UDC 621.317

Study of reading errors when calibrating analog ohmmeters

I. Zakharov[1], O. Botsiura[1], V. Semenikhin[1,2]

[1] *Kharkiv National University of Radio Electronics, Nauky Ave., 14, 61166, Kharkiv, Ukraine*
newzip@ukr.net
[2] *National Scientific Centre "Institute of Metrology", Myronosytska Str., 42, 61002, Kharkiv, Ukraine*

Abstract

The features of calibration of analog ohmmeters are considered. Two measurement schemes for calibration were studied: using a multivalued standard measure, which makes it possible to set the ohmmeter readings to the calibrated scale mark, and by a direct measurement of the resistance value of a standard single-valued measure using a calibrated ohmmeter. It is shown that in the first case, the reading error includes two components: the error due to the phenomenon of parallax and the error in aligning the ohmmeter needle with the calibrated scale mark. In the second case, instead of the last component, it is necessary to take into account the interpolation error. Expressions for the uncertainty evaluation of corrections for all components of the reading error for linear and nonlinear ohmmeter scales are given. Formulas have been obtained that make it possible to calculate the measured resistance value in the event that the ohmmeter needle falls between the marks of a nonlinear scale.

Keywords: analog ohmmeter; nonlinear scale; reading error; measurement uncertainty.

Received: 04.03.2024 Edited: 18.03.2024 Approved for publication: 21.03.2024

Introduction

In metrological practice in various areas of national economy and industry, a large number of analog ohmmeters are used, which, like any other measuring equipment, are subject to verification/calibration [1]. When calibrating analog measuring instruments, a significant contribution to the evaluation of the measurement uncertainty is made by the reading error [2, 3]. Due to the physical principles inherent in their design, analog ohmmeters have both linear and nonlinear measurement scales. The presence of a nonlinear scale makes it difficult to perform an accurate reading of the measured resistance value, which leads not only to an increase in the value of the bias of such an estimate, but also to difficulties in the measurement uncertainty evaluation. The latter leads to difficulties in assessing the conformity of ohmmeters with metrological requirements [4].

The purpose of the paper is to study the measurement uncertainty associated with the components of the reading error for analog instruments with uniform and non-uniform scales.

1. Basic variants to calibrate ohmmeters

The main calibration scheme for ohmmeters is the direct measurement of the resistance value of a standard measure by an ohmmeter to be calibrated. In this case, two measurement cases are provided: the use of a multivalued measure, which allows setting the ohmmeter readings to a calibrated scale mark and a direct measurement of the value of a single-valued measure by a calibrated ohmmeter (in the range of less than 10 Ohms and over 10^8 Ohms).

1.1. Using a multivalued resistance measure

The correction for the error from installing the calibrated ohmmeter at a given digitized mark Δ_c includes two components: correction for the error from parallax Δ_p, which occurs when the needle of the instrument is located at a certain distance from its scale and the needle is sighted by the operator at the direction not perpendicular to the surface of the scale, and the correction for inaccuracy in the alignment of the needle with a quantized scale mark Δ_n associated with the thickness of the needle and the stroke mark applied to the scale. The mathematical expectation of these corrections $\hat{\Delta}_p$, $\hat{\Delta}_n$ is taken equal to zero. Below is the uncertainty evaluation of these corrections.

1.2. Measurement uncertainty of the parallax error correction

If the distance between the needle and the scale is h, the distance from the observer's eye to the instrument scale is H, and the displacement of the observer's head from the perpendicular to the centre of the scale is equally probable within $\pm D$, then the error limits of setting the needle to the quantized scale mark $\pm\theta_p$ will be determined by the expression:

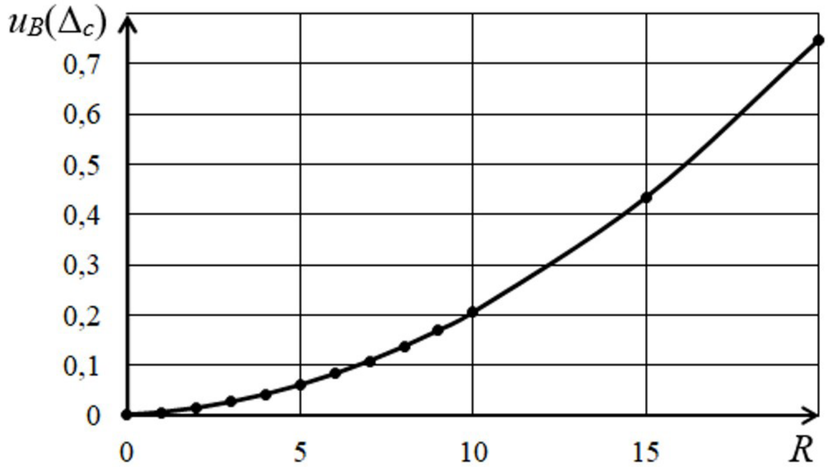

Fig. 1. Dependence of the standard uncertainty of the reading of the V7-15 ohmmeter at the limit of 10 Ohm

$$\theta_p = \frac{Dh}{HS}, \tag{1}$$

where $S = \Delta_L/\Delta_R$ is the sensitivity of the ohmmeter at a given point on the scale, i.e. length of the scale section Δ_L in millimetres per unit of resistance Δ_R near the calibration point.

If the ohmmeter scale is uniform, then taking into account the fact that the length of the entire ohmmeter scale is L, and the value of the measurement limit (end of the scale) for the selected range is R_L, the sensitivity value is determined as:

$$S = L/R_L. \tag{2}$$

If the ohmmeter scale is non-uniform, then the sensitivity value will be equal to:

$$S = \frac{LR_m}{(R+R_m)^2}, \tag{3}$$

where R_m is the resistance value corresponding to the geometric midpoint of the scale in a given measurement range; R is the resistance value corresponding to the calibration point.

Assuming a uniform distribution of the error from parallax over the interval between its limits, the standard uncertainty for a uniform scale $u_B(\Delta_p)$ will be equal to [5, 6]:

$$u_B(\Delta_p) = \frac{DhR_L}{\sqrt{3}HL}, \tag{4}$$

and for non-uniform scale it will be determined by the expression:

$$u_B(\Delta_p) = \frac{Dh(R+R_m)^2}{\sqrt{3}HLR_m}. \tag{5}$$

The standard uncertainty of the correction for the mismatch of the needle with a scale mark, the limits of which are $\pm d$, assuming its uniform distribution in this range, will be equal to [5, 6]:

$$u_B(\Delta_n) = \frac{d}{2\sqrt{3}S} \tag{6}$$

or, taking into account expressions (10) and (11), we have:

$$u_B(\Delta_n) = \frac{dR_L}{2L\sqrt{3}} \tag{7}$$

for a uniform scale, and

$$u_B(\Delta_n) = \frac{d(R+R_m)^2}{2LR_m\sqrt{3}} \tag{8}$$

for a non-uniform scale.

Thus, for a uniform scale, the combined standard uncertainty of the reading when using a multivalued standard measure will be equal:

$$u_B(\Delta_c) = \frac{R_L}{\sqrt{3}\cdot L}\sqrt{\left(\frac{Dh}{H}\right)^2 + \left(\frac{d}{2}\right)^2}, \tag{9}$$

and for non-uniform scale:

$$u_B(\Delta_c) = \frac{(R+R_m)^2}{\sqrt{3}LR_m}\sqrt{\left(\frac{Dh}{H}\right)^2 + \left(\frac{d}{2}\right)^2}. \tag{10}$$

With a distance from the observer's eye to the instrument scale equal to $H = 250$ mm, a head displacement D of ±50 mm, and a distance between the scale and needle h from 0.5 to 1 mm, the parallax error limits θ_p can range from ±0.1 to ±0.2 mm. The thickness of the needle d, as well as the thickness of the scale mark, may also affect the accuracy of the reading, and their values of 0.05...0.1 mm give an error component $d/2$ = 0.025...0.05 mm, which is an order of magnitude less than the error limits from the parallax.

In this case, the combined standard uncertainty of the reading when using a multivalued measure for a B7-15 ohmmeter with a scale length of 68 mm at a limit of 10 Ohms (resistance value corresponding to the geometric middle of the scale in a given measurement range $R_m = 1$ Ohm) will be, depending on the resistance value, corresponding to the calibration point R and will change as shown in Fig. 1 and reache a value of 0.75 Ohm at the 20 Ohm point.

Table 1

Dependency approximation of $R_c=f(L_c)$

R_i, Ohm	L_i, mm	$1/R_i$, Ohm^{-1}	$1/L_i$, mm^{-1}	$\hat{R}_{i\text{appr}}$, Ohm	$\delta_{i\text{appr}}$, %
0.1	6.4368	10	0.15536	0.100	–0.17
0.2	11.905	5	0.08400	0.202	–0.97
0.5	23.833	2	0.04196	0.503	–0.60
1.0	35.982	1	0.02779	1.011	–1.08
2.0	48.033	0.5	0.02082	2.009	–0.45
3.0	54.180	0.33(3)	0.01846	3.019	–0.64
5.0	60.184	0.2	0.01662	4.965	0.70
10	66.050	0.1	0.01514	10.270	–2.70
20	69.098	0.05	0.01447	19.885	0.58

1.3. Using a single-valued measure

In this case, the readings of an ohmmeter to be calibrated are estimated by the position of the needle of its indicator, which generally is located between the scale marks. Then the correction for the reading error, in addition to the correction associated with parallax, will include a correction associated with interpolation.

Therefore, it is necessary to estimate the measured resistance value $\hat{R}_c$ with an ohmmeter to be calibrated and evaluate the uncertainty of the correction for the interpolation error.

Usually in practice, when the indicator needle falls between two scale marks, to improve the accuracy of the reading, the division value R_g is mentally divided into an integer number q of small divisions, which is taken equal to two, five or ten, depending on the length of the division on which the instrument needle falls.

Then for an ohmmeter with a linear scale, the measured resistance value will be equal to:

$$\hat{R}_c=\hat{R}_q+m\hat{R}_g+n\hat{R}_g/q, \qquad (11)$$

where m is the number of divisions from the quantized mark R_q to the division on which the instrument needle falls; n the number of small divisions from the beginning of the division on which the needle of the device falls to the position of the needle. The standard uncertainty of the reading in this case, assuming a uniform distribution between the two scale marks, is:

$$u_B(\Delta_r)=\frac{R_g}{2q\sqrt{3}}. \qquad (12)$$

For an ohmmeter with a nonlinear scale, it is necessary to know the dependence of the ohmmeter reading R_c on the length of the scale from its beginning to the reference point:

$$R_c=f(L_c). \qquad (13)$$

In this case, the sequence of actions to determine $\hat{R}_c$ will be as follows:

1. Determine the value of the limits of the division on which $\hat{R}_c$ is located: $R_{\min}$, $R_{\max}$, and the scale-division value: $R_g = R_{\max} - R_{\min}$.

2. Using the inverse relationship $L_c=f(R_c)$, find these values in millimetres: $L_{\min}=f(R_{\min})$, $L_{\max}=f(R_{\max})$, as well as the "geometric" scale-division value $L_g = L_{\max} - L_{\min}$.

3. By mentally dividing L_g into q parts, find the measured value L_c in millimetres as:

$$\hat{L}_c=L_{\min}+nL_g/q.$$

4. Using dependence (13) find the measured value $\hat{R}_c$ in resistance units:

$$\hat{R}_c=f(\hat{L}_c).$$

5. Then the interpolation uncertainty will obviously be equal to:

$$u_B(\Delta_c)=\frac{R_g}{2q\sqrt{3}}.$$

In [7], this dependence was determined for the V7-15 ohmmeter (Fig. 2). It is given in Table 1. We approximated it by an expression $R_c=\frac{L_c}{a+bL_c}$ with preliminary linearization by the method of changing variables $R_i^*=1/R_i$, $L_i^*=1/L_i$ [8]. The linearized dependence $R_i^*=\psi(L_i^*)$ is shown in Fig. 3. The value of $a=70.5$ mm/Ohm and $b=-0.97$ Ohm^{-1} was obtained using the least squares method. The approximation error does not exceed –2.7% over the entire length of the scale.

The inverse relationship has the form:

$$L_c=\frac{70.5\cdot R_c}{1+0.97\cdot R_c}.$$

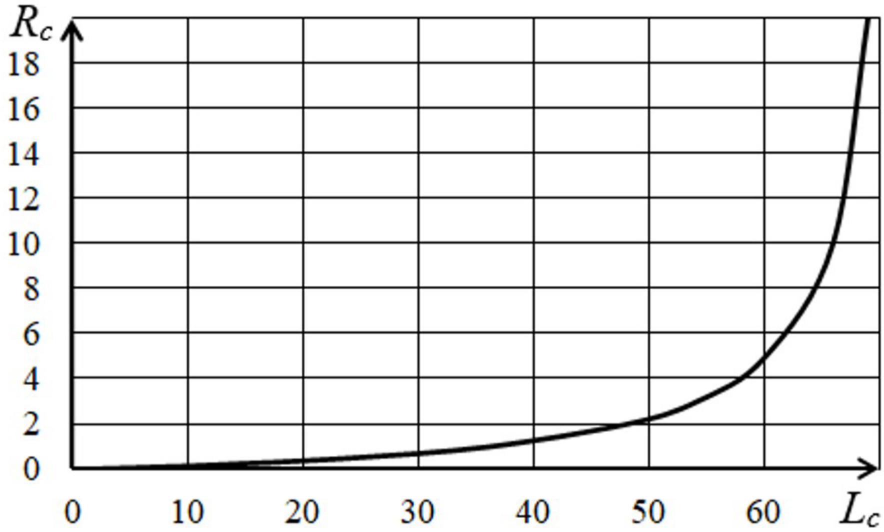

Fig. 2. Dependence of $R_c = f(L_c)$ for ohmmeter V7-15

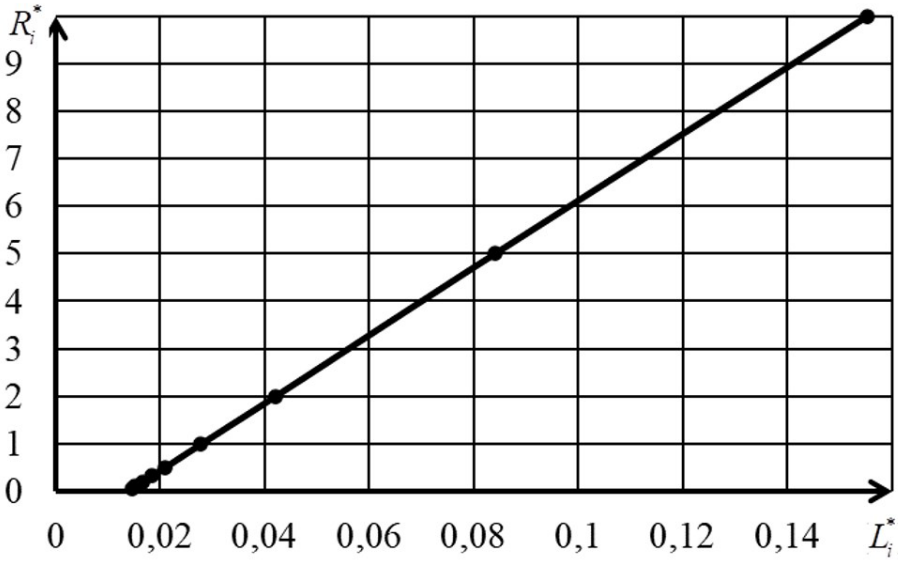

Fig. 3. Linearized dependence of $R_i^* = \psi(L_i^*)$

In this case:

$$L_g = L_{\max} - L_{\min} = 70.5 \frac{R_{c\max}(1 + 0.97 \cdot R_{c\min}) - R_{c\min}(1 + 0.97 \cdot R_{c\max})}{(1 + 0.97 \cdot R_{c\max})(1 + 0.97 \cdot R_{c\min})} =$$

$$= 70.5 \frac{R_{c\max} - R_{c\min}}{(1 + 0.97 \cdot R_{c\max})(1 + 0.97 \cdot R_{c\min})}.$$

$$\hat{L}_c = \frac{70.5 \cdot R_{c\min}}{1 + 0.97 \cdot R_{c\min}} + 70.5 \cdot \frac{n}{q} \cdot \frac{R_{c\max} - R_{c\min}}{(1 + 0.97 \cdot R_{c\max})(1 + 0.97 \cdot R_{c\min})} =$$

$$= \frac{70.5}{1 + 0.97 \cdot R_{c\min}} \left[R_{c\min} + \frac{n}{q} \cdot \frac{R_g}{(1 + 0.97 \cdot R_{c\max})} \right].$$

Then the measured value $\hat{R}_c$ in units of resistance can be found: $\hat{R}_c = \dfrac{\hat{L}_c}{70.5 - 0.97 \cdot \hat{L}_c}$.

At the beginning of the scale, at $R_{c\min} = 0$,

then $\hat{L}_c = 70.5 \dfrac{n}{q} \cdot \dfrac{R_g}{(1 + 0.97 \cdot R_g)}$ and $\hat{R}_c = \dfrac{R_g \cdot n/q}{1 + 0.97 \cdot R_g (1 - n/q)}$.

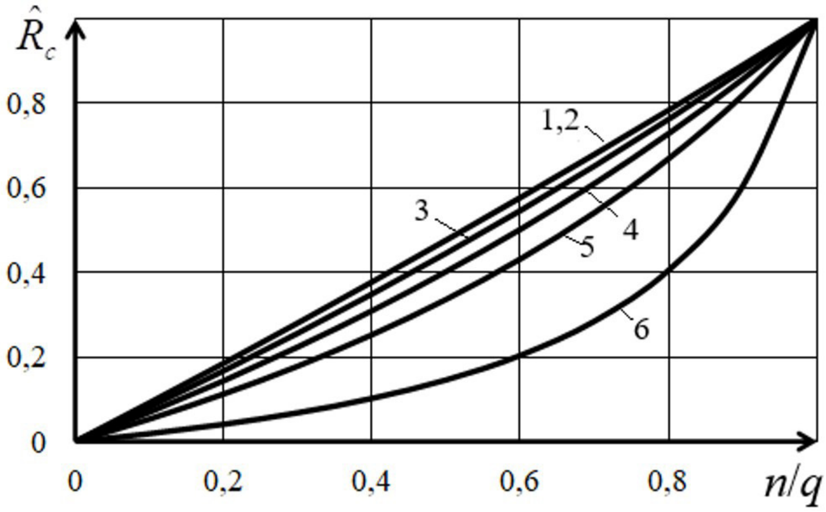

Fig. 4. Dependencies on *n*/*q* for: 1 – R_g=0.05; 2 – R_g=0.1; 3 – R_g=0.25; 4 – R_g=0.5; 5 – R_g=1.0; 6 – R_g=5.0

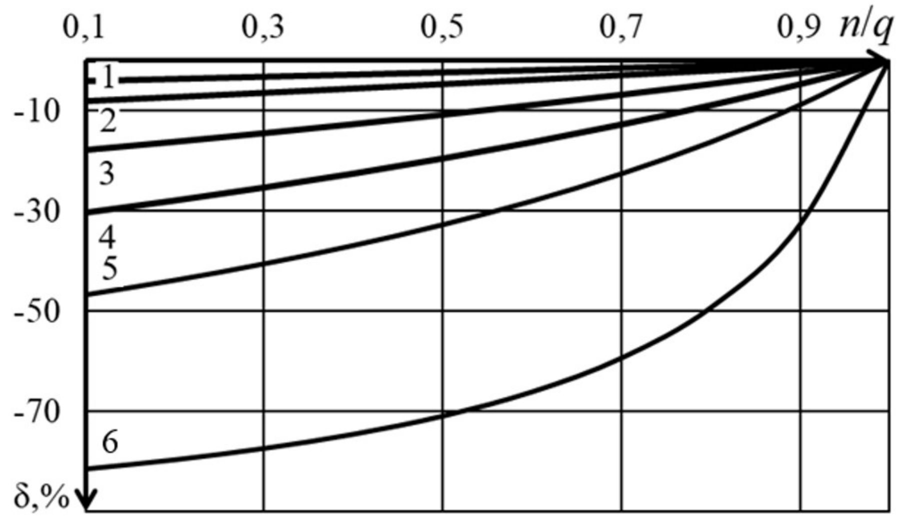

Fig. 5. Relative interpolation error obtained without taking into account the proposed formulas for: 1 – R_g=0.05; 2 – R_g=0.1; 3 – R_g=0.25; 4 – R_g=0.5; 5 – R_g=1.0; 6 – R_g=5.0

The dependences $\hat{R}_c$ on n/q for different R_g are shown in Fig. 4.

The relative interpolation error at the beginning of the scale δ, %, obtained without taking into account the proposed formulas, is shown in Fig. 5.

As can be seen from the graphs presented in Fig. 5, the maximum value of the interpolation error obtained without taking into account the proposed formulas can reach –81%.

Conclusions

1. Expressions were obtained for the uncertainty evaluation of corrections for all components of the reading error for linear and nonlinear ohmmeter scales.

2. It is shown that the combined standard uncertainty of the reading when using a multivalued measure for a V7-15 ohmmeter with a scale length of 68 mm at a limit of 10 Ohms (resistance value corresponding to the geometric middle of the scale at a given measurement range = 1 Ohm) reaches a value of 0.75 Ohm at the 20 Ohm point.

3. The dependence of the readings of the V7-17 ohmmeter on the value of the measured resistance was approximated by the least squares method, with preliminary linearization by the substitution of variables method. The resulting expression made it possible to obtain formulas that allow calculating the measured resistance value in the event that the ohmmeter needle falls between the marks of its scale.

4. It is shown that the estimate of the measured resistance value, obtained without taking into account the proposed formulas, can reach –81%.

Дослідження похибки відліку при калібруванні аналогових омметрів

І.П. Захаров[1], О.А. Боцюра[1], В.С. Семеніхін[1,2]

[1] *Харківський національний університет радіоелектроніки, просп. Науки, 14, 61166, Харків, Україна*
newzip@ukr.net
[2] *Національний науковий центр "Інститут метрології", вул. Мироносицька, 42, 61002, Харків, Україна*

Анотація

Розглянуто особливості калібрування аналогових омметрів. Досліджено дві схеми вимірювань при калібруванні: з використанням багатозначної еталонної міри, що дозволяє встановлювати стрілку індикатора омметра точно на калібрувальну відмітку шкали, та пряме вимірювання значення опору еталонної однозначної міри омметром, що калібрується. Показано, що в першому випадку похибка відліку включає дві складові: похибку, зумовлену явищем паралакса, і похибку суміщення стрілки омметра з каліброваною відміткою шкали. У другому випадку замість останньої складової необхідно враховувати похибку інтерполяції. Отримано результати для оцінювання невизначеності поправок на всі складові похибки відліку як для лінійної, так і для нелінійної шкали омметра. Пропонується алгоритм оцінювання числового значення вимірюваного опору за нелінійною шкалою омметра. Проводиться апроксимація нелінійної шкали омметра В7-15, на основі якої отримано формули, що дозволяють обчислювати вимірюване значення опору в разі потрапляння стрілки омметра між відмітками його шкали. Розраховано похибки інтерполяції, які буде отримано без урахування запропонованих формул. Наведено математичні вирази для оцінки сумарної стандартної невизначеності відліку при використанні цих схем калібрування омметрів із лінійною та нелінійною шкалами. Розроблена методика є придатною при використанні інших типів вимірювальних приладів із нелінійною шкалою: фарадометрів, вимірювачів відношення рівнів напруги змінного струму та ін.

Ключові слова: аналоговий омметр; нелінійна шкала; похибка відліку; невизначеність вимірювань.

References

1. ISO/IEC 17025:2017. General requirements for the competence of testing and calibration laboratories. 28 p.
2. Zakharov I.P., Vodotyka S.V., Shevchenko E.N. Methods, models, and budgets for estimation of measurement uncertainty during calibration. *Measurement Techniques*, 2011, vol. 54, issue 4, pp. 387–399. doi: 10.1007/s11018-011-9737-5
3. EA-4/02 M:2022. Evaluation of the Uncertainty of Measurement in calibration. European Accreditation. 2022. 78 p.
4. JCGM 106:2012. Evaluation of measurement data – The role of measurement uncertainty in conformity assessment. 2012. 64 p.
5. JCGM 100:2008. Evaluation of measurement data – Guide to the expression of uncertainty in measurement. 2008. 90 p.
6. M3003. The Expression of Uncertainty and Confidence in Measurement. Edition 3. UKAS, 2012. 82 p.
7. Zakharov I.P., Pohybko R.V., Volkov O.O. Yssledovanye neopredelennosty yzmerenyia, sviazannoi s otschetom po nelyneinoi shkale [Exploration of a measuring uncertainty, associated with nonlinear scale reading]. *Information processing systems*, 2014, vol. 3(119), pp. 82–86.
8. Zakharov I., Neyezhmakov P., Semenikhin V., Warsza Z.L. Measurement Uncertainty Evaluation of Parameters Describing the Calibrated Curves. Conference on Automation 2022: *New Solutions and Technologies for Automation, Robotics and Measurement Techniques. Advances in Intelligent Systems and Computing*. Springer, 2022, vol. 1427, pp. 391–398. https://doi.org/10.1007/978-3-031-03502-9_38