UDC 001.4:006.91:621.317

# Estimating the long-term drift of travelling measurement standards for comparisons

O. Velychko, T. Gordiyenko

*State enterprise "UKRMETRTESTSTANDARD", Metrologichna Str., 4, 03143, Kyiv, Ukraine*
*velychko@ukrcsm.kiev.ua; gordiyenko@ukrcsm.kiev.ua*

## Abstract

In metrology, it is essential to analyse the instrumental drift of measuring instruments and measurement standards. Each reference instrument is periodically calibrated according to a frequency determined by the laboratory. Calibration establishes the metrological state of the instrument on a certain date of calibration. However, it is necessary to know the state of the measuring instrument during or after the calibration.

Reliable accounting for drift plays an important role in maintaining measurement accuracy. Otherwise, it can lead to significant measurement errors. Accounting for time drift is mandatory when conducting international comparisons of national measurement standards. The drift uncertainty can be evaluated from its history of successive calibrations. In the absence of such a history, the magnitude order of the calibration uncertainty can be estimated.

The analysis of the long-term drift of travelling measurement standards is limited to examples of key and supplementary comparisons of measurement standards of electrical capacitance. Quite a lot of such comparisons were conducted both by the Consultative Committee for Electricity and Magnetism (CCEM) and by most of the Regional Metrology Organizations (RMOs). There are international standards and guides that describe various statistical methods of analysing the measurement results.

For capacitance measurement standards, time drift is predictable and nearly linear. For comparisons of measurement standards, a linear model is more than often applied, as a travelling measurement standard with excellent stability characteristics is used. The consistent results have been obtained. The linear model was applied to estimate the drift of travelling measurement standards during the key and supplementary comparisons (COOMET.EM-K4, COOMET.EM-S4, and COOMET.EM-S13) of measurement standards of electrical capacitance. The estimation of the long-term drift of measurement standards of electrical capacitance as travelling measurement standards for comparisons using a polynomial regression are presented.

**Keywords:** long-term drift; travelling measurement standard; comparison; electrical capacitance; measurement uncertainty; calibration.

Received: 04.12.2023 Edited: 22.12.2023 Approved for publication: 26.12.2023

## Introduction

In metrology, it is essential to analyse the instrumental drift of measuring instruments and measurement standards [1]. Each reference instrument is periodically calibrated according to a frequency determined by the laboratory. Calibration establishes the metrological state of the instrument on a certain date of calibration [2]. However, it is necessary to know the state of the measuring instrument during or after the calibration.

Instrumental drift of a measuring instrument (VIM, 4.21) [1] is continuous or incremental change over time in indication, due to changes in metrological properties of a measuring instrument. This drift is related neither to a change in a measurand nor to a change in any recognized influence quantity. It is applicable to both the measuring instrument and the measurement standard. A drift line is a line along which the points representing data from a certain data sets are located on a chart.

Reliable accounting for drift plays an important role in maintaining measurement accuracy. Otherwise, it can lead to significant measurement errors. Accounting for time drift is mandatory when conducting international comparisons of national measurement standards [3]. The drift uncertainty can be evaluated from its history of successive calibrations. In the absence of such a history, the magnitude order of the calibration uncertainty can be estimated [4, 5].

The calibrated values of numerous measuring instruments and measurement standards have a predictable drift over time. To provide a statement about the measurement uncertainty, when calibrating a measuring instrument for the entire calibration interval, time drift must be accounted for. For many measurement standards of electrical quantities, such as capacitance, inductance, resistance, Zener voltages, voltage dividers, and others, time drift is predictable and linear.

## General methods of estimating the long-time drift of travelling measurement standards for comparisons

Travelling measurement standard (VIM, 5.8) is a measurement standard, sometimes of special construction, intended for transportation between different locations [1]. In the guides of the International Committee on Weights and Measures (CIPM), the travelling measurement standard is also called the transfer measurement standard. The special requirements for transfer measurement standards, which are used to conduct comparisons of measurement standards, are stated in [3].

The pilot laboratory of each comparison should study metrological characteristics and drift (behaviour) of its measurement standard during the comparison. A basic requirement for a successful comparison is stable or predictable behaviour of travelling measurement standards during the entire measurement cycle. The main characteristics of transfer measurement standards for each comparison are specified in the Key Comparison Database of the BIPM [6].

Estimating and quantifying the drift of a travelling measurement standard over certain periods is an important task. A drift (trend) is the main tendency of a certain process to change over time or a time series, which is described by various equations: linear, logarithmic, power, etc. [7, 8]. The analysis of international standards and guides on statistical methods of estimating the measurement results as well as the recommendations for their application in laboratories is described in [9], and the use of statistical methods to estimate the measurement results is described in [10].

In [11], the instrumental drift of measurement standards and measuring instruments is distinguished. In particular, a systematic drift, in which the model that describes the relationship between the measured value and the “true” value changes over time, and a random drift or residual biases, which appear as deviations between the model and the values obtained during the calibration, are distinguished.

According to common practice, the relationship between $y(t)$ and $x(t)$ is established, that is called the calibration model, which often takes the form of a polynomial of a suitable $n$ degree (usually 1 or 2):

$$y(t) = a_0 + a_1 x(t) + a_2 x^2(t) + \ldots + a_n x^n(t). \quad (1)$$

The method of ordinary least squares (OLS) can also be used to assess the drift, which is one of the basic methods of regression analysis for estimating unknown parameters of regression models based on sample data. The method is based on minimizing the sum of the squared deviations of the selected function from the data under consideration.

The theoretical values are determined using a mathematical function that best represents the underlying drift of the time series. This function is called an adequate function, which is calculated by the OLS method. At the same time, the sum of the squared deviations between empirical $y(t)$ and theoretical $\hat{y}(t)$ values of the time series are minimized:

$$S = \sum_{i=1}^{n} \left( y_i(t) - \hat{y}_i(t) \right)^2 \to \min. \quad (2)$$

The coefficient of determination is used to assess the accuracy of such a drift model

$$R^2 = \sigma_{\hat{y}}^2 / \sigma_y^2, \quad (3)$$

where $\sigma_{\hat{y}}$ and $\sigma_y$ are the dispersions of theoretical data obtained according to the drift model and empircal data, respectively.

The most reliable drift line is obtained if its approximation probability value ($R^2$) is equal to or close to 1. The drift model is adequate for the process under consideration and reflects the tendency of its development over the time with $R^2$ values close to 1.

The analysis of the long-term drift of travelling measurement standards is limited to examples of key and supplementary comparisons of measurement standards of capacitance. Quite a lot of such comparisons were conducted both by the Consultative Committee for Electricity and Magnetism (CCEM) and by most of the Regional Metrology Organizations (RMOs) [6]. There are international standards and guides that describe various statistical methods of analysing the measurement results.

## The long-time drift of travelling measurement standards for comparisons of capacitance measurement standards

Eleven national laboratories participated in CCEM-K4 KC [12] comparison from March 1996 to June 1998 (27 months). Two travelling measurement standards of capacitance (10 pF) were fused silica dielectric capacitors in hermetically sealed dry nitrogen filled metal containers. Travelling measurement standards were compared at a frequency of 1592 Hz against four 10 pF standard capacitors of NIST (USA) with a linear drift rate of $2 \times 10^{-7}$ pF per year. For the drift of these measurement standards, a linear approximation was considered sufficient. The drift of the travelling measurement standards did not affect the results of the comparison.

Seventeen national laboratories participated in EUROMET.EM-K4 KC comparison [13] from August 1995 to September 1998 (37 months). Two Andeen-Hagerling travelling measurement standards (AH11A model) of capacitance (10 pF and 100 pF) were used, including frequencies 1 kHz and 1.592 kHz. The maximum rate of change in the capacitance over the whole comparison period was 0.021 ppm/year for the capacitance measurement standard of 10 pF and 0.011 ppm/year for the capacitance measurement standard of 100 pF. These were much less, than the 0.3 ppm/year limit of the manufacturer's specification. The drift of the travelling measurement standards did not affect the results of the comparison.

Thirteen national laboratories participated in APMP.EM-K4.1 KC [14] and APMP.EM-S7 SC parallel comparisons [15] from June 2003 to May 2006 (35 months). The Andeen-Hagerling AH11A fused silica measurement standard of capacitance of 10 pF (APMP.EM-K4.1) and of 100 pF (APMP.EM-S7) at a frequency of 1 kHz and 1.592 kHz was used for the comparisons. It was approximately six months before the start of the KC, when the measurement results from the pilot laboratory that maintained the travelling measurement standard of 10 pF capacitance showed a steady linear increase in the value of the measurement standard of approximately +0.2 ppm/year. The subsequent measurements showed an approximately linear decrease in the value of the measurement standard at the rate of –0.1 ppm/year. The cause of the non-steady behaviour of the capacitance measurement standard of 10 pF is not clear. The travelling measurement standard of 100 pF capacitance did not show any significant deviations from a steady linear drift rate during the entire comparison. The linear regression model was used to estimate the drift of travelling measurement standards. The estimated drift for the capacitance measurement standard of 10 pF was $-3.11\times10^{-4}$ ppm/day with an uncertainty of $0.97\times10^{-4}$ ppm/day, and for the measurement standard of 100 pF capacitance it was $2.51\times10^{-4}$ ppm/day with an uncertainty of $0.29\times10^{4}$ ppm/day.

Seven national laboratories participated in SIM.EM-K4 KC and SIM.EM-S4 SC parallel comparisons [16] from November 2003 to June 2006 (31 months). The Andeen-Hagerling (AH11A) capacitance measurement standard of 10 pF (SIM.EM-K4) and of 100 pF (SIM.EM-S4) at frequency of 1 kHz and 1.592 kHz was used. A simple linear regression model holds for the measurements performed by the pilot laboratory. The 1 kHz and 1.592 kHz capacitance drifts of the travelling measurement standards were determined from the measurement results provided by the pilot laboratory using a respective time linear $t$:

$$x_{i1000} = 1.767 + 0.282 t_{i1000}, \tag{4}$$

$$x_{i1592} = 1.612 + 0.303 t_{i1592}. \tag{5}$$

Two more national laboratories participated in SIM.EM-K4.1 KC and SIM.EM-S4.1 SC parallel comparisons [17] from December 2010 to August 2012 (20 months) with the same travelling measurement standards and on the same frequencies. The linear regression model was also used to estimate the drift of the measurement standard.

Linear regression model was applied to estimate the long-term drift of the travelling measurement standards in COOMET.EM-K4 KC [18] and COOMET.EM-S4 SC comparisons [19] (seven participants in parallel comparisons, from June 2006 to September 2009, 39 months) and COOMET.EM-S13 SC comparison [20] (three participants, from March 2012 to January 2013, 10 months) for the capacitance of 10 pF and 100 pF at frequencies of 1 kHz and 1.592 kHz. In these comparisons, the pilot laboratory was UMTS, which presented and studied the behaviour of the same Andeen-Hagerling AH11A capacitance measurement standards. The instability of these measurement standards is less than 0.3 ppm/year according to the manufacturer's specification. The drift of the travelling measurement standards was considered negligible during the comparisons.

For travelling measurement standard of capacitance (10 pF) used for COOMET.EM-K4 KC comparison, the measurement results (2009) are significantly more than the other values. This deviation is most probably caused by a certain shock that this capacitance measurement standard has experienced during its transportation from PTB to UMTS. The cause of the non-steady behaviour of the measurement standard and the frequency dependence is not clear. Ambient conditions were not monitored during the transportation of the measurement standard, so the effects of temperature cannot be ruled out. It should be noted that the accompanying travelling measurement standard of 100 pF capacitance used for COOMET.EM-S4 SC comparison did not show any significant deviations from a steady linear drift rate during the entire comparison.

## Selection of travelling measurement standards for comparisons of capacitance measurement standards

The correct choice of travelling measurement standards can affect the results of comparisons, so pilot laboratories pay great attention to this issue. As mentioned earlier, the practice of choosing measurment standards of the same type for comparisons by different RMOs has already become a common one. This contributes to the comparability of the results of such comparisons.

An important issue for certain comparisons is the choice of one of several similar measurement standards that are available from the pilot laboratory as travelling measurement standards. For such a choice, it is necessary to account not only for the proximity of the real value of the measurement standard to the nominal one, but also for the real long-term instability of such a measurement standard.

SE "Ukrmetrteststandard" was the pilot laboratory in COOMET.EM-K4 [18], COOMET.EM-S4 [19], and COOMET.EM-S13 comparisons [20] of capacitance measurement standards. The pilot laboratory has four measurement standards of 100 pF capacitance available, of which one measurement standard was selected as the travelling measurement standard and was used in both comparisons. The characteristics of long-term instability were used for the selected measurement standards (Fig. 1). The drift of the selected measurement standards at frequency 1 kHz is indicated by green dots and as a line in Fig. 1 and shown with its expanded uncertainty for 11 years and a linear model in Fig. 2.

The drift of the second travelling measurement standard of 10 pF capacitance at frequency 1 kHz for three comparisons and 11 years and a linear model is shown in Fig. 3.

The drifts of the travelling measurement standards of 100 pF and 10 pF inductances across COOMET.EM-K4, COOMET.EM-S4, and COOMET.EM-S13 comparisons (78 months) are shown in Figs 4 and 5. A linear model was used for the drifts of the travelling measurement standards.

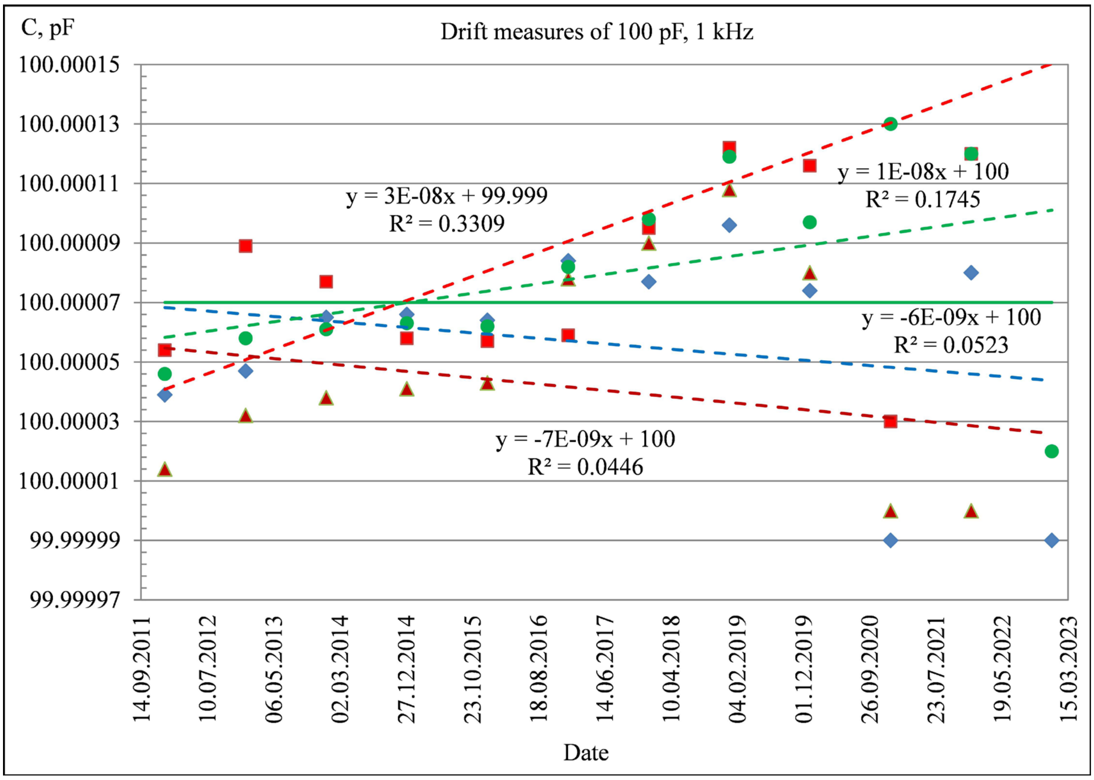

Fig. 1. Drift of capacitance measurement standards (100 pF) of pilot laboratories

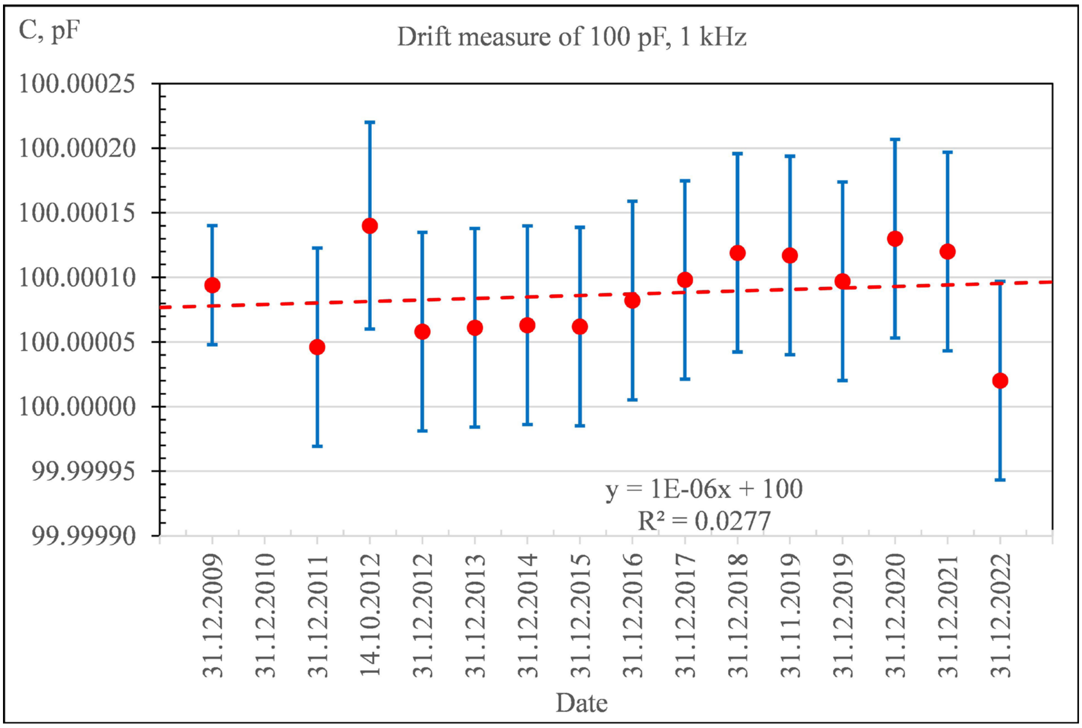

Fig. 2. Drift of capacitance travelling measurement standard (100 pF) with linear model

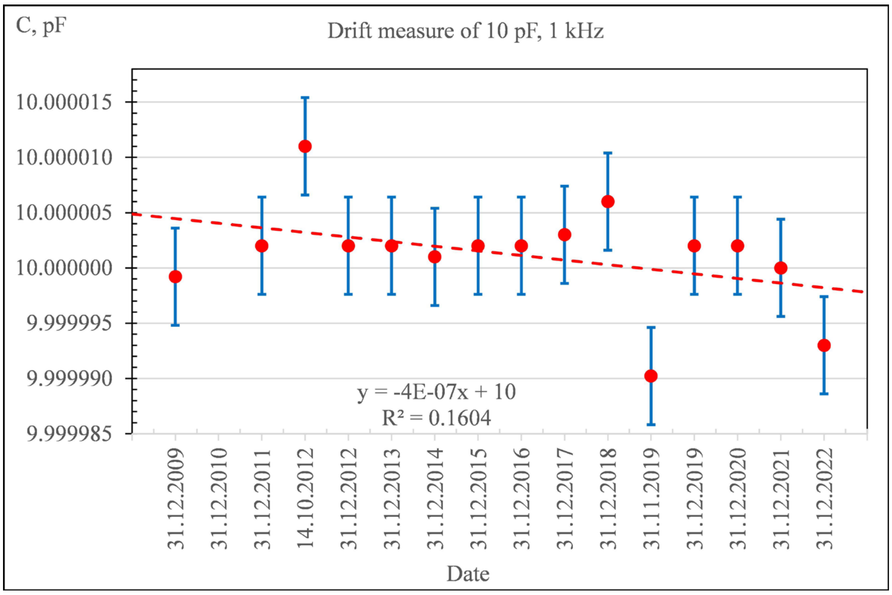

Fig. 3. Drift of capacitance travelling measurement standard (10 pF) with linear model

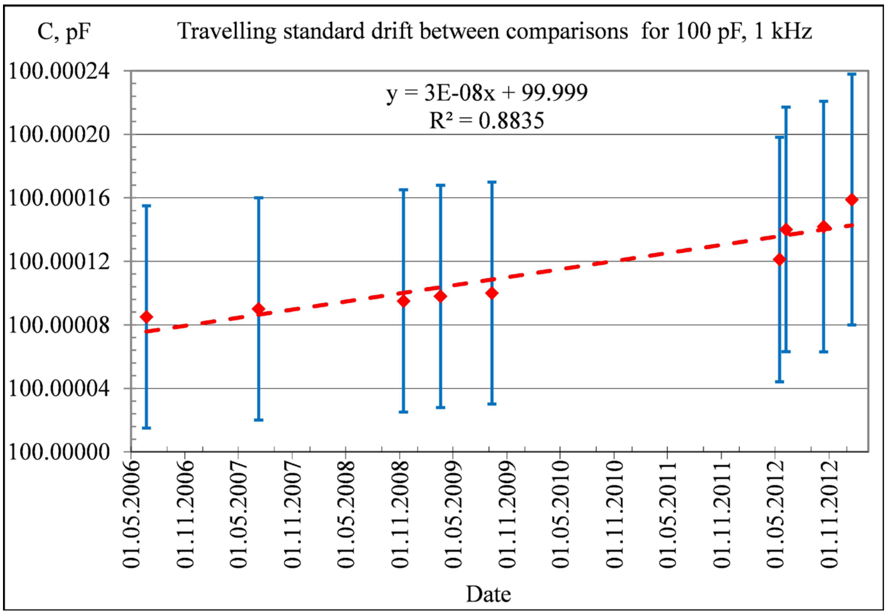

Fig. 4. Drift of travelling measurement standard of capacitance (100 pF) across comparisons

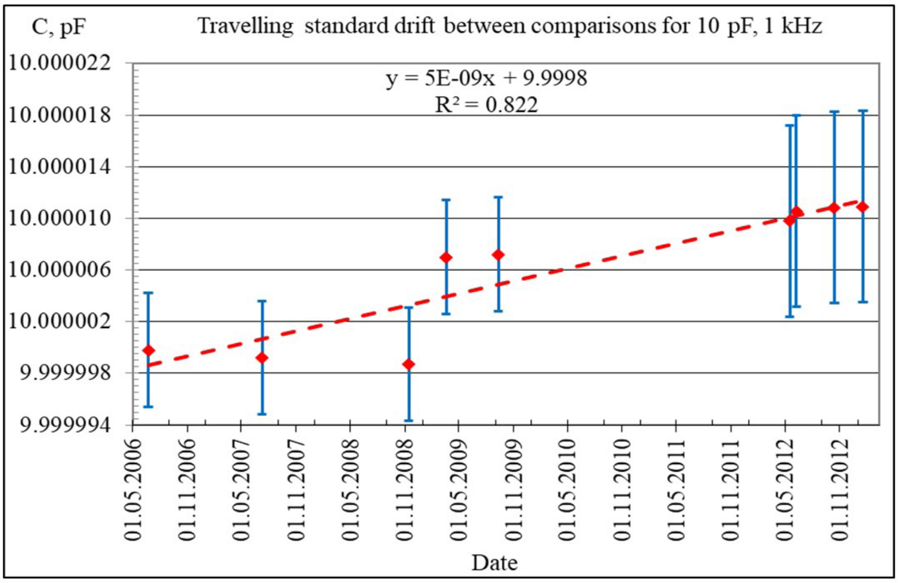

Fig. 5. Capacitance travelling standard (10 pF) drift between comparisons

## Conclusions

Accounting for time drift is mandatory when conducting international comparisons of national measurement standards. For capacitance measurement standards, time drift is predictable and nearly linear. During comparisons, a linear model is more than often applied, as a travelling measurement standard with excellent stability characteristics is used. The consistent results have been obtained. The linear model was applied to estimate the drift of travelling measurement standards in key and supplementary comparisons (COOMET.EM-K4, COOMET.EM-S4, and COOMET.EM-S13) of capacitance measurement standards.

# Оцінка довгострокового дрейфу еталона передавання для звірень

О.М. Величко, Т.Б. Гордієнко

*Державне підприємство “УКРМЕТРТЕСТСТАНДАРТ”, вул. Метрологічна, 4, 03143, Київ, Україна*
*velychko@ukrcsm.kiev.ua; gordiyenko@ukrcsm.kiev.ua*

**Анотація**

Аналіз інструментального дрейфу в засобах вимірювання та еталонах має важливе значення в метрології. Кожен референтний засіб періодично калібрується відповідно до інтервалу, визначеного лабораторією. Калібрування встановлює метрологічний стан засобу вимірювання або еталона на певну дату його проведення. Але потрібно також знати стан засобу вимірювання або еталона під час калібрування або після його закінчення.

Надійний облік дрейфу відіграє важливу роль у підтриманні точності вимірювань. Неврахований дрейф може призвести до значних похибок вимірювань. Облік дрейфу часу є обов’язковим при проведенні міжнародних звірень національних еталонів. Невизначеність дрейфу можна оцінити з історії послідовних калібрувань. За відсутності такої історії можна зробити оцінку порядку величини невизначеності калібрування.

Аналіз довгострокового дрейфу еталонів передавання обмежений прикладами ключових і додаткових звірень еталонів електричної ємності. Досить багато таких звірень було проведено як Консультативним комітетом з електрики та магнетизму (CCEM), так і більшістю регіональних метрологічних організацій (РМО). Низка міжнародних стандартів і настанов описують різні статистичні методи аналізу результатів вимірювань.

Для еталонів електричної ємності дрейф часу є передбачуваним і майже лінійним. Лінійна модель досить часто використовується при звіреннях еталонів, оскільки застосовується еталон передавання з дуже хорошими характеристиками стабільності. Були отримані сумісні результати. Лінійну модель було застосовано для оцінки дрейфу еталонів передавання у ключових і додаткових звіреннях (COOMET.EM-K4, COOMET.EM-S4 та COOMET.EM-S13) для національних еталонів електричної ємності. Надано оцінку довгострокового дрейфу еталонів електричної ємності як еталонів передавання, що використовувались для звірень за допомогою поліноміальної регресії.

**Ключові слова:** довгостроковий дрейф; еталон передавання; звірення; електрична ємність; невизначеність вимірювання; калібрування.

## References

1. JCGM 200:2012. International vocabulary of metrology – Basic and general concepts and associated terms (VIM). 3rd edition. JCGM, 2012. 108 p.
2. ISO/IEC 17025:2017. General requirements for the competence of testing and calibration laboratories. ISO/IEC, 2017. 30 p.
3. CIPM MRA-G-11:2021. Measurement comparisons in the CIPM MRA. Guidelines for organizing, participating and reporting. BIPM, 2021. 26 p.
4. JCGM 100:2008 (GUM 1995 with minor corrections). Evaluation of measurement data – Guide to the expression of uncertainty in measurement. JCGM, 2008. 134 p.
5. EA-4/02 M. Evaluation of the Uncertainty of Measurement in Calibration. EA, 2013. 75 p.
6. The BIPM Key Comparison Database (KCDB). Available at: http://kcdb.bipm.org
7. Velychko O., Gordiyenko T. Some practical issues in the evaluation of the long-term drift of travelling standards for comparisons. *Theses of reports of XX International Scientific and Technical Seminar “Uncertainty in Measurement: Scientific, Normative, Applied and Methodical Aspects” (UM-2023)*. Sofia, Bulgaria, November 27–28, 2023, pp. 66–68.

8. NIST/SEMATECH. e-Handbook of Statistical Methods, 2006. Available at: http://www.itl.nist.gov/div898/handbook/
9. Velychko O., Gordiyenko T. The implementation of general international guides and standards on regional level in the field of metrology. *Journal of Physics: Conf. Series*, 2010, vol. 238, 012044. doi: 10.1088/1742-6596/238/1/012044
10. Velychko O., Gordiyenko T. The estimation of the measurement results with using statistical methods. *Journal of Physics: Conf. Series*, 2015, vol. 588, 012017. doi: 10.1088/1742-6596/588/1/012017
11. Pou J.-M., Leblond L. Evaluate and quantify the drift of a measuring instrument. *Proceedings of 19th International Congress of Metrology*, 2019, 12004. 13 p. doi: https://doi.org/10.1051/metrology/201912004
12. Jeffery A.-M. Final report on key comparison CCEM-K4 of 10 pF capacitance standards. *Metrologia*, 2002, vol. 39(1A):01003. doi: 10.1088/0026-1394/39/1A/3
13. Belliss J.H. International comparison of 10 pF and 100 pF capacitance standards: EUROMET Project No. 345. *Metrologia*, 2000, vol. 37, no. 4. doi: 10.1088/0026-1394/37/4/8
14. Johnson L. et al. Final report on the APMP comparison of capacitance at 10 pF: APMP.EM-K4.1. *Metrologia*, 2009, vol. 46(1A):01003. doi: 10.1088/0026-1394/46/1A/01003
15. Johnson L. et al. Final report on the APMP comparison of capacitance at 100 pF (APMP supplementary comparison APMP.EM-S7). *Metrologia*, 2008, vol. 45(1A):1003-01003. doi: 10.1088/0026-1394/45/1A/01003
16. Cazabat M. et al. Final report on the SIM capacitance comparisons SIM.EM-K4 (10 pF fused-silica standard capacitor at 1000 Hz and 1600 Hz), SIM.EM-S4 (100 pF fused-silica standard capacitor at 1000 Hz and 1600 Hz) and SIM.EM-S3 (1000 pF nitrogen gas standard capacitor at 1000 Hz). *Metrologia*, 2013, vol. 50(1A):01005. doi: 10.1088/0026-1394/50/1A/01005
17. Sanchez H. et al. Final report: Interamerican Metrology System (SIM) Regional Metrology Organization (RMO) capacitance comparison. SIM.EM-K4.1, 10 pF fused-silica standard capacitor at 1000 Hz and SIM.EM-S4.1, 100 pF fused-silica standard capacitor at 1000 Hz. *Metrologia*, 2015, vol. 52(1A):01004. doi: 10.1088/0026-1394/52/1A/01004
18. Velychko O., Akhmadov O. Final report on COOMET key comparison of capacitance at 10 pF (COOMET.EM-K4). *Metrologia*, 2017, vol. 54(1A):01005. doi: 10.1088/0026-1394/54/1A/01005
19. Velychko O., Akhmadov O. Final report on COOMET key comparison of capacitance at 100 pF (COOMET.EM-S4). *Metrologia*, 2017, vol. 54(1A):01006. doi: 10.1088/0026-1394/54/1A/01006
20. Velychko O., Shevkun S. Final report: COOMET supplementary comparison of capacitance at 10 pf and 100 pF (COOMET.EM-S13). *Metrologia*, 2014, vol. 52(1A). doi: 10.1088/0026-1394/52/1A/01005