Проведено порівняльний аналіз отриманих у міжнародних звіреннях національних еталонів одиниць електричної ємності результатів з метою оцінювання збіжності. Встановлені ступені еквівалентності еталонів учасників звірень та розширені невизначеності для номіналів мір 10 пФ і 100 пФ на частотах 1 кГц і 1,592 кГц. Запропонована методика оцінювання невизначеності вимірювань у діапазоні значень ємності від 10 пФ до 10 нФ

Ключові слова: звірення еталонів, метрологічна простежуваність, електрична ємність, національний метрологічний інститут, калібрувальні та вимірювальні можливості

Проведен сравнительный анализ полученных в международных сличениях национальных эталонов единиц электрической ёмкости результатов с целью оценивания сходимости. Установлены степени эквивалентности эталонов участников сличений и расширенные неопределенности для номиналов мер 10 пФ и 100 пФ на частотах 1 кГц и 1,592 кГц. Предложена методика оценки неопределенности измерений в диапазоне значений ёмкости от 10 пФ до 10 нФ

Ключевые слова: сличения эталонов, метрологическая прослеживаемость, электрическая ёмкость, национальный метрологический институт, калибровочные и измерительные возможности

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SUPPORT OF METROLOGICAL TRACEABILITY OF CAPACITANCE MEASUREMENTS IN UKRAINE

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1. Introduction

The system of national standards is created for realization and transmission of the size of the legalized measurement units of various physical quantities to meet the needs of the national economy. In the case when national standards realize measurement units independently, they must be regularly compared with the national standards of other countries for confirmation of equivalence.

International comparisons of standards are conducted under the aegis of the Consultative Committees (CC) of the International Committee of Weights and Measures (CIPM) or by regional metrology organizations (RMO) [1, 2]. Confirmation of equivalence of national standards with the standards of other countries is carried out under the procedures set at an international level within the framework of multilateral "Mutual recognition of national measurement standards and of calibration and measurement certificates issued by national metrology institutes of CIPM" (hereinafter – the CIPM MRA) [3].

In accordance with the International vocabulary of metrology (VIM) [4], metrological traceability is the property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty. The metrological traceability concept is important for practical application, as it allows measurement accuracy comparison according to the standardized procedure of estimation of measurement uncertainty [5].

An important element of providing metrological traceability is estimation of measurement uncertainty. In accordance with the VIM, metrological traceability is determined as an inalienable parameter that characterizes dispersion of quantitative values that can be ascribed to the measurand on the basis of the information used. The basis for the evaluation of measurement uncertainty at an international level is the Guide to the expression of uncertainty in measurement (GUM) [6]. The requirements of regional organizations for the evaluation of measurement uncertainty are based on the provisions of the GUM.

Calibration and Measurement Capabilities (CMC) are the greatest level of calibrations and measurements that are guaranteed by national metrology institutes (NMIs) to the consumers of metrology services, as a value of the expanded uncertainty of the results of measurements conducted by NMIs at a confidence level of 0.95. CMC characterize the quality of metrological services provided to the consumers on a permanent basis [7, 8].

For providing the metrological traceability of measurements of the electrical capacitance in Ukraine, at the international level, it was necessary to carry out corresponding comparisons of standards within the framework of RMO –

Euro-Asian cooperation of national metrological institutions (COOMET), of which Ukraine is a member.

2. Literature review and problem statement

Modern trends of the world economy considerably promote the role of NMIs in providing mutual recognition of measurement results obtained by NMIs, and effective functioning of national metrological services in the conditions of globalization of the world economy and international division of labour.

In [9], the analysis of the general guides and international standards that are used for the evaluation of elements of metrological traceability is conducted. The procedures used for the CIPM key comparison (KC) data evaluation are worked out in order to provide connection with CIPM KC data with low uncertainty. The specified procedures must correspond to those used for the RMO KC data evaluation. During KC by both the CIPM CC and RMO, it is expedient to use the concerted method (general rules) of evaluation of measurement results [1]. In [10], a general approach for evaluation of KC results is presented, in [11] – clarification of a general approach to the determination of the largest successive subset, in [12] – an example of the model of selection in the average of inconsistent data. However, in many practical cases of evaluation of comparison results, it is quite difficult and sometimes impossible to apply the specified approaches in practice.

In 1996–1998, international KC of national standards of units of electrical capacitance with the nominal value of 10 pF CCEM-K4 within the framework of CC for electricity and magnetism (CCEM) of CIPM were conducted [13]. In 2003–2013, the specified comparisons became the basis for similar comparisons within the framework of different RMO. Within the framework of RMO of European countries, comparisons for the capacitance of 10 pF [14], RMO of American countries – for the capacitance of 10 pF [15] and 100 pF [16] took place. Within the framework of COOMET, the Ukrainian NMI participated in comparisons: for the capacitance of 10 pF on frequencies of 1 kHz and 1.592 kHz [17], for the capacitance of 100 pF on frequencies of 1 kHz and 1.592 kHz [18], and for the capacitances of 10 pF and 100 pF on a frequency of 1 kHz [19]. The evaluation of the comparison~~s~~ results of all RMO was carried out under the procedures described in [14], which allows estimating the achievements of NMIs participants of RMO comparisons.

The evaluation of the state of providing the metrological traceability of measurements of electrical capacitance needs:

– scientific-reasonable selection of a methodology for the analysis of results of comparisons of national standards of capacitance units of 10 pF and 100 pF and evaluation of equivalence of the existing national standard for the indicated capacitances on frequencies of 1 kHz and 1.592 kHz, having regard to the large variety of similar methodologies;

– development of a methodology of evaluation of measurement uncertainty of capacitance in the range of capacitance values from 10 pF to 10 nF, which is absent in the scientific and technical literature.

3. The aim and objectives

The conducted studies aimed to estimate all basic components of the state of providing the metrological traceability of measurements of electrical capacitance in Ukraine.

For the achievement of the aim, such tasks were set:

– to carry out the comparative analysis of the results of COOMET international comparisons of national standards of units of electrical capacitance with the aim of convergence evaluation;

– to determine the degrees of equivalence of standards of the comparison participants and expanded measurement uncertainties;

– to develop a methodology and conduct the evaluation of measurement uncertainties of electrical capacitance in the wide range of capacitance values for the evaluation of existing CMC of Ukraine.

4. Materials and research methods within the framework of international comparisons of national standards of the unit of electrical capacitance

International key and supplementary comparisons of national standards of the unit of electrical capacitance were conducted within the framework of COOMET project 345/UA/05 (COOMET.EM-K4, COOMET.EM-S4) [17, 18], the pilot laboratory of which was State Enterprise (SE) "Ukrmetrteststandard", were conducted with the participation of NMIs of Ukraine, Germany, Japan, Bulgaria, Russian Federation, Kazakhstan and Belarus during 2006-2009. The NMIs participants of these comparisons are SE "Ukrmetrteststandard" (UMTS, Ukraine); PTB (Germany); NMIJ/AIST (Japan); BIM (Bulgaria); VNIIM (Russia); KazInMetr (Kazakhstan); BelGIM (Belarus).

International supplementary comparisons of national standards of the unit of electrical capacitance with the nominal value of 10 pF and 100 pF on a frequency of 1 kHz within the framework of COOMET project 554/UA/12 (COOMET.EM-S13) [19] were conducted with participation of NMIs of Ukraine, Poland and Belarus during 2012–2013. The pilot laboratory of the conducted comparisons was SE "Ukrmetrteststandard". The NMIs participants of these comparisons are SE "Ukrmetrteststandard" (UMTS, Ukraine); GUM (Poland); BelGIM (Belarus).

These comparisons were conducted between the NMIs participants that represent three RMO: COOMET (UMTS, VNIIM, KazInMetr and BelGIM), EURAMET (PTB, BIM, GUM), and APMP (NMIJ/AIST). The pilot laboratory provided the NMIs participants of comparisons with the transfer standard (TS), investigated the drift of TS over the whole time of comparisons, worked out and executed the chart of comparisons, collected and analyzed the obtained data of comparisons, prepared preliminary and final reports, etc.

In all these comparisons, Ukraine presented the State primary standard of the units of electrical capacitance and dissipation factor (DETU 08-06-01) that ~~is~~ has been used in SE "Ukrmetrteststandard" since 2001.

For comparisons, the TS of Andeen-Hagerling (USA) AH11A model with the nominal values of capacities of 10 pF and 100 pF, mounted in the box of AH1100 was selected. The TS provides control of critical parameters of temperature control, and every measure of capacity of AH11A of TS has a built-in thermostat with the double system of thermostatting.

SE "Ukrmetrteststandard" (UMTS) as a pilot laboratory systematically carried out measurements for determination of time drift of TS for the nominal values of measures of capacities of 10 pF and 100 pF on a frequency of 1 kHz. Having regard to the measurement results obtained by the pilot laboratory, it can be established, that the drift was insignificant and does not have a substantial influence on the TS research results obtained by the NMIs participants.

Metrological traceability of the national standard of every NMI participant to SI units was given to the pilot laboratory and was as follows:

– PTB – to the primary standard of the capacitance unit (Calculable Capacitor);

– VNIIM – to the primary standard of the capacitance unit (Calculable Capacitor);

– BIM – to the primary standard of the capacitance unit PTB (Calculable Capacitor);

– KazInMetr and BelGIM – to the primary standard of the capacitance unit VNIIM (Calculable Capacitor);

– UMTS – to the primary standard of the resistance unit PTB on the base of the Quantized Hall Effect (Quantized Hall Resistance) and the primary standard of the capacitance unit NIST (Calculable Capacitor);

– NMIJ/AIST – to the primary standard of resistance unit on the base of the Quantized Hall Effect (Quantized Hall Resistance);

– GUM – to the primary standard of the International Bureau of Weights and Measures (BIPM) on the base of the Quantized Hall Effect (Quantized Hall Resistance).

Calculations of measurement uncertainty were carried out by each NMI participant in accordance with the guide [6]. The NMIs participants developed their own measurement uncertainty budgets for the nominal values of capacitance measures of 10 pF and 100 pF.

5. Comparison of the results of international comparisons of standards

Deviations of the obtained values of capacities δC_i from the nominal values of 10 pF (COOMET.EM-K4, COOMET.EM-S13) and 100 pF (COOMET.EM-S4, COOMET.EM-S13) on frequencies of 1 kHz and 1.592 kHz with the standard uncertainties u_{ci} for the NMIs participants of all comparisons are presented in Table 1 [17–19].

Table 1

Deviations from the nominal value for the NMIs participants of comparisons with standard uncertainties, μF/F

NMI	10 pF				100 pF			
	1 kHz		1.592 kHz		1 kHz		1.592 kHz	
	δC_i	u_{ci}	δC_i	u_{ci}	δC_i	u_{ci}	δC_i	u_{ci}
COOMET.EM-K4				COOMET.EM-S4				
BIM	0.300	1.160	–	–	1.000	6.050	–	–
PTB	0.033	0.208	–0.300	0.060	0.600	0.195	0.650	0.060
VNIIM	–0.190	0.182	–0.230	0.190	0.550	0.204	0.500	0.210
NMIJ/AIST	–	–	0.100	0.122	–	–	0.815	0.106
KazInMetr	–0.540	0.352	–	–	0.500	0.420	–	–
UMTS	–0.080	0.220	–0.025	0.350	0.940	0.230	0.750	0.350
BelGIM	–0.230	1.100	–0.280	1.100	1.034	2.030	1.223	2.030
COOMET.EM-S13								
GUM	0.900	0.250	–	–	1.000	0.500	–	–
UMTS	1.053	0.384	–	–	1.405	0.396	–	–
BelGIM	1.114	1.076	–	–	1.649	1.016	–	–

The reference value of comparisons x_{ref} is obtained as an average of all values of NMIs participants of comparisons by the expression [20, 21]

$$x_{ref} = \sum_{i=1}^{N} \frac{x_i}{u^2(x_i)} \Bigg/ \sum_{i=1}^{N} \frac{1}{u^2(x_i)} \qquad (1)$$

with the corresponding standard uncertainty

$$u^2(x_{ref}) = 1 \Bigg/ \sum_{i=1}^{N} \frac{1}{u^2(x_i)}, \qquad (2)$$

where x_i is the i-th result of the NMI participant of comparisons; $u(x_i)$ is the standard uncertainty of the result of the i-th NMI participant of comparisons; N is the number of comparison participants.

The calculated values of reference values with the expanded uncertainties are given in Table 2.

Table 2

Reference values of comparisons with expanded uncertainties, μF/F

10 pF				100 pF			
1 kHz		1.592 kHz		1 kHz		1.592 kHz	
x_{ref}	U_{ref}	x_{ref}	U_{ref}	x_{ref}	U_{ref}	x_{ref}	U_{ref}
COOMET.EM-K4				COOMET.EM-S4			
–0.131	0.219	–0.219	0.102	0.662	0.231	0.681	0.100
COOMET.EM-S13							
0.952	0.411	–	–	1.283	0.594	–	–

The degree of equivalence of the standard of the i-th NMI and expanded uncertainties in the sense of reference values of comparisons were determined by the expressions [20, 21]:

$$D_i = x_i - x_{ref}, \qquad (3)$$

$$u^2(D_i) = u^2(x_i) + u^2(x_{ref}). \qquad (4)$$

The declared uncertainties of NMIs participants must satisfy the following inequality

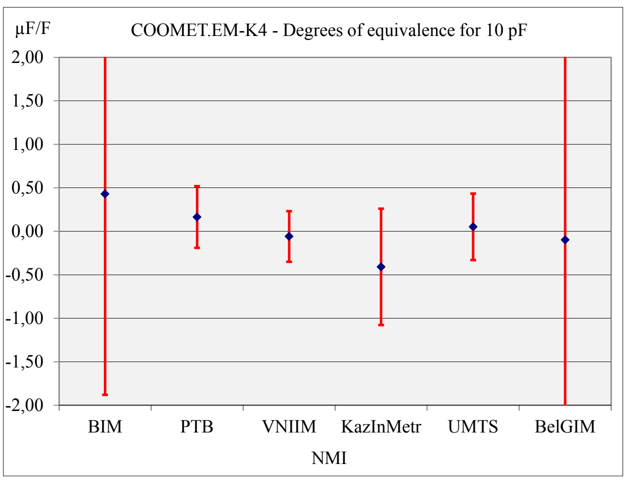
$$|D_i| < 2u(D_i). \qquad (5)$$

The degrees of equivalence of standards of NMIs participants in comparisons with expanded uncertainties (k=2) for 10 pF and 100 pF on frequencies of 1 kHz and 1.592 kHz in the sense of the reference value of comparisons are presented in Table 3 and Fig. 1, 2 for a frequency of 1 kHz.

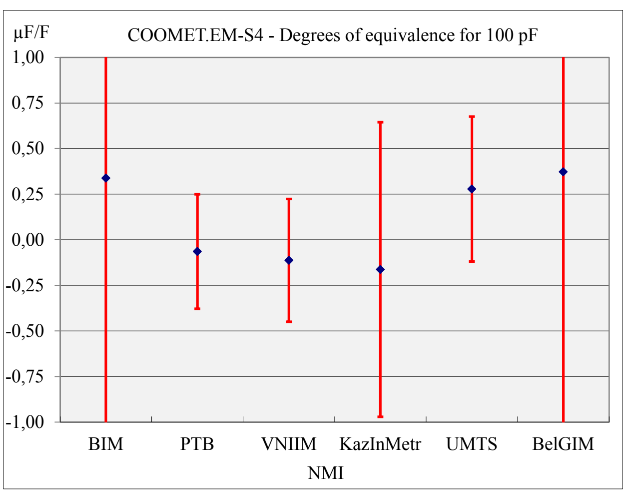
Table 3

Degrees of equivalence of standards of NMIs participants in both comparisons with expanded uncertainties, μF/F

NMI	10 pF				100 pF			
	1 kHz		1.592 kHz		1 kHz		1.592 kHz	
	D_i	$U(D_i)$	D_i	$U(D_i)$	D_i	$U(D_i)$	D_i	$U(D_i)$
COOMET.EM-K4				COOMET.EM-S4				
BIM	0.430	2.310	–	–	0.338	12.098	–	–
PTB	0.164	0.354	−0.081	0.063	−0.065	0.314	−0.031	0.066
VNIIM	−0.059	0.291	−0.011	0.366	−0.113	0.337	−0.181	0.408
NMIJ/AIST	–	–	0.318	0.221	–	–	0.134	0.187
KazInMetr	−0.409	0.669	–	–	−0.163	0.808	–	–
UMTS	0.051	0.382	0.194	0.692	0.278	0.398	0.069	0.693
BelGIM	−0.099	2.189	−0.061	2.198	0.372	4.053	0.542	4.059
COOMET.EM-S13								
GUM	−0.052	0.963	–	–	−0.263	1.552	–	–
UMTS	0.101	1.125	–	–	0.122	1.427	–	–
BelGIM	0.162	2.302	–	–	0.366	2.352	–	–



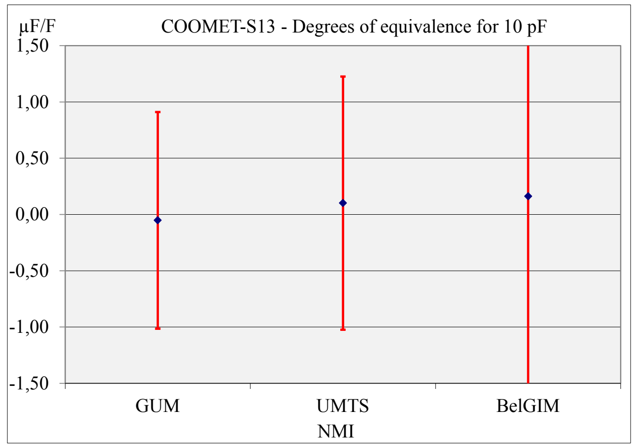
a



b

Fig. 1. Degrees of equivalence for NMIs participants on a frequency of 1 kHz: *a* — COOMET.EM-K4 for 10 pF; *b* — COOMET.EM-S4 for 100 pF

The results of comparisons COOMET.EM-K4 (10 pF), COOMET.EM-S4 (100 pF), and COOMET.EM-S13 (10 pF and 100 pF) on frequencies of 1 kHz and 1.592 kHz show a good convergence of the results of NMIs participants.



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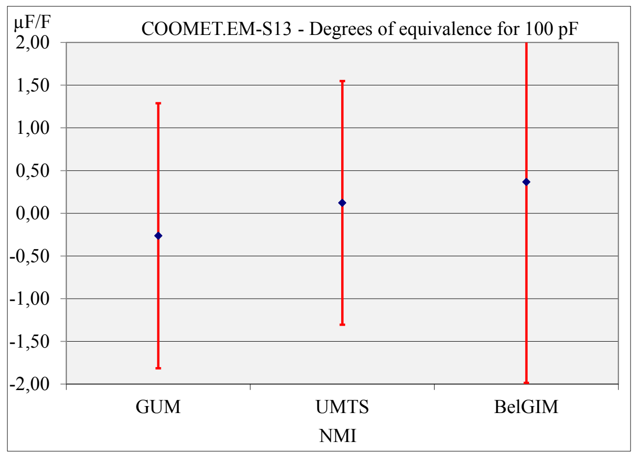

b

Fig. 2. Degrees of equivalence for NMIs participants in COOMET.EM-S13 on a frequency of 1 kHz: *a* — 10 pF; *b* — 100 pF

6. Results of verification of consistency of the results of comparisons

For verification of consistency of the results of comparisons, the values of the χ^2 criterion (Table 4) for the results of comparisons of standards of NMIs participants taking into account the measurement uncertainties $(\{x_i, u(x_i)\}$, $i = 1,...N)$ were calculated by the expression [21]

$$\chi^2 = \sum_{i=1}^{N} \frac{(x_i - x_{ref})^2}{u^2(x_i)}. \qquad (6)$$

Table 4

The values for the criterion χ^2 for the nominal values of capacitance of 10 pF and 100 pF on frequencies of 1 kHz and 1.592 kHz

Frequency, kHz	Capacitance, pF	χ^2	$\chi^2_{0.95(N-1)}$
COOMET.EM-K4			
1	10	2.74	11.07 (N=6)
1.592		7.09	7.81 (N=4)
COOMET.EM-S4			
1	100	2.77	11.07 (N=6)
1.592		3.93	9.49 (N=5)
COOMET.EM-S13			
1	10	0.06	5.99 (N=3)
	100	0.24	

The value for the criterion χ^2 for comparisons does not exceeds the critical values with the coverage level of 0.95 by the inequality

$$\chi^2 = \sum_{i=1}^{N} \frac{(x_i - x_{ref})^2}{u^2(x_i)} < \chi^2_{0.95(N-1)}, \quad (7)$$

i. e., the obtained values of NMIs participants can be considered consistent, which is the objective confirmation of the measurement uncertainties declared by NMIs participants.

7. Evaluation of uncertainty in the calibration of capacitance measures for the unit of electrical capacitance

The DETU 08-06-01 standard includes the measures of Andeen-Hagerling (USA) AH11A model with the nominal values of capacitance measures of 10 pF and 100 pF. For them, in addition to the results of international comparisons, there are calibration certificates of NMIs NIST (USA), PTB (Germany), and NPL (Great Britain). The values of these measures have the expanded uncertainty $U_{AH}=7.4\cdot10^{-6}$ pF with a probability P=0.95 at the coverage factor k=2.

The transmission of the unit size of capacitance over the value range is carried out with the use of the universal automated precision comparator included in the DETU 08-06-01 standard. The comparator has two transmission ratio values: 1:1 (K1) or 1:10 (K1). Using these two transmission ratio values only, it is possible to realize the transmission of the unit size of capacitance by consecutive calibrations of capacitance measures in the wide range of values toward both high and low impedance.

An example of transmission of the unit size of capacitance over the value range in the calibration of capacitance measures with the nominal value of 10 nF based on the standard capacitance measure of 100 pF and with the use of intermediate capacitance measure of 1 nF is represented in Fig. 3.

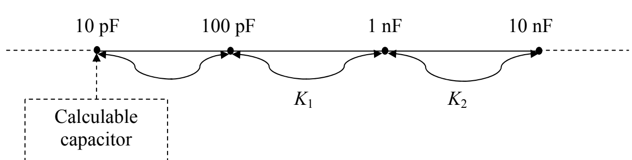

Fig. 3. The transmission of the unit size of capacitance over the value range

The estimation of uncertainty in the calibration of capacitance measures is carried out according to the model (equation) of measurement by the expression:

$$C_X = \frac{C_S + \Delta C_{TS} + \Delta C_{fS} + \Delta C_{\gamma S}}{K_1 K_2}, \quad (8)$$

where C_S is the value of capacitance of a standard measure with the nominal value of 100 pF, indicated in a calibration certificate; ΔC_{TS} is correction for temperature dependence of standard measures; ΔC_{fS} is correction for frequency dependence of standard measures; $\Delta C_{\gamma S}$ is correction for a drift of standard measures from the moment of the last calibration; K_1 is the transmission factor of the comparator in the calibration of the intermediate capacitance measure of 1 nF C_S from the set of the temperature-stabilized measures CA 5200RC based on the capacitance measure with the nominal value of 100 pF:

$$K_1 = \frac{C_{1nF}}{C_S}; \quad (9)$$

K_2 is the transmission factor of the comparator in the calibration of the intermediate capacitance measure C_X with the nominal value of 10 nF based on the intermediate capacitance measure with the nominal value of 1 nF:

$$K_2 = \frac{C_{10nF}}{C_X}. \quad (10)$$

The example of the uncertainty budget of measurements of the capacitance value in the calibration of the measure C_X is presented in Table 5.

Table 5

The measurement uncertainty budget in the calibration of the measure C_X

Quantity x_i	Value x_i	Relative standard uncertainty $w(x_i)$	Distribution law	Type of evaluation	Sensitivity coefficient p_i	Contribution to uncertainty $p_i\cdot w(x_i)$
K_1	0.099996	$1.20\cdot10^{-7}$	normal	A	–1	$-1.20\cdot10^{-7}$
K_2	0.099999	$1.40\cdot10^{-7}$	normal	A	–1	$-1.40\cdot10^{-7}$
C_S	100.000020 pF	$3.70\cdot10^{-6}$	normal	B	1	$3.70\cdot10^{-6}$
ΔC_{TS}	0 pF	$7.10\cdot10^{-7}$	normal	B	1	$7.10\cdot10^{-7}$
ΔC_{fS}	0 pF	$4.10\cdot10^{-7}$	normal	B	1	$4.10\cdot10^{-7}$
$\Delta C_{\gamma S}$	$-1.10\cdot10^{-6}$ pF	$5.08\cdot10^{-7}$	normal	B	1	$5.08\cdot10^{-7}$
C_X	10000.4399pF					
Relative total standard uncertainty					$w(C_X)$	$3.76\cdot10^{-6}$
Effective number of degrees of freedom					ν_{eff}	>200, k=2
Relative expanded uncertainty (P≈0.95)					$W(C_X)$	$7.52\cdot10^{-6}$

Calculation of the relative total standard uncertainty $w(C_X)$ and relative expanded uncertainty $W(C_X)$ in the transmission of the size of the physical quantity from the capacitance measure with the nominal value of 100 pF to the calibrated capacitance measure with the nominal value of 10 pF is carried out in a relative form by the formulas:

$$w(C_X) = \sqrt{w^2(C_S) + \sum_{i=1}^{N} p_i^2 w_i^2(x_i)}, \quad (11)$$

$$W(C_X) = kw(C_X). \quad (12)$$

The value of standard uncertainty of the factors K1, K2 takes into account:

– the deviation caused by the comparator quantization error;

– correction for the sensitivity of the comparator and the error of comparisons.

The values of the factors K1, K2 are indicated in the comparator certificate, but these factors can be specified for every point of the measurement range by the comparison of pre-calibrated measures.

It should be noted that in the total standard measurement uncertainty of the calibration result, it is also necessary to take into account the frequency dependence of the transmission factor of the comparator, which has a substantial influence on the measurement result in the calibration of capacitance measures. However, during the measurements, the frequency drift is negligible and the measurement uncertainty is about the value of $1\cdot10^{-10}$. Thus, the components of uncertainty introduced by the frequency dependence can be neglected.

The measurable value of capacitance of the measure with the nominal value of 10 pF at the measurement temperature of (22÷24) °C and relative humidity of (30÷45) % at the frequency of the examined signal of 1 kHz made up 10.0004399 nF ±7.52 μF/F.

CMC of NMIs of countries are published as pdf files in the Annex C of the BIPM Key Comparison Database (KCDB) in the form of tables [2]. The above-mentioned values of measurement uncertainties correspond to the data published in the KCDB for Ukraine in the range of capacitance values from 10 pF to 10 nF.

8. Discussion of the results of evaluation of the state of the metrological traceability of measurements of electrical capacitance

The comparative analysis of the results of the RMO international key and supplementary comparisons of national standards of units of electrical capacitance showed the convergence of the results for 10 pF and 100 pF on frequencies of 1 kHz and 1.592 kHz. This allowed determining the degrees of equivalence of standards of NMIs participants and expanded uncertainties for the specified nominal values of capacitance measures. Metrological traceability of the national standard of Ukraine to the units of the International system of units SI to the primary standard of the unit of resistance of PTB (Germany) on the basis of the Quantized Hall Effect and to the primary standard of the unit of capacitance of NIST (USA) is determined.

Verification of consistency of the results of comparisons of NMIs participants taking into account the measurement uncertainties on the criterion χ^2 showed that the results can be considered consistent. This is the objective confirmation of the measurement uncertainties declared by the participants.

The results of the calculations of the values of measurement uncertainties according to the proposed methodology of evaluation of measurement uncertainty in the wide range of capacitance values (from 10 pF to 10 pF) showed that the measurement uncertainties correspond to the data published in the international key comparison database for Ukraine on CMC for electrical capacitance units in the range of capacitance values from 10 pF to 10 nF on frequencies of 1 kHz and 1.592 kHz.

9. Conclusions

1. The comparative analysis of the results of international comparisons of the national standards of units of electrical capacitance is conducted with the aim of evaluation of convergence. For the comparisons, the reference values with the expanded uncertainties are calculated and the degrees of equivalence of standards of participants and expanded uncertainties for the nominal values of measures of 10 pF and 100 pF on frequencies of 1 kHz and 1.592 kHz are determined. Metrological traceability of the national standard of every participant of comparisons to the units of the International system of units SI is determined.

2. For verification of consistency of the results of comparisons, the values of the χ^2 criterion for the results of comparisons of standards of participants taking into account the measurement uncertainties are calculated. The obtained values of the criterion of consistency for the participants can be considered consistent, which is the objective confirmation of the measurement uncertainties declared by the participants.

3. The methodology of evaluation of measurement uncertainty in the wide range of capacitance values is proposed. The results of the calculations of the values of measurement uncertainties revealed that the results correspond to the data published in the international key comparison database for Ukraine in the range of capacitance values from 10 pF to 10 nF on frequencies of 1 kHz and 1.592 kHz.

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ANALYSIS OF MASS-ENERGY BALANCE OF UNMANNED AIRCRAFT FUELED BY SOLAR ENERGY

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Визначені принципи забезпечення живленням систем літака на всіх режимах польоту. Описані фактори, що впливають на продуктивність роботи сонячних панелей літака. Запропоновано модель для визначення маси літака вцілому, яка враховує масові характеристики промислових складових літального апарату. Отримано розрахункову модель масово-енергетичного балансу літака з урахуванням типових режимів польоту та законів генерації енергії сонця

Ключові слова: масово-енергетичний баланс, літак на сонячній енергії, умови реалізації польоту

Определены принципы обеспечения питанием систем самолета на всех режимах полета. Описаны факторы, влияющие на производительность работы солнечных панелей самолета. Предложена модель для определения массы самолета в целом, которая учитывает массовые характеристики промышленных составляющих летательного аппарата. Получена расчетная модель массово-энергетического баланса самолета на основе типовых режимов полета и законов генерации энергии солнца

Ключевые слова: массово-энергетический баланс, самолет на солнечной энергии, условия реализации полета

1. Introduction

Thanks to technical progress, today there is an opportunity to perform long flights using solar energy. Despite significant energy capacities of solar radiation, the efficiency of its conversion into translational motion of an aircraft largely depends on the mass-energy characteristics of photoelectric converters. In addition, this process is significantly