrology VNIIM

4.2.1 Brief description of the measurement method

The standard is designed to measure the length of line gauges of the 1st and 2nd digit in the range (0.1 – 1000) mm.

The standard includes a set of measuring instruments based on a frequency-stabilized laser. Measurements are performed by the method of counting interference fringes. Grating period of the interference fringe is determined by the frequency of the laser radiation, the speed of light in vacuum and the refractive index of air in the measurement zone.

Lines of gauges are registered with a laser microscope in a dynamic mode. The length of the gauge is calculated by the joint computer processing of the analog signals of the microscope and the laser interferometer. Signals are input to the computer using an analogue digital converter.

The refractive index of air is measured by an interference refractometer during measurement of the gauge, by changing the optical length of the refract meter chamber during the evacuation of air from it.

The temperature of the gauges is measured by a platinum resistance thermometer PTS10 (10 Ohm) and three differential thermocouples that are fixed to the measure. This allows us to calculate the length of the measure, reduced to a temperature of 20 °C.

4.2.2 Conditions of performing measurements

The standard is located in a passive thermostat, which is located in a thermostated room, where the temperature is maintained (20.0 ± 0.1) °C. The standard is mounted on a vibration-insulated foundation.

4.2.3 The results of measurements

The temperature coefficient of linear expansion of the comparison gauge was assumed to be $10.0 \cdot 10^{-6}$ K^{-1}.

The results of measurements in Table 4 are given for 20 °C.

Table 4 – the results of measurements

Interval, mm	Nominal length of intervals, mm	Actual length of intervals, mm	The deviation of the actual lengths of intervals from their nominal value, µm
0 – 0.1	0.1	0.100034	+0.034
0 – 0.2	0.2	0.200040	+0.040
0 – 0.3	0.3	0.300031	+0.031
0 – 0.4	0.4	0.400044	+0.044
0 – 0.5	0.5	0.500035	+0.035
0 – 0.6	0.6	0.600056	+0.056
0 – 0.7	0.7	0.700063	+0.063
0 – 0.8	0.8	0.800082	+0.082
0 – 0.9	0.9	0.900090	+0.090
0 – 1.0	1.0	1.000081	+0.081

Budget of uncertainties (making errors)

Table 5 gives an estimate of the uncertainty in measuring the length of the glass measure.

Table 5 – Budget of uncertainties

Components of uncertainty and their dimensions	The value of the component	Influence coefficient	Relative uncertainty	Absolute uncertainty (nm)	Square of an absolute uncertainty
Independent from length					
Nonideality of optics (nm)	5			5	25
Line defects (nm)	6			6	36
Determination of line center (nm)	2			2	4
Interferometer sensibility (nm)	1			1	1
Nonlinearity of interferometer (nm)	2			2	2
Mechanics errors (nm)	5			5	25
Dependent from length					
Laser wavelength (relative.)	$2\cdot10^{-8}$	1	$2\cdot10^{-8}$	20·L*	$400\cdot L^2$
Refractive index (relative.)	$3\cdot10^{-8}$	1	$3\cdot10^{-8}$	30·L	$900\cdot L^2$
Gauge temperature (K)	0,0035	$10\cdot10^{-6}$	$3.5\cdot10^{-8}$	35·L	$1225\cdot L^2$
Expansion coefficient of the measure at (T–20) = 0.1 K (K^{-1})	$1\cdot10^{-7}$	0,1	$1\cdot10^{-8}$	10·L	$100\cdot L^2$
Sq. Sums that are independent of length					93
Sq. Sums depending on the length					$2625\cdot L^2$

* – here and further parameter L – it is length in meters.

$$u_c = 9.6 + 51\cdot L \text{ nm.}$$

$$U_c = 19.2 + 102\cdot L \text{ nm, at } k = 2.$$

4.3 National scientific center "Institute of metrology"

Measurements were made on a complex of measurements of line and end gauges of the length of the state primary standard of a unit of length.

4.3.1 Complex includes:

– thermal chamber with comparator;

– laser interferometer measuring system;

– system of photoelectron microscopes;

– drive of the movable carriage of the comparator;

– a system for measuring environmental parameters;

– an electronic system for controlling the operation of the comparator and processing the measurement results.

4.3.2 Conditions of measurements

Thermal chamber of the comparator is located on vibration-proof supports and the foundation and is located in a separate room in which the required temperature is maintained. Inside the chamber there is a thermoregulation system to maintain the temperature during the measurements within (20.0 ± 0.1) °C.

4.3.3 Brief description of the measurement method

The measurements are carried out by an interference method using a laser interferometer system based on a stabilized He-Ne laser. Guidance to the center of the line is carried out using a photoelectron microscope with the exact positioning of the movable carriage of the comparator relative to the measure being measured.

Accurate measurement of the temperature of the measure and air in the chamber is carried out with the help of platinum and differential temperature sensors for measuring the environmental parameters. The influence of the environmental parameters as a result of the measurement is taken into account by using the Edlen's formula. The temperature coefficient of linear expansion of the comparison measure is assumed to be $10.0 \cdot 10^{-6}$ K^{-1}. The length of the measure is determined, given for 20 °C.

4.3.4 Results of measurements

The results of measurements of the length of the comparison measure, given for 20 °C are presented in Table 6.

Table 6 – Results of measurements

Interval, mm	The measured length of intervals, mm	Deviation of the measured lengths of intervals from their nominal value, mm
0 – 0.1	0.100025	+0.000025
0 – 0.2	0.200024	+0.000024
0 – 0.3	0.300015	+0.000015
0 – 0.4	0.400033	+0.000033
0 – 0.5	0.500035	+0.000035
0 – 0.6	0.600043	+0.000043
0 – 0.7	0.700046	+0.000046
0 – 0.8	0.800069	+0.000069
0 – 0.9	0.900080	+0.000080
0 – 1.0	1.000086	+0.000086

4.3.5 Budget of uncertainty

The uncertainty budget for measuring a typical line gauge on a comparator is shown in Table 7.

Table 6 – Budget of uncertainty

Sources of uncertainty	Type of uncertainty Type of distribution	Standard uncertainty $u(x_i)$	Influence coefficient c_i L, m	Contribution to total uncertainty nm
Independent from the length of interval				
Determination of line center	on type A normal			9
Variation of line	on type B uniform.			4
Dependent from the length of interval				
u_A, dependent from the length of interval	on type A normal			$110 \cdot L$
Wavelength (relative)	on type B uniform.	$1.5 \cdot 10^{-10}$	$L \cdot 10^9$	$0.15 \cdot L$
Air temperature	on type B uniform	0.003 °C	$0.937 \cdot 10^3 \cdot L$	$3 \cdot L$
Air pressure	on type B uniform	8.0 Pa	$0.361 \cdot 10^3 \cdot L$	$22 \cdot L$
Air humidity	on type B uniform	8.0 Pa	$0.054 \cdot 10^3 \cdot L$	$3.2 \cdot L$
Method of calculating the refractive index of air	on type B uniform	$3 \cdot 10^{-8}$	$L \cdot 10^9$	$30 \cdot L$
Measure temperature	on type B uniform	0.003 °C	$11.5 \cdot 10^3 \cdot L$	$35 \cdot L$
Gradient of temperature measure	on type B uniform	0.003 °C	$11.5 \cdot 10^3 \cdot L$	$35 \cdot L$
Gauge uncertainty of TCLE at (20–T=0.1) ˚C	On type B uniform.	$5.8 \cdot 10^{-7}$	$0.1 \cdot 10^9 \cdot L$	$58 \cdot L$
Total standard uncertainty u_c				$\sqrt{97+19416 \cdot L^2}$

The total standard uncertainty u_c can be written as:

$$u_c=\sqrt{97+19416 \cdot L^2}=\sqrt{9.8^2+139^2 \cdot L^2}$$ nm, where L – in metres.

The expanded uncertainty with a confidence level of 0.95 and a coverage factor of k = 2 is defined as:

$$U=k \cdot u_c=2 \cdot \sqrt{9.8^2+139^2 \cdot L^2}=\sqrt{19.6^2+278^2 \cdot L^2}$$ nm, where L – in metres.

5 Analysis of measurements results

Comparative results of measurements of the comparison participants for each interval are shown in Fig. 2 - 11.

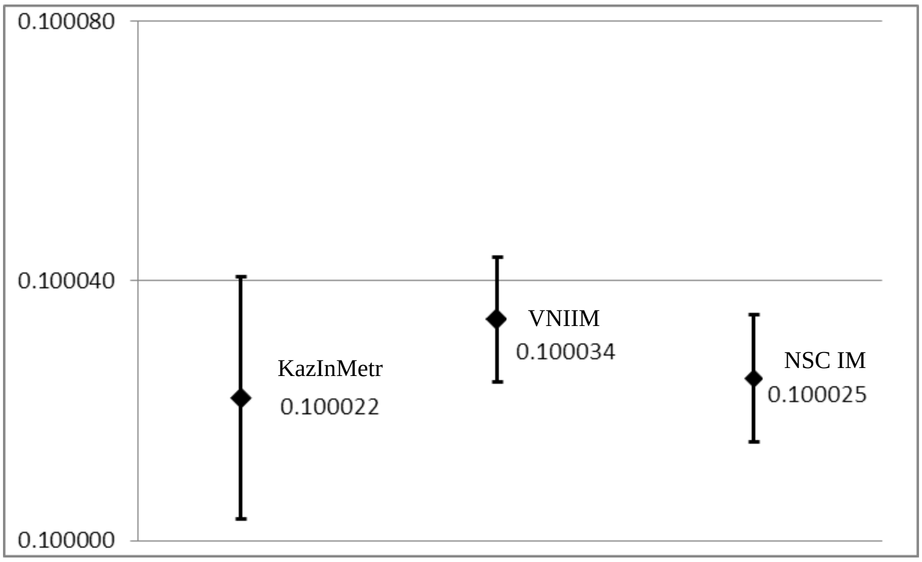

Figure 2 – The measurement results of the interval 0 – 0.1 mm

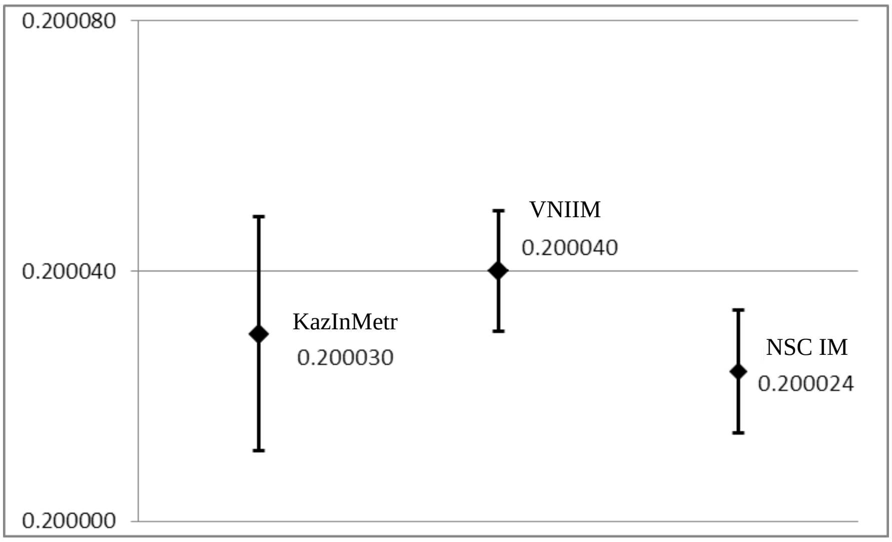

Figure 3 – The measurement results of the interval 0 – 0.2 mm

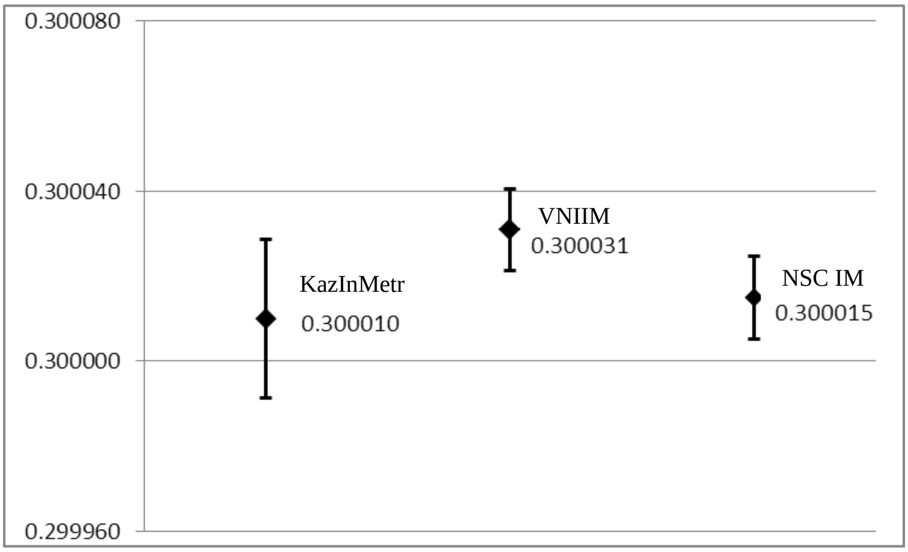

Figure 4 – The measurement results of the interval 0 – 0.3 mm

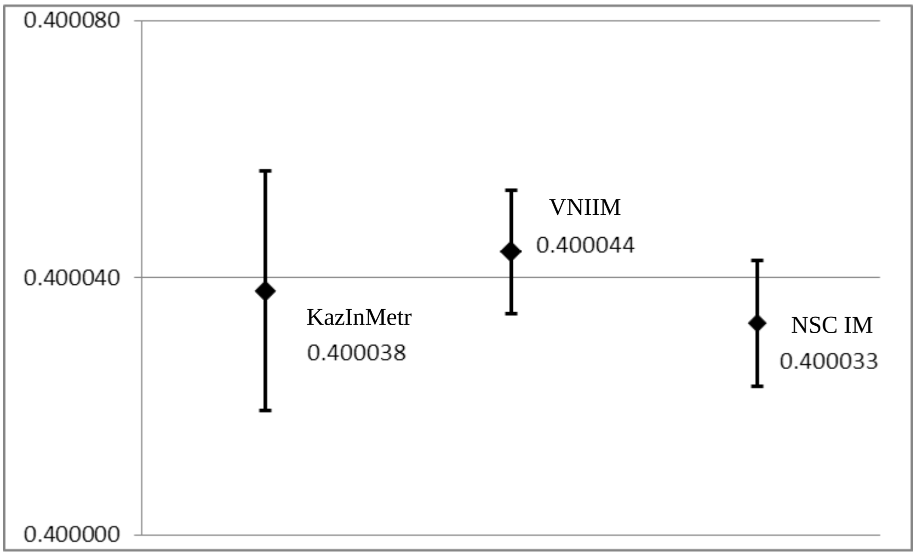

Figure 5– The measurement results of the interval 0 – 0.4 mm

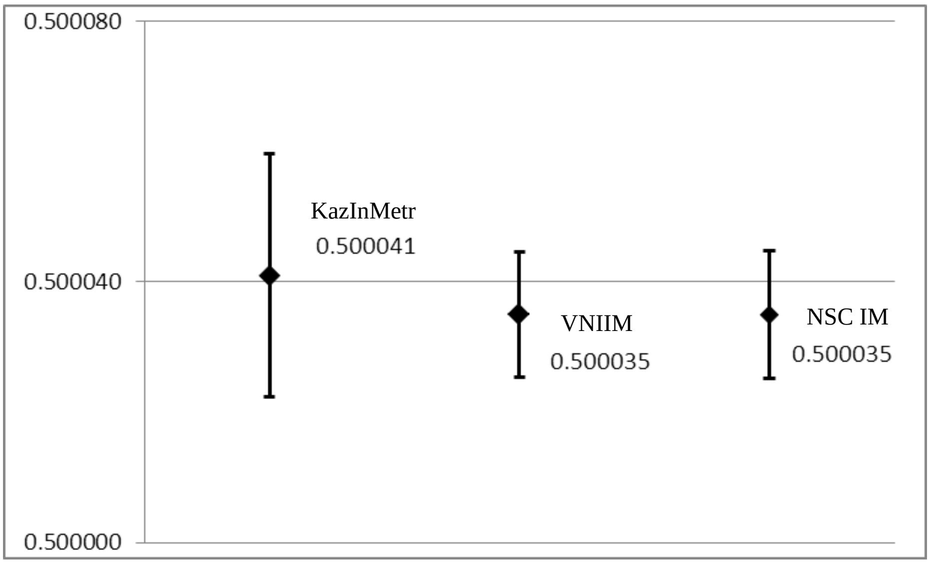

Рисунок 6 – The measurement results of the interval 0 – 0.5 mm

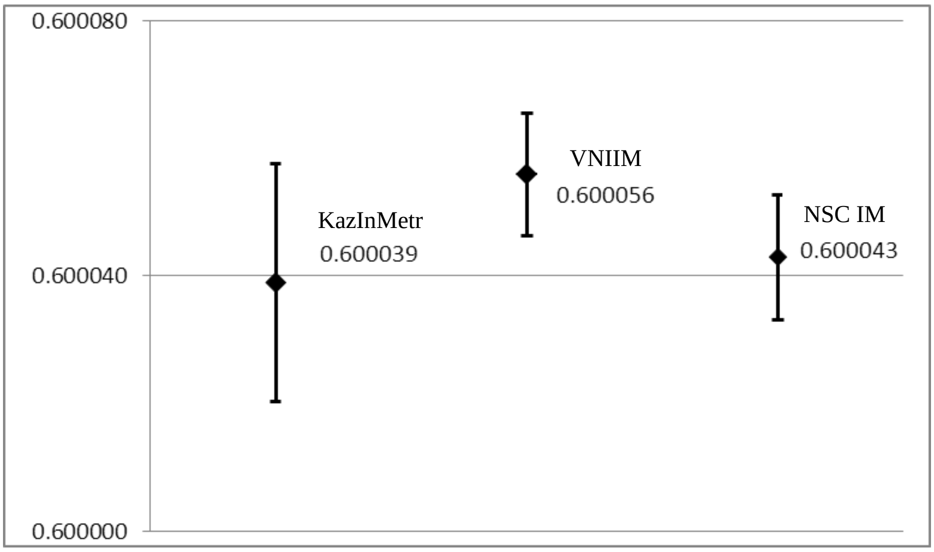

Figure 7 – The measurement results of the interval 0 – 0.6 mm

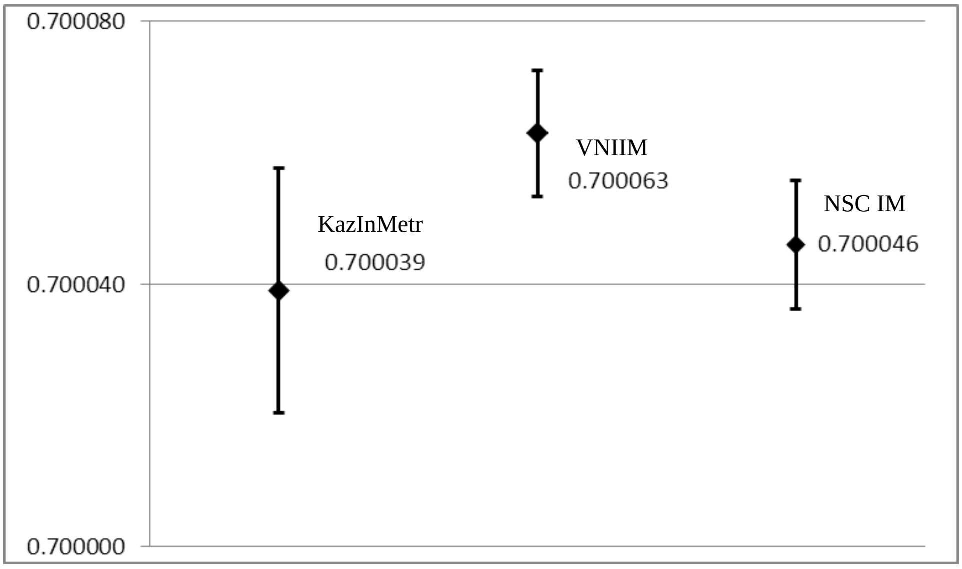

Figure 8 – The measurement results of the interval 0 – 0.7 mm

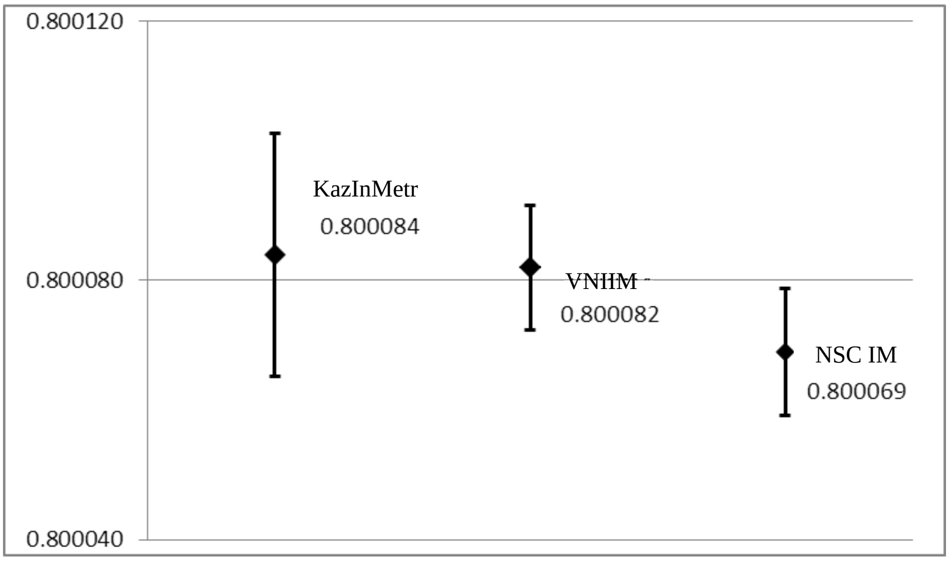

Figure 9 – The measurement results of the interval 0 – 0.8 mm

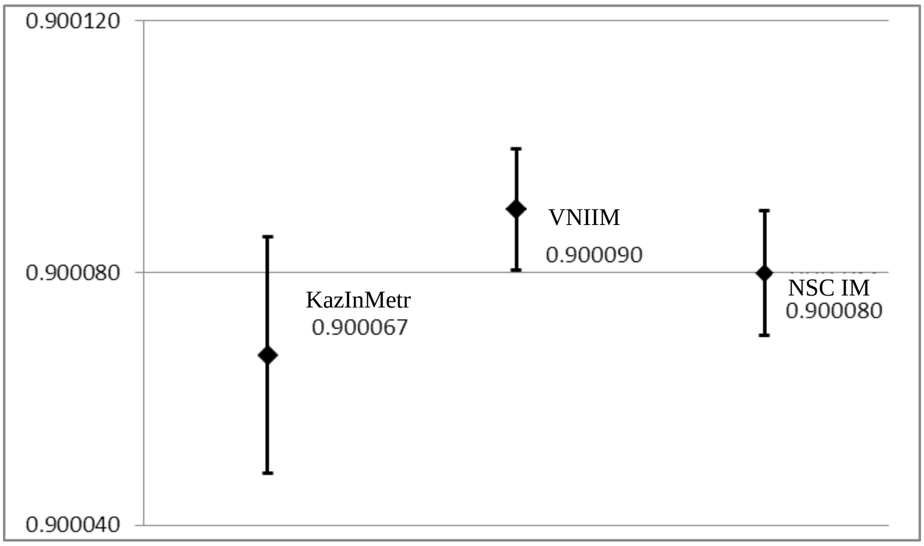

Figure 10 – The measurement results of the interval 0 – 0.9 mm

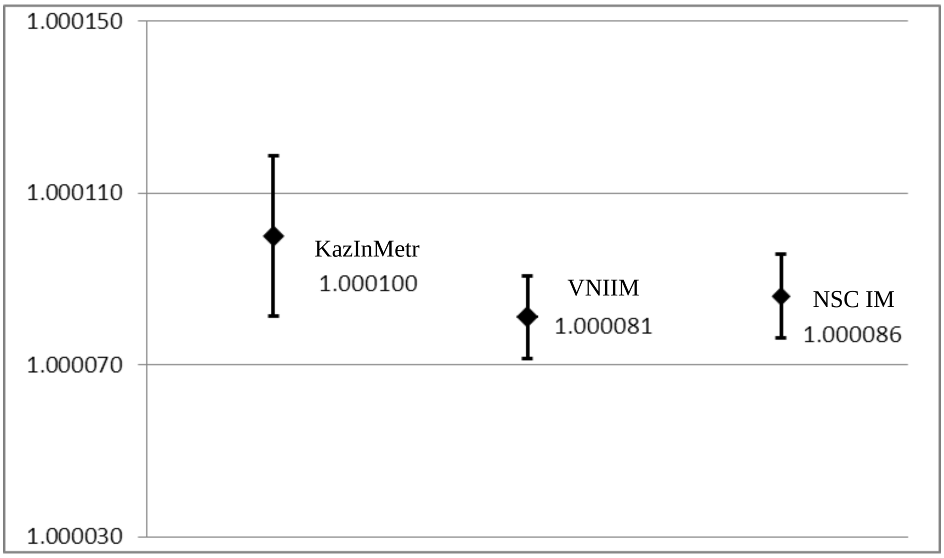

Figure11 – The measurement results of the interval 0 – 1.0 mm

According to the results of the analysis provided by all participants of the data comparisons, in accordance with § 5.1.2 [2], the value of criterion χ^2 does not exceed the critical value ($\chi^2_{0.95}$ = 5.99) for all measured intervals of the comparison measure, that is the objective confirmation of the announced uncertainties.

The summary of the results and the En calculations is given on the next page.

	Deviation / nm			Expanded uncertainty / nm			Weight			Wt mean	U(Wt mean)	Result - Wt mean / nm			En		
L/mm	KazInMetr	VNIIM	NSCIM	KazInMetr	VNIIM	NSCIM	KazInMetr	VNIIM	NSCIM	/nm	/nm	KazInMetr	VNIIM	NSCIM	KazInMetr	VNIIM	NSCIM
0.1	22	34	25	37.4	19.2	21.8	1.60	6.07	4.73	29.0	13.4	-7.0	5.0	-4.0	-0.20	0.36	-0.23
0.2	30	40	24	37.4	19.2	22.5	1.63	6.16	4.48	32.8	13.6	-2.8	7.2	-8.8	-0.08	0.53	-0.49
0.3	10	31	15	37.4	19.2	21.4	1.59	6.02	4.86	22.1	13.4	-12.1	8.9	-7.1	-0.35	0.64	-0.42
0.4	38	44	33	37.4	19.2	23.1	1.65	6.22	4.31	39.3	13.7	-1.3	4.7	-6.3	-0.04	0.35	-0.34
0.5	41	35	35	37.4	19.3	21.9	1.61	6.07	4.70	35.8	13.5	5.2	-0.8	-0.8	0.15	-0.06	-0.05
0.6	39	56	43	37.4	19.3	25.0	1.71	6.46	3.83	49.4	14.1	-10.4	6.6	-6.4	-0.30	0.50	-0.31
0.7	39	63	46	37.4	19.3	26.3	1.76	6.63	3.56	54.4	14.4	-15.4	8.6	-8.4	-0.45	0.67	-0.38
0.8	84	82	69	37.4	19.3	30.1	1.91	7.19	2.96	79.1	14.9	4.9	2.9	-10.1	0.14	0.23	-0.39
0.9	67	90	80	37.4	19.3	31.8	1.99	7.47	2.75	84.0	15.1	-17.0	6.0	-4.0	-0.50	0.50	-0.14
1.0	100	81	86	37.4	19.3	29.9	1.90	7.15	2.99	85.2	14.9	14.8	-4.2	0.8	0.43	-0.34	0.03

6 Conclusion

The obtained data of all comparison participants can be recognized as supporting their existing declared CMCs (calibration and measurement capabilities) in the field of measurements of these length scales.

For information, the expanded uncertainty achieved in this comparison and the CMC expanded uncertainty in the Key Comparison Database are as follows.

KazInMetr

Comparison U = Q[18.7, 419L] nm, L in metres

CMC U = Q[15, 207L] nm, L in metres

VNIIM

Comparison U = 19.2 nm + 102L nm, L in metres

CMC U = Q[20, 300L] nm, L in metres

NSCIM

Comparison U = Q[19.6, 278L] nm, L in metre

CMC U = Q[20, 300L] nm, L in metres

where Q[a, bL] means $\sqrt{a^2 + (bL)^2}$

Literature

1 ISO Guide for the Expression of Uncertainty in Measurement

2 COOMET R/GM/19:2008 Guideline on COOMET supplementary comparison evaluation