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Content

THE JOINT COMMITTEE FOR GUIDES IN METROLOGY, WG1: TRYING TO ESTABLISH SOME CERTAINTY IN MEASUREMENT UNCERTAINTY

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Measurement uncertainty as a scientific topic is highly uncertain. Basic concepts, evaluation procedures and interpretation of their outcome are surrounded, still nowadays, by a cloud of confusion and endless misunderstandings.

The historical development that led to the present situation is *per se* a fascinating and instructive time travel that spans a couple of centuries. The travel starts with Gauss, the inventor of the method of uncertainty propagation. It visits Bridgman, the Nobel laureate for his activity in the field of ultra-high pressure who also wrote on philosophy of science to become the father of operationalism. It does not neglect Thomas Bayes, whose theorem lacked any practical application in measurement until a revolution in numerical calculation, made possible by the dramatic improvement in computer power, made it the reference tool in modern scientific inference (and in many other fields, such as web-searching motors). These intertwined historical paths coalesce in the present situation.

The Joint committee for guides in metrology (JCGM), specifically through its working group 1 (WG 1), is mandated with the challenging task of producing guidance that is worldwide accepted and adopted. I will try to elucidate how we try to cope with the task, and I will focus on (some of) the currently more debated issues.

Among these:

- Should we use the concept of true value or rather adopt a view based on non-idealised concepts?
- Does uncertainty relate to the measurand or to its estimate?
- Is uncertainty a quantity or not?
- Which is preferable, a point estimation or an interval estimation?
- This can be formulated equivalently as: given that the measurement model is both an algebraic relationship among physical quantities (the physicist's attitude) and a statistical relationship among random variables (the statistician's attitude), which attitude should we adopt in estimation?
- Should we continue using first and second moments as estimates and uncertainties, respectively, or it would be better to move to different measures, perhaps based on quantiles?
- To what extent a metrologist wants to use prior knowledge?

These are the topics I am interested in and on which I will try to expound my views. These are of course personal, and do not necessarily represent those of the JCGM-WG1.

MULTIVARIATE RANDOM EFFECTS MODEL FOR EVALUATION OF MEASUREMENT UNCERTAINTY

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Random effects model is a well-established approach for evaluation of measurement uncertainty [1,2,3]. It is also widely used in other fields of science, like in medicine [4] and in physics [5,6].

The extension of the univariate model to the multivariate random effects model has recently become an important and challenging research direction. The generalization is motivated by the need to model several measurement results simultaneously. In such a situation, the application of the univariate random effects model to each characteristic separately would lead to potential loss of important information which determines the dependence structure between the measurement results.

Initially, statistical inference procedures for the parameters of the multivariate random effects model were suggested by using the methods of the frequentist statistics [7,8]. Recently, the problem has been treated from the perspectives of Bayesian statistics. Endowing the parameters of the multivariate random effects model with the Jeffreys prior and the Berger and Bernardo reference prior, the Bayesian inference procedures were derived in [9,10]. For the practical implementation two types of the Metropolis-Hastings algorithm were developed.

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MEASUREMENT UNCERTAINTY EVALUATION AT DETERMINATION OF TECHNICAL CHARACTERISTICS OF PYROELECTRIC DETECTOR

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The purpose of this study is the development of metrological assurance for pyrometric measurements by solving two problems. At first, it is an improvement of the method of identification of transient characteristics of pyroelectric detector (PD). Secondly – measurement uncertainty evaluation at determination of transient characteristics of PD.

Determination of the transient characteristics of PD is very important, since their electrical response occurs only under the influence of a changing flow of thermal radiation. Therefore, one of the main characteristics of PD is their transition function. By the amplitude and time parameters of the pyroelectric response, it is possible to decide whether this or that sensor is suitable for working in certain conditions.

The transformation processes in the pyrodetector are quite simply described by a mathematical model that takes into account dynamic temperature changes in its sensitive element:

$$\tau_T \frac{d\Delta T_{SE}(t)}{dt} + \Delta T_{SE}(t) = \pm \frac{\alpha}{G_T} \Delta\Phi_{SE}(t) \quad , \qquad (1)$$

where τ_m – the thermal time constant, Φ_{SE} – heat flow, G_T – thermal losses.

Relevant studies were conducted on the simulator proposed by the authors [1, 2], based on the specified model. Based on them, the influence of factors (both thermal and electrical parameters) on the transient characteristics of PD was analyzed. A method of research is proposed, which in general is based on obtaining with the help of a simulator one or another output characteristic of the converter with successive changes in the influence parameter. The dependences of the increase and decrease of the temperature of pyrodetectors, the pyroelectric response of current, voltage and their normalized graphs were obtained. A group of transient characteristics was obtained from the influence of various factors. The standard uncertainty of the approximation of the characteristics was estimated. According to the recommendations [3], the standard total uncertainties of the pyroelectric voltage response EV, V; noise characteristics - minimum value U_{minN}, V and maximum value U_{maxN}, V were estimated.

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MEASUREMENT UNCERTAINTY EVALUATION OF THE RADIAL COMPONENT OF THE MAGNETIC FIELD

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Magnetic measurements are widely used in many fields of science and technology. Such measurements are in demand in electric power engineering, design, development and operation of electric machines and devices, space research, navigation, military affairs, electromagnetic compatibility, etc. [1]. To solve a number of tasks in the listed areas of technology, there is a need to improve metrological assurance.

The development and improvement of metrological assurance for measurements of magnetic quantities involves two interrelated ways. The first is the development of new, more accurate methods of measuring magnetic quantities. The second is the development of a evaluation methodology for the uncertainty of measurements of magnetic quantities by the developed methods. These activities will contribute to the comparison of the results of measurements in the field of magnetic measurements and the harmonization of regulatory documents in the field of magnetic measurements at the international level.

The article [2] makes general recommendations on the uncertainty evaluation of indirect measurements, but there is no new scientific methodology for uncertainty evaluation for indirect measurements of the radial component of the magnetic field. The work [3] shows the necessity of the uncertainty evaluation of magnetic measurements.

The purpose of this work is to improve the metrological assurance of measurements of magnetic quantities. Within this goal, two tasks were solved. The first is the improvement of the measurement method. The second is the evaluation of measurement uncertainty.

The evaluation of the standard and expanded uncertainty was performed for the point method of measuring the radial magnetic moment M_R, Am^2.

This measurement method assumes the use of induction sensors as primary measuring transducers. Sensors are located at control points with given coordinates. Sensors are electrically integrated into the system and have a predetermined switching algorithm.

The totality of several primary transducers, which are placed and connected in a certain way, is a functionally complete component part of the means for measuring the radial magnetic moment.

Previously, direct repeated measurements of the useful signal (V, mV) coming from the sensor system were performed to estimate the measured quantity. Measurements of the distance r from the geometric centre of the studied magnetic field source to the sensor were also performed.

Gross errors and blunders were excluded from the number of observations and corrections were made for known systematic effects.

Compiled model equation:

$$M_R = \frac{V_{ind} \cdot r_{ind} \cdot k}{8\sqrt{2}}, \qquad (1)$$

where V_{ind} – useful signal from the magnetic field sensor, mV; r – distance from the geometric center of the studied magnetic field source to the sensor, mm; k – coefficient of the sensor.

Correlation: None of the inputs is considered to be correlated with the others to any significant degree.

The uncertainty budget (Table) of the magnetic moment measurements was compiled. The total uncertainty in the estimate of the magnetic moment is found. In view of the nonlinearity of the model, the total uncertainty was found taking into account the higher terms of the Taylor series. The type A standard uncertainty of indirect measurement is determined. The expanded uncertainty is found.

Table

Input value	Estimated input value	Standard uncertainty	Number degrees of freedom	Distribution of the probability of the input quantity	Sensitivity coefficient	Contribution of uncertainty, Am^2
r_{ind}	600 mm	0,16 mm	19	Normal distribution	0.002 Am	$3.2 \cdot 10^{-7}$
U_{ind}	15.8 mV	0,003 mV	19	Normal distribution	$0.014\ \frac{\mathrm{Am}^2}{\mathrm{V}}$	$5.1 \cdot 10^{-7}$
k	$5\ \frac{\mathrm{A}}{\mathrm{mV}}$	$5 \cdot 10^{-4}\ \frac{\mathrm{A}}{\mathrm{mV}}$	∞	Uniform distribution	$0.4 \cdot 10^{-4}$ Vm^3	$0.16 \cdot 10^{-7}$
M_R	$1.6 \cdot 10^{-4}$ Am^2	$1.97 \cdot 10^{-7}$ Am^2	–	–	–	–

The proposed approach can be applied in assessing the uncertainty of existing and developing methods of measuring magnetic quantities. The obtained results contribute to the comparison of measurement results and the harmonization of regulatory documents in the field of magnetic measurements at the international level. The results of the work contribute to the introduction of the concept of uncertainty into national metrological practice.

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EVALUATION OF TYPE B UNCERTAINTY OF THE TWO CHANNAL MEASUREMENTS

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The paper presents the problems of estimating by the type B method the standard uncertainty of a measurement of a quantity, the result of which is the average value of the results obtained from two (or more) channels with the same parameters, for example, the readings (indications) of meters of the same type. It is shown that using given values of the maximum permissible errors (MPE) of the meters and their readings, the uncertainty of the result determined in the inverse (a posteriori) problem is not equal to the uncertainty determined by the traditional method (GUM) [1].

It is shown that when the readings of both meters are x_1 and x_2, from which the result of measurement determined as $y=(x_1+x_2)/2$, additional information can be obtained, using of which the standard uncertainty of such measurement can be determined more accurately. Depending on the readings of the meters, it can vary from a maximum value (the readings of both meters equal) theoretically to zero (with maximum divergence of readings). Uncertainty analysis was carried out for uniform, triangular and truncated normal distributions of possible meter deviations within the MPE.

For example, defining the parameter $v=(x_2-x_2)/2$ as half of readings, and assuming uniform a priori distributions of the meter readings, the probability distribution of possible values of measurand has the form:

$$p_X(X|y,v;\Delta_{MPE})\frac{1}{2\Delta_{MPE}\cdot\left(1-\frac{|v|}{\Delta_{MPE}}\right)}\cdot\begin{cases}1, & 0\le\frac{|X-y|}{\Delta_{MPE}}\le 1-\frac{|v|}{\Delta_{MPE}};\\ 0, & otherwise;\ 0\le\frac{|v|}{\Delta_{MPE}}<1\ .\end{cases}\qquad(1)$$

Thus, standard uncertainty in such measurement depend on the half of difference between indications (v):

$$u(X|v;\Delta_{MPE})=\frac{\Delta_{MPE}}{\sqrt{3}}\cdot\left(1-\frac{|v|}{\Delta_{MPE}}\right),\ 0\le|v|\le\Delta_{MPE}.\qquad(2)$$

If half of the difference in meter readings meets the condition $|v|/\Delta_{MPE}>0.293$, the uncertainty calculated according to (2) is smaller than the standard uncertainty $\Delta_{MPE}/\sqrt{6}$, calculated by the usual method.

Modifications of the Monte Carlo method for simulation studies of uncertainty in inverse problems are proposed.

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STUDY OF CORRELATION AT THE UNCERTAINTY EVALUATIN OF RESULTS OF NON-CONTACT THERMAL CONTROL OF BIOLOGICAL OBJECTS

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Today it is a well-known fact that the body temperature of a warm-blooded biological object (BO) is one of the health indicators of its organism.

In works [1, 2], it is noted that it is necessary to control the temperature of the BO for the timely identification of patients in the group in order to counteract the spread of a dangerous disease. Temperature control is carried out by a non-contact method, thanks to the use of a thermal imager installed on the quadcopter. However, at this time, the issue of determining the impact of seasonal changes in temperature and air humidity on the result of determining the temperature of the BO has not been resolved. In order to establish a relationship between the specified factors and the control parameter, to determine the degree of significance of the correlation coefficient and the need to take it into account when calculating the uncertainty of measurements, it is suggested to use correlation analysis.

The calculation was carried out in order to detect the presence of a correlation dependence in the interaction of three quantities, namely, we will establish the relationship between the temperature of the human body (*t*), air humidity (*h*) and air temperature (*a*). The measure of dependence between the value (*t*) and the values (*h*) and (*a*) is the combined correlation coefficient:

$$R=\sqrt{\frac{r_{ht}^2+r_{at}^2-r_{ha}\cdot r_{ht}\cdot r_{at}}{1-r_{ha}^2}}==\sqrt{1-\frac{1}{(N-1)\cdot s_t^2}\cdot\sum_{i=1}^{N}\left[t_i-\bar{t}-b_{t|h}\left(h_i-\bar{h}\right)-b_{t|a}\left(a_i-\bar{a}\right)\right]^2}\;. \quad (1)$$

Correlation coefficients are determined by the following formulas:

$$r_{ha}=\frac{\sum_{i=1}^{N}\left(h_i-\bar{h}\right)\cdot\left(a_i-\bar{a}\right)}{(N-1)s_h s_a},\quad r_{at}=\frac{\sum_{i=1}^{N}\left(a_i-\bar{a}\right)\cdot\left(t_i-\bar{t}\right)}{(N-1)s_a s_t},\quad r_{ht}=\frac{\sum_{i=1}^{N}\left(h_i-\bar{h}\right)\cdot\left(t_i-\bar{t}\right)}{(N-1)s_h s_t},$$

where N – the total number of experimental results, that is, the total number of points (h_i, a_i, t_i), and s_h, s_a, s_t – the empirical standards:

$$s_h^2=\frac{\sum_{i=1}^{N}\left(h_i-\bar{h}\right)^2}{(N-1)},\quad s_a^2=\frac{\sum_{i=1}^{N}\left(a_i-\bar{a}\right)^2}{(N-1)},\quad s_t^2=\frac{\sum_{i=1}^{N}\left(t_i-\bar{t}\right)}{(N-1)}.$$

The combined correlation coefficient always lies in the range from 0 to 1.

The significance test of the correlation coefficient calculated from a limited number of observations was performed. To check the significance of the correlation coefficient for its further accounting (or ignoring) it is possible to apply the Student's criterion:

$$\frac{|R|}{\sqrt{1-R^2}}\sqrt{n-2}\ge t_p(n-2), \quad (2)$$

where $t_p(n-2)$ is Student's coefficient for the number of degrees of freedom $(n-2)$.

The results of calculations of the main parameters of correlation dependences for the summer and winter periods are shown in Table.

Table

Summer 10.08.22			Winter 20.01.22		
$s_h = 4{,}459$	$s_a = 21{,}652$	$s_t = 0{,}834$	$s_h = 4{,}926$	$s_a = 2{,}964$	$s_t = 1{,}282$
$s_h^2 = 19{,}88$	$s_a^2 = 468{,}81$	$s_t^2 = 0{,}695$	$s_h^2 = 24{,}26$	$s_a^2 = 8{,}783$	$s_t^2 = 1{,}644$
$r_{ha} = -0{,}986$	$r_{at} = -0{,}105$	$r_{ht} = 0{,}078$	$r_{ha} = -0{,}932$	$r_{at} = 0{,}954$	$r_{ht} = -0{,}932$
	$R = 0{,}184$			$R = 0{,}961$	

When inequality (2) is fulfilled, the correlation coefficient is significant and must be taken into account when calculating the expanded uncertainty for correlated data, which is calculated by the formula:

$$U(y) = k \cdot u_c(y), \tag{3}$$

where k – the coverage factor; $u_c(y)$ – the total standard uncertainty.

Since the total standard uncertainty $u_c(y)$ has a contribution of type A uncertainty, the coverage factor k should be defined as [3]:

$$k = t_{0,95}(\nu_{eff}), \tag{4}$$

where ν_{eff} – the effective number of degrees of freedom.

Let's evaluate the significance of the combined correlation coefficient between the value of (t) and the values of (h) and (a) obtained in the winter period (20.01.22).

$$\frac{|0{,}961|}{\sqrt{1-0{,}961^2}}\sqrt{25-2} > t_{0,95}(23).$$

Thus, the aggregated correlation coefficient between the value of (t) and the values of (h) and (a) is significant $(16{,}7 > 2{,}069)$ and should be taken into account when calculating the expanded uncertainty for correlated data.

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PROCEDURE FOR MEASUREMENT UNCERTAINTY EVALUATION AT GONIOMETERS CALIBRATION

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Goniometers are used to precision measure angles and are widely used in optical laboratories. Using a goniometer, the refractive indices and refractive angles of prisms and crystals are determined, the parameters of diffraction gratings are studied, the wavelengths of spectral lines are measured, etc.

In accordance with the requirements of ISO/IEC 17025:2017 [1], when calibrating goniometers, it is necessary to evaluate the measurement uncertainty. Unfortunately, there is no standard procedure for uncertainty evaluating at goniometer calibration, so it must be developed by the calibration laboratory.

When calibrating the goniometer, the given angle α_s of the reference multifaceted prism is repeatedly measured. In this case, the bias of the value of the measured angle α_c from the actual one is expressed as [2]:

$$\Delta_\alpha = (\alpha_c + \Delta_c) - (\alpha_s + \Delta_s), \qquad (1)$$

where Δ_c is correction for goniometer readout resolution; Δ_s is correction for the error of basing the reference measure.

The result of the measurement is taken as an estimate

$$\hat{\Delta}_\alpha = \bar{\alpha}_c - \hat{\alpha}_s, \qquad (2)$$

where $\bar{\alpha}_c$ is the arithmetic mean of the results of tenfold measurements of the angle of a polyhedral prism; $\hat{\alpha}_s$ is value of the angle of the prism, taken from the certificate of its calibration.

The standard uncertainty of the measured quantity was found by the formula:

$$u(\hat{\Delta}_\alpha) = \sqrt{u_A^2(\bar{\alpha}_c) + u_B^2(\Delta_c) + u_B^2(\hat{\alpha}_s) + u_B^2(\Delta_s)} \qquad , (3)$$

where $u_A(\bar{\alpha}_c)$ is the standard uncertainty of type A for measuring a given angle with a goniometer; $u_B(\Delta_c)$, $u_B(\hat{\alpha}_s)$, $u_B(\Delta_s)$ are standard uncertainties of type B due to the readout resolution of the goniometer, the instrumental error of the reference measure and the error of its basing, respectively.

For a more reliable assessment of the uncertainty of the goniometer, it is necessary to take into account the following sources: the correction for parallax when reading from the goniometer vernier and the correction for the deviation of the goniometer scale from its zero readings.

An example of goniometer calibration is considered.

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DETERMINATION OF CALIBRATION INTERVALS OF MEASURING EQUIPMENT

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Calibration of measuring equipment (standards, measuring instruments) is one of the factors that ensures confidence in measurement results and determines metrological traceability and is carried out at certain intervals of time - calibration intervals.

Correctly determined calibration interval of measuring equipment makes it possible to minimize the risks of deterioration of measurement quality.

According to [1, 2], one of the important issues regarding the calibration of measuring equipment is the determination of calibration interval.

In general, the following methods can be used to determine the calibration interval [2]: automatic adjustment or “staircase” (calendar-time); control chart (calendar-time); “in-use” time; in service checking, or “black-box” testing; other statistical approaches.

Let’s consider one of the above methods of determining the calibration interval - the method of automatic adjustment.

When using the automatic adjustment method, each time the equipment has been calibrated after a set time interval, the next interval is adjusted as follows. If it is established that the deviation of the equipment readings is within the limits, then the calibration interval increases.

If it is determined that the deviation exceeds the limit value, the calibration interval is reduced. This method of “steps” helps to quickly adjust the intervals and is described by the following analytical expression:

$$\left|K_i\right| = \frac{\left|X_1 - X_2\right|}{\sqrt{U_1^2 + U_2^2}} \leq 1, \tag{1}$$

where X_1, X_2 – reading deviations or equipment readings for the last two calibrations; U_1, U_2 – expanded uncertainty for the last two calibrations.

The parameter K is the criterion for adjusting the calibration interval. If it is in the range from 0.90 to 1.00, then the calibration interval is left unchanged, if it is in the range from 0.50 to 0.90, then the calibration interval is increased by 30%, if it is in the range from 0.30 to 0.50, then the calibration interval is increased by 70%, if it is in the range from 0.01 to 0.30, then the calibration interval is increased by 100%, if $K \geq 1$ then calibration interval must be reduced.

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STATE OF MEASUREMENT UNCERTAINTY EVALUATION IN THE REPUBLIC OF UZBEKISTAN

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The issues of measurement uncertainty in the Republic of Uzbekistan began to be dealt with in 2000, and so far, based on the results of research, we have published more than 90 works (monographs (1), textbooks and teaching aids (2), abstracts and materials of world, international and republican symposiums, conferences (35) and seminars (9), journal articles (44)).

Main areas of research:

- study of the frequency and temperature dependence of the dynamic shear viscoelastic properties of vegetable oils, polymer solutions and viscous liquids by the acoustic impedance method, by measuring the reflection coefficient and phase change of ultrasonic waves from the solid-vegetable (cotton, castor, soybean, tung) interface" [1-3] and its uncertainty [4-8] by the linearization method;
- uncertainty of the manometric method for determining the moisture content of fibrous materials;
- methodology and uncertainty of transferring the unit size of the total thermal resistance of textile materials;
- evaluation of the accuracy characteristics of determining the compression class of a compression knitwear;
- automation of measurement uncertainty calculation;
- development of a collection of tasks and exercises on measurement uncertainty.

The use of the method “Linearization for estimating the reflection coefficient and its accuracy characteristics” is substantiated. It has been established that the greatest contribution to the combined standard measurement uncertainty (CS) of the reflection coefficient is made by the SI of the ultrasound amplitude after the test liquid is applied to the working surface of the acoustic cell.

From the analysis of the obtained results, it follows that: the largest contribution to the total standard measurement uncertainty of the reflection coefficient is made by the measurement uncertainty of the signal amplitude A after applying the liquid to the working surface of the acoustic cell.

The uncertainty of the method for measuring the phase shift of an ultrasonic wave reflected from the interface between a solid body (fused quartz) and the investigated liquid (distilled water and tung oil) by the impedance method is also estimated. The research results showed the insignificance of the correlation coefficients between the input values: the ultrasound frequency (f), the change in the length of the smooth delay line when the compensation of the signals of the working and reference channels (ΔL) and the speed of light propagation (c) is achieved. The phase shift ϑ of the acoustic wave in the studied frequency range increased by more than 5 times. The largest contribution to the total standard uncertainty in the measurement of phase change is the uncertainty in the measurement of change in length (ΔL).

The effects of temperature, humidity, measurement time, as well as the number of layers of materials on the total thermal resistance of textile materials have been studied.

Automation of measurement uncertainty calculations by developing a program, for example, in the Excel environment [9]. The program [10] developed by the authors makes it possible to: calculate the results of direct, indirect, joint and combined measurements; evaluate their standard, total and expanded uncertainties of type A and B, by reduction and linearization methods; prepare an uncertainty budget when: the measurement model is the product, quotient, sum and/or difference of VxV; the number of observations when measuring all IxV are the same (equal) and/or different.

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FEATURES OF CALIBRATION OF SHUNTS FOR MEASURING STRONG IMPULSE CURRENTS

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Electric shunts are quite widely used in various fields of activity. Based on the results of the current measurement, other parameters of the technological processes are determined. Therefore, it is advisable to minimize the uncertainty of calibration results. A significant achievement is the creation of the latest electrical resistance standards based on the quantum Hall effect. The use of the "bridge circuit" provides the ability to determine the resistance with an uncertainty of less than 10^{-9}.

The calibration of electric shunts, which are used to measure the amplitude-time parameters of strong current pulses, has a number of features related to the influence of the shunt inductance, the skin effect, and thermal heating. Is it possible to determine the level of integral influence of these factors experimentally, by using a circuit with current flow? Yes, but there are only constant and harmonic voltage / current standards. This does not allow direct interpretation of the results for impulse processes. More correctly, calibration is carried out with the use of impulse voltage and current standards created at the NDPKI "Molniya" of the NTU "KhPI".

The most powerful currents are characteristic of lightning, therefore, for measuring the parameters of such currents, the electric shunt must meet special requirements. The shunt must have stable metrological characteristics when measuring the current form of 10/350 μs with an amplitude of up to 200 kA, since in this mode the worst operating conditions are ensured due to the occurrence of electrodynamic forces and withstand the heating of the resistive element as a result of the flow of component C. The shunt can be described by an electrical model in which inductance and capacitance are added to purely active resistance. For shunts with a resistance from 0.1 to 10 mΩ, the capacitive resistance $1/\omega C$ approaches the active resistance only at frequencies above 100 MHz. [1]. At the frequencies inherent in lightning, the voltage on the shunt includes the following components:

$$v_L(t) = L\frac{\partial i(t)}{\partial t}; \qquad v_R(t) = Ri(t).$$

It must be taken into account that with small resistances, the inductance becomes increasingly important. The voltage on the inductance can be many times higher than the voltage on the active shunt resistance at a high rate of rise of the pulse front. The results of calculating the voltage for a shunt with an inductance of 10 nH and an active resistance of 0.1 mΩ for a biexponential current form of 10/350 μs with an amplitude of 200 kA give the following values: voltage on the active resistance of the shunt $V_R = 20$ V, voltage on the inductance $V_L = 200$ V.

The above shows the need to strive to reduce the inductance of the shunt. At the same time, the value of the active resistance must exceed the reactive resistance of the shunt for the studied pulse by at least 10 times. For example, there are coaxial shunts for measuring currents up to 10 kA with active resistances from 10 mΩ to 50 mΩ with inductances from 1 nH to 3 nH. At 10 mΩ, a current of 200 kA flows at the output of the shunt with a voltage of 2 kV, which is very undesirable for such measurements. Therefore, an algorithm for selecting the optimal ratio of ohmic and inductive resistance is needed.

When a strong current flow through a shunt, measurement errors may occur due to the skin effect and the proximity effect. These effects can lead to an increase in the active resistance of the shunt. To evaluate this, computer simulations using the finite element method in COMSOL Multiphysics will be applied.

To reduce the inductance, a bifilar (coaxial) design is used. Work [2] describes the design of the ShK-300M2 disk shunt for measuring impulse current up to 200 kA. 12X18H10T stainless steel is used as a resistive element, the outer diameter of the resistive disc is 80 mm, the inner diameter is 10 mm. It is shown that from the point of view of thermal stability, the thickness of the resistive disk element is 2 mm, sufficient. The active resistance of the shunt, which was measured by the metrological service at direct current, was 0.094 mΩ.

The research materials present the results of mathematical modeling for a resistive element with an inner diameter of d_2 = 12 mm and an outer diameter of d_3 = 100 mm. The calculation was made for nichrome material with a specific resistance of $1.1 \cdot 10^{-6}$ Ω·m for different thicknesses h = 1 mm and 2 mm. For a disk with h = 1 mm, the ohmic resistance is R = 0.392 mΩ, for h = 2 mm R = 0.196 mΩ. The use of nichrome as a converter is advisable due to the smallest temperature dependence and ensuring a sufficient level of resistance.

An alternative design of the shunt in the form of a set of parallel rods is considered. This version of the active element significantly reduces its inductance and provides resistance to thermal and electrodynamic action of the current. As a result of numerical simulation, the optimal parameters of such a shunt were determined: rods in the amount of 80 pieces are located in a circle with a diameter of 140 mm. The diameter of the nichrome rod is 2 mm, and the length is 10 mm. According to all operational characteristics, this option turned out to be better than the disk shunt.

The presented data indicate that the results of shunt calibration using direct current (standard technique) have uncertainty, the level of which depends on the design of the shunt and the parameters of the measured current. That is, calibration of shunts should be carried out by impulse currents taking into account the inductance of the shunt.

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USING SVD IN MEASUREMENTS

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When performing joint or aggregate measurements, multiple measurements are often taken to improve accuracy. In this case, an overdetermined system of equations is obtained, in which the number of equations exceeds the number of unknown values.

In matrix form, the system of linear equations can be represented as

$$\mathbf{Ax} = \mathbf{B}, \tag{1}$$

where **A** is the $m \times n$ coefficient matrix, **x** is the column vector of variables (the solution of system) with n entries and **B** is the column vector of constant terms with m entries. **A** and **B** contain the measured values obtained by direct measurements, **x** is result of joint or aggregate measurement.

To solve overdetermined systems of linear equations, it is convenient to use the programming and numeric computing platform MATLAB, in which solution (1) can be found using: **x** = **A****B**; **x** = linsolve(**A**,**B**) or the singular value decomposition (SVD) [1]: **x** = **V***pinv(**S**)***U**'***B**, where **U**, **S**, **V** are obtained from [**U**,**S**,**V**]=svd(**A**).

By the magnitude of the singular values (**s** = svd(**A**)) obtained in the SVD, one can judge the validity of the solutions obtained.

The SVD method was used to simulate the measurement of the temperature dependence of electrical resistance measures in accordance with the polynomial dependence:

$$R_T = R_0[1 + \alpha(T - T_0) + \beta(T - T_0)^2], \tag{2}$$

where R_T is the resistance at temperature T; R_0 is the resistance at reference temperature T_0; α and β are temperature coefficients. R_T and $(T–T_0)$ are measured values; R_0, α and β are values to be determined.

The simulation was carried out as follows:

1) nominal values R_0, α and β have been chosen; T_0 = 23 °C; $(T - T_0) = (0; -1; -2; -3)$ °C; from equation (2), the nominal values of R_T were calculated;

2) inaccuracies of measurements of $(T - T_0)$ and R_T were simulated by set of random variables ΔT and ΔR_T with normal distribution, zero means and with a given standard deviations;

3) for several sets of ΔT and ΔR_T for each of the four nominal values $(T - T_0)$, the values R_0, α and β were calculated by the SVD method.

The obtained simulation results are supposed to be used for experimental study of reference resistance measures and evaluation of the uncertainty of measurements carried out by using these measures.

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AUTOMATIC CALCULATION OF MEASUREMENT UNCERTAINTY IN THE LABORATORY

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Calculation of measurement uncertainty is an integral procedure when processing measurement results during testing. Based on the established measurement uncertainty, a decision is made on the compliance of the test object with the established requirements [1]. In addition, the laboratory shall report the measurement uncertainty obtained during the tests [1]. In view of this, the automation of the uncertainty calculation process is an urgent issue, the solution of which in conjunction with the automatic generation of the uncertainty report will ensure the effective operation of the laboratory management system in this direction. In [2], an information model of the testing laboratory is proposed. This model provides all the functions of the laboratory, from accepting an application to issuing results, and provides for the automation of the management system. The block of calculation of measurement uncertainty is presented as a separate module. The virtual laboratory presented in [2] is built using the Microsoft Access database. This platform was chosen because of its availability to the general public, ease of learning the interface and the ability to work remotely.

Structurally, the uncertainty assessment module consists of:

– tables: “Record”, “Result”, “Measurement type”; moreover, the tables “Record” and “Result” are connected by a one-to-many relation by the field "Record code" with ensuring data integrity and cascading update;

– queries: “Uncertainty”, “Uncertainty_A”, “Uncertainty_A_STDev", "Uncertainty_B", "Uncertainty_Report", which provide the calculation of uncertainty by its types;

– report “Log”, which is built on the form established in the laboratory;

– forms: “Type of measurement”, “Record”, “Uncertainty”, “Result”.

The input data for the uncertainty calculation in the module are: measuring instrument, measurement results (at least three), coverage factor and the name of the person performing the calculation. After pressing the “Calculation” button, all the information necessary for drawing up the uncertainty budget is displayed on the screen. Pressing the “Journal” button displays the uncertainty budget in the established form and can be printed.

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OPTICAL-MECHANICAL SENSOR CONVERSION FUNCTION FOR MEASURING GEOMETRIC CHARACTERISTICS OF THE BORE OF BARRELS OF FIREARMS

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An important condition for ensuring the effective use of firearms is the improvement of the operational measurement control system of their parameters. Measuring information about the geometric characteristics of the surfaces of bore is of particular importance. The analysis of these characteristics allows, in particular, to assess the technical condition and identify typical defects of firearm samples, as well as to investigate the influence of operating conditions and firing modes on wear rates of the bore. Thus, the creation of a specialized measuring tool (MT) of the geometric characteristics of the bore surface is an urgent scientific and technical task.

One of the promising ways of solving this problem is based on the construction of the MT based on a suitable optical (laser) triangulation method. However, the specific conditions of the measurements make it necessary to take into account such factors as the fundamental nonlinearity of the conversion function of the optical-mechanical sensor (OMS) and the limitation of the geometric dimensions of the elements of the optical circuit when they are located inside the bore, the asymmetry of the measurement range of the bore diameter relative to zero, etc.

The construction of a specialized OMS for measuring the geometric characteristics of the bore surface includes such basic elements as a laser radiation source, a focusing lens, a receiving lens and a light-sensitive detector (a charge-coupled device). The receiving lens and the light-sensitive detector are fixed in space and coordinated. During OMS operation, laser radiation is diffusely reflected from the object of measurement, a certain part of it passes through the receiving lens, focuses and falls on the corresponding cell of the light-sensitive detector. When the point from which the laser radiation is reflected on the measurement object is shifted by a certain distance (for example, when the bore radius increases due to its erasure), the light spot on the surface of the light-sensitive detector also acquires a corresponding displacement. Processing of signals from the output of the detector, which carry information about the illumination of the line of light-sensitive elements, as well as calculation of the distance to the measurement object, is entrusted to the microprocessor controller.

One of the important tasks in substantiating the construction features and parameters of the OMS is to obtain ratios that determine its transformation function, as well as the relationship between the basic geometric parameters of the OMS optical scheme. In addition, the study of the limitations that are imposed on the parameters of the OMS and are caused by the specific conditions of the measurements is of particular interest.

The basic initial geometric parameters of the optical circuit of the sensor, which are determined by the caliber of the bore, include the distances r and r' from the center of the receiving lens to the point of focus of the beam on the surface of the bore and to the light-sensitive detector respectively (the ratio between which, in turn, depends on the focal length f of the lens), as well as the angle α between the optical axes of the focusing and receiving lenses and the angle β between the optical axis of the receiving lens and the light-sensitive detector. When using OMS, a relative measurement is implemented, i.e. the measured value is the increase Δz in the bore radius relative to its nominal value, and the output value is the corresponding increase Δx in the coordinate of the light spot on the surface of the light-sensitive detector relative to its initial position. It is appropriate to consider the point of focus of the beam as corresponding to the middle of the measurement range, but it should be noted that due to the nonlinearity of the conversion function, the range of movement of the light spot on the surface of the light-sensitive detector will be asymmetric with respect to the projection of such a point.

Consider the receiving objective as a thin lens. The expression for the angle β will be determined based on trigonometric transformations of the initial parameters, taking into account the basic formula for a thin lens:

$$\beta = \operatorname{arctg}\left[\operatorname{tg}(\alpha)\left(\frac{r}{f}-1\right)\right], \tag{1}$$

Using the basic relationships for the triangles formed by the optical axis of the receiving lens, the line passing through the starting point of the measurement range and the center of the receiving lens, and the line of photosensitive elements, it can be shown that the OMS conversion function will have the form

$$\Delta x = \frac{\Delta z \cdot r \cdot \sin\beta}{r' \cdot \sin\alpha + \Delta z \cdot \sin(\alpha+\beta)}, \tag{2}$$

Algorithmic support of the microprocessor controller involves obtaining an expression for solving the inverse problem – calculating the input value Δz on the basis of measurement information about the output value Δx. After carrying out algebraic transformations, the desired expression can be presented in the form

$$\Delta z = \frac{\Delta x \cdot r' \cdot \sin\alpha}{r \cdot \sin\beta - \Delta x \cdot \sin(\alpha+\beta)}. \tag{3}$$

In the future, the obtained mathematical relations should be used as a basis for building mathematical models of errors of the MT. In addition, at the stage of development of recommendations for the practical implementation of the MT, the substantiation of the scientific and methodological bases of uncertainty of measurements assessment, MT calibration, etc., will be of special interest.

ANALYSIS AND COMPARISON OF BAYESIAN METHODS FOR TYPE A UNCERTAINTY EVALUATION WITH PRIOR KNOWLEDGE

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The problem of evaluating Type A standard uncertainty for the case of a small set of normal independent observations arises frequently in practice. As is well known, the GUM´s approach to that problem is frequentist in nature and applies to as little as two data points. However, as attested by the publication of Supplement 1 to the GUM and of several other papers, the Bayesian method of analysis seems to have gained preference among many metrologists. Unfortunately, a practical drawback of this method is that it cannot be applied to analyze the case of less than four observations. This limitation was one of the reasons why the Committee Draft (CD) of the review of the GUM, circulated at the end of 2014 –and which was intended to make the GUM fully Bayesian– was largely rejected by the metrological community [1].

Since then, a few papers have been recently published, which propose to solve this problem by using Bayesian methods that incorporate prior knowledge. Thus, a prior is used in [2] that consists in the provision of lower and upper bounds for the variance of the Gaussian population from which the data are assumed to have been drawn. This procedure leads to a closed-form expression for a factor by which the standard deviation of the mean of the observations should be multiplied, to calculate the standard uncertainty associated with the measurand.

References [3] and [4] consider also informative prior distributions for the variance: a half-Cauchy in the case of [3] and a scaled inverse chi-squared in the case of [4]. The half-Cauchy approach leads to a posterior which may be sampled via Markov Chain Monte Carlo (MCMC). Instead, the inverse chi-squared approach produces a scaled-and-shifted t-posterior.

Another procedure for a Bayesian uncertainty computation using prior knowledge is described in [5]. It applies to measurement models that depend linearly on a single input quantity for which Type A information is available, together with several input quantities for which Type B information is given. By using a normal inverse Gamma (NIG) prior, uncertainty evaluations are carried out using a simple Monte Carlo procedure that allows drawing uncorrelated samples from the posterior distribution. The procedure does not require MCMC and applies to the case of a small number of observations for the Type A input quantity, even to only a single one.

Reference [6] generalizes the measurement model adopted in [5] and considers specific prior distributions with which analytical expressions for the posterior distribution of the measurand are derived. Results can be calculated with MCMC. Finally, in [7] a rejection-based Monte Carlo sampling method is proposed to account for prior knowledge.

In this contribution, a summary of all these papers is presented and discussed, with a focus on the case of a measurement model consisting of a single input quantity for which Type A information and other prior knowledge are available, as in [2 – 4].

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PROBLEMS OF APPLICATION OF THE RESULTS OF MEASUREMENT UNCERTAINTY ASSESSMENT IN PRACTICE

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In accordance with ISO/IEC 17025:2017 [1], testing and calibration laboratories must evaluate Evaluation of measurement uncertainty. More than 20 years have passed since the creation of the Guide to the Expression of Uncertainty in Measurement (GUM) [2]. During this time problems of application of the results of measurement uncertainty assessment in practice constantly appear. But there are no solutions to these problems in order to eliminate them.

The main unsolvable problem is the significant difference in the results of measurements/tests and calibrations of different laboratories. When measuring/testing the characteristics of identical product samples, the results are so different that the user does not have confidence in them. For example, EUROCHEM gives the following example in its methodological recommendations: “Mr. Race decided to sell oranges for juice. He entered into a contract with laboratory C to study his orange. But the juice manufacturer tested these figures in his laboratory B and got completely different results. As a result, Mr. Race received much less money than he expected”. Got the results shown in Table 1 (*k* – coverage factor for coverage interval).

Table 1

Parameter	Laboratory C	Laboratory B
1	(0,592 ± 0,019) мg·кg^{-1} (*k* = 2; 95 %)(	(0,51 ± 0,20) мg·кg^{-1} (*k* = 2; 95 %)
2	(70 ± 25) °Bx (*k* = 2; 95 %)	(61,2 ± 1,1) °Bx (*k* = 2; 95 %)

The justification for such a difference in the results is due to the lack of target uncertainty and the too small value of the uncertainty of indicator 1 and the too large value of the uncertainty of indicator 2 in laboratory C. But at the same time, the too small value of the uncertainty of indicator 2 and the too large value of uncertainty of indicator 1 in laboratory B are not considered.

ISO/IEC 17025 specifies the possible performance characteristics of measurement procedures. Among them is uncertainty. But, unfortunately, uncertainty does not provide confidence in the results obtained. And very often contributes to misconceptions in the application of these results by users.

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THE SOURCES OF UNCERTAINTY OF THE MEASUREMENT RESULT AS ELEMENTS OF THE MEASUREMENT PROCESS

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In the paper [1] was explained the duality of the measurement process – measurements results. The main presented idea there is that the result is not an element of the measurement process because it is a product the process. This concept opposes some other classifications where the result is considered as a component of the process [19]. Based on this concept, we can classify and separate the elements of the measurement process and the elements of the measurement results.

In the paper [1], after analysis of well-known sources [2, 4-9, 12-15, 18], the five elements of the measurement process are specified as follow:

- measurement object;
- measurement method;
- measuring instrument;
- measurement subject;
- influence factors.

According VIM [2] §2.9 NOTE 2 "*A measurement result is generally expressed as a single* ***measured quantity value*** *and a* ***measurement uncertainty***". Therefore, the elements of the measurement results are:

- measured quantity value;
- measurement uncertainty.

From its own side VIM [2] §1.19 the quantity value consists "*value number and reference*". For completeness, we note that uncertainty is also expressed by value number and dimension.

A fundamental issue in measurement, and especially in calibration, is the correct estimation of uncertainty, which is possible by accounting for the contributions of all its significant components. While uncertainty assessment methods are well analyzed, developed and described [3-11], the detection and determination of the contributing components associated with the sources of uncertainty remains within the realm of the metrologist's empirical expertise.

As emphasized in [3] “*The errors characterize the measurement process*”. The analysis [1] of the elements of the measurement process define the respective errors. Consequently, the sources of uncertainty can be specified by considering un-excluded errors in the measurement process as the cause of measurement uncertainty.

The primary sources of the components of uncertainty are related with the elements of the measurement process [1].

The purpose of this report is to specify and detail essential components of the uncertainty inherent in the individual elements of the measurement process.

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PRELIMINARY ANALYSIS OF THE UNCERTAINTY EVALUATION FOR THE THOUSAND SEED WEIGHT

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Evaluation of seed material quality indicators is an integral component of testing in accredited seed laboratories. The thousand seed weight is a quality indicator, which must be specified in Seed Analysis Certificates for sowing qualities of seeds [1].

Boundary values for the thousand seed weight are not normalized during certification. However, they are taken into account when forming the cost of the batch and determining the seed sowing rates. At the same time, particular attention is paid to the uncertainty of the result.

Preliminary analysis of the uncertainty evaluation for the thousand seed weight is considered in the report. The determining of uncertainty components, according to testing methodology, given in [2], is considered in details.

It is shown, that random component of measurement result depends on the methods of counting. The cases of using following methods of selecting a certain number of seeds are considered [2]:

- eight repetitions of 100 seeds;
- two repetitions of 500 seeds.

For the second case according to the methodology [2] mean value for masses of both repeats, their sum and the actual difference between them are evaluated. The actual difference between them shall not exceed 3%. It has been determined, that uncertainty sourses may depend on the seed shape, for example lamellar seeds shape and needle-shaped seeds.

It was established that during the development of the methodology, the effect of repeatability and correctness of the result should be taken into account. Special attention should be paid to the cases, that will allow to ignore the significance of the correctness of the methodology.

Further methods of applying the results of the uncertainty evaluation of the thousand seed weight were determined in accordance with [3]. This is, for example, ensuring the validity of results, monitoring competence of personnel.

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PARETO CHART AS A TOOL FOR IMPLEMENTING THE CRITERIA FOR UNCERTAINTY INSIGNIFICANCE

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During the metrological analysis of model equations for indirect measurements in practice, a situation often arises when the total standard uncertainty contains a large number of components that analysing for the purpose of further reduction is impractical due to economic and labour-intensive factors. In this case, a classic metrological criterion called the “criteria for negligible error” is used. In modern metrological literature which is based on the application of the measurement uncertainty theory, this criterion is considered under the name “criteria for negligible uncertainty"” [1] or “criteria for uncertainty insignificance” [2]. The uncertainty insignificance criteria allows to single out the components of the combined standard uncertainty u_i that do not make a significant contribution to it, and their reduction will not lead to a significant decrease in the combined standard uncertainty u_c. Uncertainty components can be neglected if the inequality $u_i<0{,}312u_c$ [3] holds.

In the context of the intensification of a multidisciplinary STEAM (Science, Technology, Engineering, Art, Mathematics) approach to solving engineering problems, for the quick and visual identification of component uncertainties that can be determined as insignificant, the authors suggest applying the world-famous Pareto principle (the 80/20 rule or the principle of a small number of causes). The Pareto principle was proposed by the Italian economist and sociologist Vilfredo Pareto in 1906. Based on statistical studies, the scientist had proved that 80% of the effects are caused by 20% of the causes. The Pareto principle has found wide application in many fields of science and technology, in particular in quality management (introduced by the outstanding theoretician in the quality field J. Juran in 1951). On its basis, the quality control tool “Pareto chart” was developed which allows you to rank individual components of the whole by importance and determine the required percentage of results.

So, if the combined standard uncertainty is presented as a whole, and the partial uncertainties as separate components, then the construction of a Pareto chart and the separation of the components at the level of 68.8% (according to the uncertainty insignificance criteria) will allow to identify and visualize the dominant (on the left side of the reference line 68.8%) and small uncertainty components that can be neglected (on the right side of the reference line 68.8%) quickly, simply and visually.

Construction of the Pareto chart can be done in many ways including popular computer packages. One of the most popular computer algebra system (CAS) is Maple.

To build a Pareto chart in CAS Maple, use the pareto command from the plot's library:

pareto(Fdata, tags=Lab, misc=Others, colour=blue, thickness=5);

where Fdata is data for plotting the Pareto chart (components of the combined standard uncertainty); Lab is the names of the columns in the Pareto chart, the misc parameter indicates that the Others column should be added to the Pareto chart; the Colour parameter determines the colour used to display the chart on the screen; the Thickness parameter determines the thickness of the line in pixels.

The practical application of the Pareto tool for identification and visualization of the dominant components of the combined standard uncertainty was carried out during the metrological analysis of the optical-thermal method' model equation for gas flow measurement [4]. The non-contact optical-thermal method of gas flow measurement was developed by the authors based on a combination of optical and thermal methods. The analysis of the Pareto chart constructed based on the calculation results of the combined standard uncertainty and the influence on it of the components that arise when measuring the flow of natural gas using the optical-thermal method, showed that the following components can be neglected according to the insignificance uncertainty criteria: uncertainty of the heating power ($2{,}11\cdot10^{-5}$ m^3/s), uncertainty of measuring the internal radius of the pipeline ($3{,}03\cdot10^{-5}$ m^3/s), uncertainty of setting the gas dynamic viscosity coefficient ($3{,}06\cdot10^{-6}$ m^3/s), uncertainty of measuring the gas density ($7{,}75\cdot10^{-6}$ m^3/s), pipeline thickness measurement uncertainty ($1{,}04\cdot10^{-5}$ m^3/s), pipeline material density measurement uncertainty ($1{,}98\cdot10^{-5}$ m^3/s), uncertainty of pipeline heat capacity measurement ($4{,}2949\cdot10^{-6}$ m^3/s), uncertainty of gas heat capacity measurement ($2{,}28\cdot10^{-5}$ m^3/s), etc.

Accordingly, the dominant components that require detailed analysis in order to reduce them are the component of uncertainty due to inaccuracy of the number of interference fringes measuring ($2{,}45\cdot10^{-4}$ m^3/s), the uncertainty of measuring the studied cross-sections location ($1{,}17\cdot10^{-4}$ m^3/s), the uncertainty, related to the determination of the distribution coefficient of gas flow velocities ($1{,}08\cdot10^{-4}$ m^3/s).

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DETERMINATION OF ATMOSPHERIC CORRECTIONS IN LASER RANGING FROM MEAN ALONG -TRACE AIR TEMPERATURE: UNCERTAINTY ANALYSIS

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To account for the influence of the Earth's atmosphere on the results of laser ranging measurements, the mean integral refractive index of air $\overline{n}$, defined through the average air temperature along the trace $\overline{T}$, is sometimes used as a correction. This approach is not strictly justified, since from the general relations [1], which establish the relationship between the air refractive index and the meteorological parameters, it follows that the value $\overline{n}$ depends on temperature in a more complex way, and the main contribution to this dependence gives not $\overline{T}$, but the average value of the quantity inverse to the temperature $\overline{(1/T)}$.

The analysis of the methodical component of the uncertainty due to the difference $\overline{T}$ from $\overline{(1/T)}$, is performed for model spatial profiles of air temperature $T(x)$ (x - coordinate along the straight line connecting the end points of the trace). The cases of both monotonic dependence $T(x)$ (linear function) and non-monotonic dependence (symmetric parabola) were considered.

Numerical estimates were performed for the following initial data. In case of linear dependence: temperature values at the end points of the trace are taken as 293.15K and 291.15K. In case of symmetric parabola: the same temperature was taken as 293,15K at the end points and 291,15K at the middle point of the trace. Air pressure and humidity for the cases under consideration were assumed to correspond to normal conditions at all points of the trace.

The methodical component of the $\overline{n}$ determination uncertainty for the considered models with the specified initial data on traces with a length of 1...5 km does not exceed $1.2 \cdot 10^{-9}$. This is a negligibly small value, which allows it to be used $\overline{T}$ to determine the atmospheric correction for measurements on traces with temperature profiles corresponding to the discussed models with the above parameters.

If the real profiles do not correspond to the model profiles, it is necessary to perform estimates using real profiles according to the methodology described above in order to find out whether the value $\overline{T}$ can be used in determining the atmospheric correction.

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CALIBRATOR FOR INDUCTION METERS OF VARIABLE MAGNETIC FIELDS

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Low-frequency variable magnetic fields, especially the industrial frequency of 50 Hz, are increasingly used in various technologies. To control their level and ensure safety, magnetic induction meters are used, which measure the intensity of the geomagnetic field, magnetic properties of substances, and electromagnetic safety standards when conducting a comprehensive sanitary and hygienic inspection of production facilities, when assessing working conditions, workplaces, office and residential premises, in studies of the negative impact of magnetic fields on the human body.

Industrial portable magnetometers are designed to measure the induction of magnetic fields in a significant dynamic and frequency range. The magnetic field is detected by three sensors on the orthogonal axes X, Y and Z, then analog-digital conversion of the signal into numerical information takes place. Working tools for measuring magnetic induction have errors of up to 15-20%. For the reliability of measurements and confidence in their results, magnetic induction meters must undergo periodic calibration. Therefore, a calibrator of induction meters of variable low-frequency magnetic fields was developed, the uncertainty of which measurements is 2-3 times less than the uncertainty of measurements of working tools.

A Helmholtz coil was used to obtain calibrated magnetic induction values. According to the well-known formula for the relationship of induction, current and radius of the coils, it is possible to calculate the value of the magnetic induction in the center between the coils. The magnetic field in the Helmholtz coil is proportional to the current, so a significant current is required to generate magnetic fields. It is advantageous to use a low-frequency amplifier on the TDA 1875 module. It is built on an operational amplifier of the LM1875 type, which has a minimum number of external components, protection against overload and short circuits to ground, internal protection diodes at the output, internal current limiting, thermal shutdown, high slew rate and a wide bandwidth of 70 kHz, a large output voltage range, large currents and a wide supply range, internal compensation and works stably at a gain of 10 and above. The typical value of the gain of the operational amplifier LM1875 is 90dB, low distortion Kg=0.015%, Load resistance, 4-8 ohms.

The Helmholtz coil has a large inductance, whose resistance to alternating current increases with increasing frequency and causes a decrease in current and, accordingly, magnetic induction at frequencies above 50 Hz. To solve this problem, series resonance [1] is used, in which compensation of the inductive resistance of the coil is achieved by the capacitive resistance of the capacitor. The advantage of this method is to increase the magnetic field induction at the same source voltage. At the resonant frequency, the current reaches its maximum value. By switching different capacitors, we get the maximum value of the current at the bottom of the resonant frequencies, and the frequency range of reproduced inductions is expanded to 20 kHz. When choosing capacitors, high voltages on their contacts were taken into account, which can reach high voltage values (up to 300 V), therefore measures are necessary to protect against electrical breakdown of the equipment and ensure the safety of personnel.

To clarify the proportionality factor between current and magnetic induction, a number of induction measurements were carried out at different current values and frequencies using a Narda type EHP-50F meter, which has an uncertainty of 3-5%. By processing series of non-equivalent measurements according to the method [2], the uncertainty of this coefficient was reduced to 2%.

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TOWARD THE NEXT EDITION OF THE INTERNATIONAL VOCABULARY OF METROLOGY

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The International Vocabulary of Metrology (VIM) is presently at its 3rd Edition (2012) (VIM3). VIM3 was a major achievement and numerous comments can be found in the literature concerning the evaluation of VIM3 that will be taken here as a reference for the future developments.

The present paper is based mainly on the concept that such a Vocabulary is assumed to be of great help for the practitioners of metrology, i.e., in general of people that must correctly apply the idiom of metrology according to the current meaning of its terms.

The core of VIM3, i.e., its few basic terms, which are those currently used in metrology (defined according a paper’s Glossary), are identified, and their current meaning recalled together with the rationale of having chosen them.

Author's position will be illustrated, as assuming that a Metrology Vocabulary is not supposed to be of much interest for the scientists whose activity already develops under the discipline of metrology, since they are supposed to be well informed on its terminology. Rather, such a Vocabulary is assumed to be of great help for the practitioners of metrology, i.e., in general of people that must correctly apply the idiom of metrology according to the current meaning of its terms.

In addition, an International Vocabulary is assumed being used in every Country of the World, so taking into account as much as possible the need of easy and unambiguous translations in many different languages, where the local metrological idioms may be expressed differently, a major difficulty.

The core of VIM3, i.e. its main basic terms, which are those currently used in metrology, are identified as being: “Quantity” vs. “Amount”, “Magnitude”; “Quantity” vs. “Property”; “Value” vs. “Scale”. Their current meaning will be recalled, together with the rationale of having chosen them. The above illustration is compared with recently proposed changes of several of them, including some terms to be newly introduced.

The analysis will also take into account that, for the basic terms, any substantial change in their meaning, or the suppression of some of them, should be carefully pondered for being strictly necessary, because it may entail unnecessary confusion for many Dictionary users. In fact, it is possible and reasonable that in other disciplines the same terms might express different concepts and in a different way according to the specific idiom of those disciplines – e.g., according to an idiom basically originating from branches of philosophy of science or from set theory, where important differences in their meaning could be inappropriate or difficult to understand in measurement science, and metrology in particular.

PROCESSING RESULTS OF MEASUREMENT WHEN DETERMINING THE RAPESEED OIL DENSITY

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The high-quality products indicators include purpose indicators, aesthetic indicators, safety indicators, and identification indicators (density, refraction factor, fatty acid composition, etc.).

Today, there is a need to develop an updated reference table for the density of unrefined rapeseed oil vs. temperature within the temperature range of 273-373 deg K (with the step of 1 deg K), because the existing tables are incomplete. The currently existing tables include the density readings every 5 ºC, which is not sufficient for technological calculations, and they also contain the outdated data (the oil is obtained from rapeseed breeds and hybrids that are no longer used in production).

There was a random impersonal aggregate of five samples was formed. The samples were provided by a different supplier. The abovementioned population was used as a representative sample to conduct the studies.

Measurements were conducted within the temperature range from 0 deg C to 100 deg C, through a 10 deg C step. Each measurement was conducted in five parallels at each point. Additionally, in order to increase the accuracy of measurements, there were additional measurements conducted at 273 deg K (0 deg C), 298 deg K (25 deg C), 323 deg K (50 deg C), 348 deg K (75 deg C), 373 deg K (100 deg C). The abovementioned measurements were conducted in five groups of five parallels in each group.

Statistical processing of the measurement results was performed in Mathcad software including the following factors: evaluation of statistical data for combined processing, verification of a significant systematic error with the method of successive differences (Abbe's criterion), detection of abnormal results according to the Grubbs, Dixon-Gardner and Irwin criteria, calculation of mean value, dispersion, mean square deviation, estimation of absolute and relative errors, estimation of absolute and relative standard measurements uncertainties of type A.

The relative expanded measurement uncertainty of unrefined rapeseed oil density measurements was 7.2×10^{-5}, the absolute expanded measurement uncertainty of density measurements was 6.48×10^{-2}. The obtained data were approximated by a linear function. The maximum deviation of the tabular data from the approximate dependence was no more than 1.8×10^{-4} kg/m3. Errors in determining the approximation coefficients were no more than 10^{-4} kg/m^3.

Therefore, based on the abovementioned studies, tables of the dependence of the density of unrefined rapeseed oil vs. temperature within the temperature range of 273-373 deg K were developed. Those tables were approved as standard reference data in the Ministry of Economic Development, Trade and Agriculture of Ukraine.

NIST DECISION TREE FOR KEY COMPARISONS IN MEASUREMENT SCIENCE AND FOR META-ANALYSES IN MEDICINE

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The NIST Decision Tree, available at https://decisiontree.nist.gov, makes recommendations for how to model and reduce the measurement results obtained in key comparisons (and interlaboratory comparisons generally) conducted in measurement science, and in meta-analyses carried out in medicine [1].

The presentation will illustrate applications of the NIST Decision Tree to key comparisons involving measurements of the mass fraction of nickel in bovine liver (CCQM-K145) [2], and of the equivalent activity of zinc-65 (BIPM.RI(II)-K1) [3].

The meta-analysis of the effect of rosiglitazone (Avandia) on the risk of myocardial infarction, in the breakthrough study that Steven Nissen and Kathy Wolsky published in the New England Journal of Medicine in 2007 [4], will be revisited to illustrate the application of conventional statistical procedures, and also as an example of model selection aided by the NIST Decision Tree.

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ESTIMATION OF THE NONLINEAR CALIBRATION CHARACTERISTIC FROM THE CORRELATED DATA OF MEASUREMENTS BY THE LEAST SQUARES METHOD

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Characteristics of some measuring instruments, like sensors and electronic transducers, are described by an unambiguous non-linear function [1]. In presentation it is described how to fit a second-degree curve to coordinates of measured points on the example of the parabola part.

In the calibration process both coordinates of tested points can be measured, and parameters of this curve fitted to their values should be found. Let us, e.g., consider an equation as a part of the parabola arm

$$y = Ax^2 + Bx + C \tag{1}$$

The sets $\boldsymbol{X}$, $\boldsymbol{Y}$ of both coordinates x_i, y_i of n tested points can be represented together as common vector of $2n$ elements $\boldsymbol{Z} = [\boldsymbol{X}, \boldsymbol{Y}]^{\mathrm{T}} = [x_1, \dots x_i, \dots x_n; y_1, \dots y_i, \dots y_n]^{\mathrm{T}}$. In general case both x, y variables are measured with random errors, and between their sets the autocorrelation and cross-correlation may occur [1]. Covariance matrix $\boldsymbol{U_Z}$ of $\boldsymbol{Z}$ contains $2n$ variances as squares of standard uncertainties: $u_{x1}, \dots u_{xi}, \dots u_{xn}, u_{y1}, \dots u_{yi}, \dots u_{yn}$ on the main diagonal and covariances $\rho_{ij} \cdot u_i \cdot u_j$ (where $U_{ij} = u_{ji}$) in other positions, arranged symmetrically with respect to this diagonal.

The parameters A, B, C of function (1) have to be found. That can be done by the linear regression method. In the general case, with unequal uncertainties and the occurrence of correlations, this solution can be obtained only numerically [2]. In simplified cases of the matrix $\boldsymbol{U_Z}$ there are also analytical solutions [2]. The new variable $\xi = (x + v)^2$ can be implemented, where $v = B/2A$. For variable ξ the straight-line equation is obtained, i.e.:

$$y = a\xi + b = A\xi + C - v^2 A \tag{2}$$

where $a = A$, $b = C - Av^2$.

And it is enough now numerically to find only two parameters.

The WTLS linear regression method (minimum weighted squares of distance) matching with the occurrence of cross-correlation of measured variables is used. Therefore, one can look for a minimum of the one-parameter function:

$$G(a) = a^2\left(S_{xx} - \frac{S_x^2}{S}\right) + 2\left(\frac{S_x S_y}{S} - S_{xy}\right)a + S_{yy} - \frac{S_y^2}{S}, \tag{3}$$

where $S = \mathbf{1}^{\mathrm{T}}\, \boldsymbol{U}_{\boldsymbol{eff}}^{-1} \mathbf{1} = \sum_{i=1}^{n} \sum_{j=1}^{n} [\, u_{yeff}^{-1}]_{ij}$, $S_x = \boldsymbol{X}^{\mathrm{T}} \boldsymbol{U}_{\boldsymbol{Yeff}}^{-1} \mathbf{1} = \mathbf{1}^{\mathrm{T}} \boldsymbol{U}_{\boldsymbol{Yeff}}^{-1} \boldsymbol{X}$, $S_{xx} = \boldsymbol{X}^{\mathrm{T}} \boldsymbol{U}_{\boldsymbol{Yeff}}^{-1} \boldsymbol{X}$, $S_y = \boldsymbol{Y}^{\mathrm{T}} \boldsymbol{U}_{\boldsymbol{Yeff}}^{-1} \mathbf{1} = \mathbf{1}^{\mathrm{T}} \boldsymbol{U}_{\boldsymbol{Yeff}}^{-1} \boldsymbol{Y}$, $S_{xy} = \boldsymbol{X}^{\mathrm{T}} \boldsymbol{U}_{\boldsymbol{Yeff}}^{-1} \boldsymbol{Y} = \boldsymbol{Y}^{\mathrm{T}} \boldsymbol{U}_{\boldsymbol{Yeff}}^{-1} \boldsymbol{X}$, $S_{yy} = \boldsymbol{Y}^{\mathrm{T}} \boldsymbol{U}_{\boldsymbol{Yeff}}^{-1}$.

Matrices: $\boldsymbol{U}_{\boldsymbol{Yeff}}^{-1} = \boldsymbol{U}_{\mathbf{22}} - \left(\boldsymbol{U}_{\mathbf{12}}^{\mathrm{T}} a \boldsymbol{U}_{\mathbf{22}}\right) \boldsymbol{U}^{-\mathbf{1}} (\boldsymbol{U}_{\mathbf{12}} + a\boldsymbol{U}_{\mathbf{22}})$ and $\boldsymbol{U} = \boldsymbol{U}_{\mathbf{11}} + a(\boldsymbol{U}_{\mathbf{12}}^{\mathrm{T}} + \boldsymbol{U}_{\mathbf{12}}) + a^2 \boldsymbol{U}_{\mathbf{22}}$ are positively defined, and then occurring matrices $\boldsymbol{U}_{\mathbf{11}}, \boldsymbol{U}_{\mathbf{12}} \boldsymbol{U}_{\mathbf{22}}$ form the inverse matrix to $\boldsymbol{U_Z}$, i.e.:

$$\boldsymbol{U}_{\boldsymbol{Z}}^{-1} = \begin{bmatrix} \boldsymbol{U}_{11} & \boldsymbol{U}_{12} \\ \boldsymbol{U}_{12}^{T} & \boldsymbol{U}_{22} \end{bmatrix} \qquad (4)$$

describing the criterion for the offset v, that changes of vectors $\boldsymbol{X}$ and $\boldsymbol{Y}$ of measured points coordinates and their standard uncertainties. The covariance matrix of new coordinates contains standard uncertainties:

$$u(\xi_i) = |\frac{\partial x'_i}{\partial x_i}| = 2|\xi_i + v|u(x_i) \qquad (5)$$

where $x'_i + v \neq 0$ for i =1, …, n.

All correlation coefficients in the covariance matrix of variables ξ i y are identical as in the covariance matrix for variables x and y. The parameters are $A = a_{\min}$, $B = 2a_{\min}\nu_{\min}$, $C = b_{\min} + a_{\min}(\nu_{\min})^{2.}$

The uncertainty band is determined from the parameters of covariance matrix U_{ab}

$$U(x) = t_{0.95,n-2}\sqrt{(x+v_{min})^4 u_a^2 + 2\rho_{ab}(x+v_{min})^2 u_a u_b + u_b^2}\ . \qquad (6)$$

Above method was tested on a few cases. Some of them will be discussed in detail during the presentation.

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THE INFLUENCE OF UNCERTAINTY ON THE CHOICE OF THE CALIBRATION INTERVALS OF MEASURING INSTRUMENTS

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An important aspect for traceability ensuring and obtaining reliable measurement results in the laboratory is to determine the maximum interval that should be allowed between sequential calibrations.

After the calibration on a regular basis, a revision of intercalibration intervals (ICI) can be conducted in order to optimize the balance of risks and costs. The most well-known methods of revision of the intercalibration interval (ICI) [1-3] do not take into account the uncertainty of measurements performed during calibrations. In [4] to correction the ICI, it is proposed to use the E_n criterion, which uses the ratio of the change in biases Δ_{N-1} and Δ_N, obtained with two successive calibrations (N-1) and N to the expanded uncertainty of this difference $\sqrt{U_{N-1}^2 + U_N^2}$. If $|E_n| < 0{,}6$, the ICI can be extended one step higher than the initial one from the series given in [1]; if

$0{,}6 \le |E_n| \le 1$, the ICI should be left unchanged; if $|E_n| > 1$, the ICI needs to be reduced by one step below the initial one from the series given in [1].

In [5], the authors proposed, before applying the E_n criterion, to verify the metrological suitability of the measuring instrument (MI) after the *N*-th calibration based on the calculation of the compliance probability p_c according to the formula [6]:

$$p_c = F_N\left(\frac{\mathrm{MPE} - |\Delta_N|}{u_N}\right) = F_N\left(\frac{\mathrm{MPE} - |\Delta_N|}{U_N/2}\right),$$

where MPE is maximum permissible error of MI; F_N is a function of the normal standard distribution. For $p_c < 0.975$, the decision on the suitability of the MI is must be by the Customer.

The report discusses examples of the application of this technique for various types of measuring instruments.

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CHANGES IN THE METROLOGICAL CHARACTERISTICS HOUSEHOLD GAS METERS UNDER THE INFLUENCE OF GAS-HYDROGEN MIXTURES

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In accordance with the developed methodology [1], representative studies were conducted to determine the influence of hydrogen and mixtures of natural gas with hydrogen on changes in the metrological characteristics of household gas meters. Two stages of experiments were carried out: static tests and dynamic tests.

Before conducting the experiments and at the end of each stage of the experiment, the control of the metrological characteristics of the meters was carried out in laboratory conditions with the working environment - air, at a pressure close to atmospheric with the use of a reference device, with the help of which the metrological characteristics were determined at the initial stage of the tests.

The first stage of static tests consists in checking the tightness of the meter housing and, accordingly, detecting the influence of hydrogen and gas-hydrogen mixtures on the metal from which the meters are made.

The criterion for evaluating the impact of hydrogen on the internal parts of gas meters was the difference in measurement errors before the beginning of the experiments and after they ended, which are determined in laboratory conditions.

After carrying out a set of static tests, dynamic tests are carried out in the conditions of a pilot model of the layout of the medium and low pressure gas distribution system of the timing operator.

As a master meter, a drum-type gas meter with a predefined calibration characteristic was used in laboratory conditions with the working medium - air.

The experiments were carried out using three types of working medium: gaseous hydrogen with a purity higher than 99%; mixtures of methane and hydrogen in the proportion of 80% / 20%; a mixture of methane and hydrogen in the proportion of 90% / 10%.

According to the results of the analysis of the set of consistently determined metrological characteristics of experimental meters, it is possible to conclude that no general trend regarding a significant change in metrological characteristics in favor of any of the parties (consumer or supplier of natural gas) when accounting for gas (mixtures) was not found. That is, after conducting research using pure hydrogen and mixtures, a critical change in metrological characteristics was not detected. A slight deviation within (1.5 - 2) % can be explained by the design of the household gas meters.

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UNCERTAINTY CALCULATION OF THE PROVER FOR VERIFYING GAS METERS IN THE RANGE OF VOLUME FLOW RATE UP TO 6500 M^3/H

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The prover is intended for verification gas meters in the range of volume flow gas up to 6500 m^3/h with an internal diameter up to 300 mm. The prover allows verifying turbine, rotary, ultrasonic types of gas meters and gas meters with built-in conversion devices.

The prover principle operation is based on the comparison the gas volume reduced to standard conditions, which was calculated by the reference meter, with the volume measured by the experimental meter, which is being verified. A set of turbine, two rotary and drum meters is used as reference meters in the prover.

The calculation extended uncertainty the prover is carried out during its calibration. The calibration procedure is carried out according to the methodology [1]. The method involves step-by-step calibration of pressure, temperature and time measurement channels. A pressure calibrator, a thermostat and a frequency meter are used for calibration. For each channel, the component of total uncertainty according to type A and type B is determined. In addition, the uncertainty component is calculated, which is caused by the effect of volume accumulation due to the change in temperature during the verification. To reduce the influence of this effect, the prover is designed using two parallel lines (D 300 mm and D 200 mm) for the installation of meters, with the possibility of cutting off the additional connected volume.

The calibration of the gas volume measurement channel, i.e. the reference meter, takes place using transfer standards. For transfer standards periodic calibration is carried out on national state primary and secondary gas volume and flow standards. Calibration of each reference meter the prover consists in determining the conversion factor corresponding to 1 m^3. According to the results of all measurements using the method of least squares, the coefficients of the approximation polynomial of the form are determined:

$$\delta_N(q) = A_{-2}q^{-2} + A_{-1}q^{-1} + A_0 + A_1q^1 + A_2q^2, \quad (1)$$

where A_i – where are the coefficients of the approximation polynomial, which are determined based on the calibration results; q – volume flow rate.

The expanded standard uncertainty of the volume measurement U_i is calculated individually for each i-th reference meter, taking into account the components of type A and components of type B, according to the following formula:

$$U_i = 2 \cdot \sqrt{u_{Ai}^2 + u_{Bi}^2}\ . \quad (2)$$

Based on the results of the calculations, the largest value of the expanded uncertainty is selected.

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METROLOGICAL MODEL OF THE REFERENCE INSTALLATION FOR THE REPRODUCTION OF MOIST AIR FLOW BASED ON THE CONCEPT OF UNCERTAINTY

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Today, metrological studies in the field of accounting for gaseous media are relevant. The object of research under these conditions is reference installations that reproduce the volume and flow of gaseous environment. Such reference installations allow to determine the metrological characteristics of measuring equipment, primarily meters and gas flow meters. However, almost all installations that measure natural gas operate on air. Along with this, new methods of gas flow measurement, for example, thermo-anemometric ones, are becoming more and more widely used [1]. These tools are quite simple in terms of design, but the influence of moisture in the working environment is unexplored for their functioning. Theoretical aspects of the influence of moisture on the operation of thermoanemometers are outlined in [2]. For practical confirmation, development and metrological studies of relevant reference installations are required.

The purpose of the work is to develop a metrological model of a reference installation for reproduction of air flows of different humidity and its metrological analysis.

With the participation of the authors, a schematic diagram of the installation was developed, that provides for the generation of an air flows range with a different degree of humidity. The generation of moisture is carried out using an ultrasonic generator during the passage of air flow through the vaporous part of the gas environment in a container with water. Measuring the change in the mass of water in the container will characterize the degree of moisture saturation of the air working environment. At the same time, the placement of any flow meter or counter in the output line of such an installation will allow investigating its error under various operating conditions.

The algorithm of the installation operation, taking into account the known physical patterns of changes in the density and partial pressure of the water vapor of the gas mixture, involves the implementation of such an algorithm:

$$q_m = \frac{V}{\tau}\left(283{,}73\rho_S \frac{P - \varphi P_{W\max}}{TK} + \varphi\rho_{W\max}\right) + \frac{m}{\tau}, \tag{1}$$

where q_m – mass flow of moist air; V – volume of air measured by the reference meter during time τ; φ, P, T – relative humidity, pressure and temperature of air; $P_{W\max}$, $\rho_{W\max}$ – partial pressure and density of water vapor in a saturated state; m – mass of water evaporated over time τ; K – coefficient of compressibility of moist air; ρ_S – air density under standard conditions.

The error δ of the investigated flowmeter can be experimentally calculated using the formula:

$$\delta = (q - q_m)\cdot 100/q_m,\% \tag{2}$$

where q – flow, which is measured by the studied flow meter.

The metrological model based on the uncertainty theory contains standard uncertainties of type A and B, which in their combination will form the total and extended uncertainty of the installation.

Uncertainties of type A are determined by parameters that are subject to experimental investigation during metrological studies. This is the volume of air measured by the reference meter, the duration of reproduction of the control volume, the mass of generated water vapor during the period of reproduction of the volume V, the relative humidity of the environment air.

Uncertainties of type B are formed by the standard uncertainties of the used measuring equipment, the uncertainty of the compressibility coefficient, which is determined by calculation, as well as reference data related to the determination of the partial pressure of water vapor and its density in the state of saturation, the density of air under standard conditions.

Based on the results of theoretical studies, algorithms were developed for calculating the standard uncertainties specified above.

The expanded uncertainty during the operation of the installation in the reproduction mode of consumption $U_p(q)$ is calculated according to the formula:

$$U_P(V) = k_0 \sqrt{\frac{\sum_{k=1}^{N} U_{Bk}^2}{3} + \sum_{l=1}^{M} U_{Al}^2}\ , \qquad (3)$$

where U_{Bk} – uncertainty of type B k-th components that form the standard uncertainty of the installation; U_{Al} – type A uncertainties caused by the reproducibility of the results of experimental determination of the structural and operating l-th parameters of the installation; k_0 – the coverage factor that forms the numerical value of the expanded uncertainty for the corresponding chosen confidence probability; N – the number of k-th type B uncertainty components; M – the number of l-th components of type A uncertainty.

The developed model concerns the mass measurement of wet gas and allows to evaluate the influence of the operating conditions of the installation on the indications of mass flow measuring equipment of various principles of operation, for example, thermo-anemometric, ultrasonic. According to the results of numerical simulation, the extended uncertainty of the installation was established to be within ±(0.6-0.8) %, which justifies the possibility of its use as a working standard.

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MODERNIZATION OF THE SECONDARY STANDARD OF THE ELECTRIC POWER UNIT AT INDUSTRIAL FREQUENCY

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Recently, in many countries, due to the energy resources cost increase, including electricity, state programs of mass transition to clean sources of electricity and energy consumption reduction have been developed. This, in turn, leads to a significant increase of the requirements to the accuracy of electrical energy metering devices. The presence on the market of a large number of standard electric power and electric energy meters used for debugging, testing, calibration and verification of industrial and household meters (MTE PTS 3.3, Applied Precision RS series, MTE SWS 1.3, etc. [1-

3]) implies the use of appropriate standard base that has the necessary accuracy, high productivity and a modern level of automation to ensure their calibration.

At the enterprises producing electric power and electric energy meters during production output control in the metrological and calibration laboratories the test and calibration installations are used. For calibrating standard electric power and electric energy meters, which are part of these installations, the SE "Ukrmetrteststandart" operates the Secondary standard of the electric power unit at industrial frequency VETU 08-08-01-08. However, VETU 08-08-01-08 due to long-term operation has almost exhausted its resource and is morally obsolete, which is evidenced by the low level of automation and numerous failures of the constituent parts. That is why, all electricity meters of accuracy classes 0.1 and 0.05 (more than 110 units annually) are calibrated on the National standard of units of electric power and power factor DETU 08-08-02, which can lead to a reduction of its resource and decrease in reliability.

To solve the mentioned problems, the Secondary standard of the electric power unit at industrial frequency VETU 08-08-01-08 needs modernization to restore its resource, increase the level of automation and expand the dynamic range [4]. Based on the results of the analysis of ways to modernize VETU 08-08-01-08, a number of requirements for standard equipment, which should be included in the improved standard, were defined:

- high precision and power of three voltage sources and three current sources – one for each phase in order to calibrate the entire range of three-phase electric power and electric energy meters in the full range of values;
- constructive and program compatibility of the precision three-phase standard electricity meter with standard voltage and current sources;
- the meter must create a single standard hardware and software complex with voltage and current sources;
- the equipment of the standard should allow the calibration of several meters at the same time;
- the standard must support a high-performance automated mode with automatic documentation of calibration results.

To implement the specified requirements, it is proposed to include to the standard a three-phase power supply PS3 [5] for calibrating standard electricity meters manufactured by MeterTest (Poland), in a set with a precision three-phase standard electricity meter RD-33 [6] manufactured by Radian Research (USA).

It should be noted that the PS3 three-phase power supply includes high-precision and high-power integrated voltage sources VIS-400 [8] and current sources CIS-600 [7] (3 pcs., 1 for each phase), as well as a control unit ACU-3000.

Due to the compatible software, the three-phase reference standard Radian Research RD-33 will create with the three-phase power supply MeterTest PS3 a single standard software-hardware complex that will provide calibration and testing of electric power and electric energy meters of accuracy classes 0.1 and 0.05 and worse in the full range of values in high-performance automated mode.

In turn, the inclusion to the standard of a stationary measuring test system ASTeL will allow simultaneous calibration of several meters.

In the case of modernization of the standard, the expanded uncertainty of measurements during the calibration of standard power meters will improve from $U = 0.02\,\%$ ($k = 2$, $P = 0.95$) to $0.005\,\%$, which in terms of accuracy measures to the best world analogues.

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METROLOGICAL APPROACH FOR BEARING FAULT DIAGNOSIS

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The equipment is faced with such factors as high loads, special properties of the working environment, intense fluctuations in rotation speed and significant overloads. Monitoring the condition of equipment is becoming increasingly important for predicting failures due to the size of the equipment and the delivery time of spare parts. In addition, monitoring the condition is related to security issues and resource savings. It is especially important to compile a database of reactions to equipment failures. The use of vibration parameters (vibration displacement, vibration velocity and vibration acceleration) is difficult at low and very high shaft rotation speeds, in the absence of shock loads or at too high a vibration frequency. Effective use of vibration acceleration changes and its derivatives in the analysis of vibration intensity. The order of the derivative can be any real number. If the vibration frequency is not constant, fractional derivatives are used. The intensity of the vibration acceleration change is estimated by the frequency spectrum of the vibration power [1]. When processing signals informing about the level of vibration and balancing, accuracy is very important, in assessing which the ISO 16063 series of standards is used [2]. Without a tachometer, in the absence of conditions for performing repeated multiple measurements and with a rapidly changing speed of rotation of the drive shaft, the diagnostic method described in [3] is known.

The dynamic model of the electric drive was studied in the torque control mode. Drive composition: Three-phase asynchronous motor C71B-2 with cage rotor, a rotary optical encoder with IR-LED, precision ball bearings, grooved ball bearing 6004-2ZR, belt drive with eccentric belt pulley with a pretension V-belt. Before the experiment, the belt was pre-tensioned, thereby maintaining the speed of rotation of the shaft.

In the experiment, a vibration stand with the following characteristics was used: non-linearity ±1%; measuring range ±490 m/s^2 or ±50 g; broadband resolution 3434 $\mu m/s^2$. Small transverse and angular vibrations of the vibration stand table do not significantly affect the measurement results. The deviation of the acceleration amplitude during the measurement process is not more than 0.05% of the displayed value. The test unit's own electronic noise is below the maximum value of the output signal. The Fluke 45 voltmeter was used as a device for measuring the root mean square (RMS) value of the accelerometer output signal. The frequency range and measurement uncertainty allow you to accurately evaluate the results of comparing different bearing fault signature extraction.

Under these conditions, at the first stage, we establish the ratio between the values of frequencies occurring due to damage in the reference bearing depending on the speed, taking into account the measurement uncertainties. At the second stage, we use this information to establish the ratio necessary to obtain the result of assessing the condition of a bearing with an unknown nature of damage based on the readings of the measurement system. As a reference, we use a bearing with a known nature of damage. According to the calculations of the metrological characteristics of the measurement system, the error in transmitting signal information over communication lines is ±1 ms.

Diagnostics of rolling bearings using the proposed method allows us to evaluate the accuracy of the classification of bearing faults. This method is suitable not only for the identification of single faults. The time-frequency method with an accurate data transmission system will also identify multiple bearing failures. The experiments conducted show that increasing the data transfer rate and reducing the interval between pulses in a real situation increase the accuracy of diagnostics.

The effectiveness of the proposed diagnostic program is proved by the example of fault monitoring of both the reference bearing and the bearing with the expected malfunction on the inner ring. For experimental testing of the program using bearings with multiple defects, a modification in print only mode is needed, since large time delays occur in Write/Read File mode.

This method will cover the entire frequency range of vibration diagnostics and identify defects at an early stage, track their appearance in real time. The results obtained have a high degree of reliability of 95% [5]. Thus, the high accuracy of determining time intervals makes it possible to further improve the information capacity of this method.

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TAKING INTO ACCOUNT MEASUREMENT UNCERTAINTIES IN CONFORMITY ASSESSMENT

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According to ISO/IEC 17000:2020 [1] the term “conformity assessment” defined as “demonstration that specified requirements are fulfilled”. The object of conformity assessment may be products, process, service, system, installation, project, data, design, material, claim, person, body or organization, or any combination thereof. Conformity assessment is an integral part of the technical regulation system that ensures that object meet consumer expectations in terms of safety, economy, reliability, compatibility and other characteristics. Conformity conclusion is based on the results of object testing. The task of testing is to obtain quantitative or qualitative assessments of object characteristics.

A testing laboratory that performs quantitative tests and is accredited to comply with the requirements of ISO/IEC 17025:2017 [2] shall evaluate measurement uncertainties.

In this case, it is logical, when deciding on compliance, to take into account the uncertainty of the measurements carried out during the tests. When taking into account uncertainty in conformity assessment, regulatory document [3] distinguish conformity and nonconformity zone as well as uncertainty range.

For the uncertainty range, the OIML G 19:2017 [4] recommends determining the probability of compliance, by the value of which a decision should be made on the conformity of products to the requirements of regulatory documents. Naturally, the probability of compliance depends on the reliability of the estimate of measurement uncertainty. The report deals with the influence of the probability density (pdf), attributed to the measured value on the resulting probability of compliance. As a parameter that determines the type of pdf, its kurtosis is taken. The dependence of the probability of compliance on the value of measurement uncertainty and kurtosis pdf attributed to the measured value is obtained. Examples of the practical application of the proposed criterion are given.

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UNCERTAINTY OF MEASUREMENTS IN THE WORK OF CLINICAL DIAGNOSTIC LABORATORIES

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Laboratory information plays an important determining role in providing diagnosis and therapy, but as with any other clinical information, all limitations in diagnostic tests affect diagnostic and therapeutic decisions. As for the results of laboratory studies, it is possible to assess the reliability of laboratory data using such an indicator as measurement uncertainty.

The need to assess measurement uncertainty is a special requirement of DSTU EN ISO 15189:2015 (clause-5.5.1.4). Knowledge of calculation methods taking into account the specifics of medical laboratories, establishing the maximum permissible uncertainty of measurement, and further use of data on the uncertainty of individual test results in various clinical situations is relevant for specialists of modern medical laboratories [1].

Medical inconsistencies can be classified by several models, such as the clinical pathway (i.e., diagnosis, treatment, prevention, etc.) or the consequences of harm to the patient (i.e., omissions, no harm, or adverse events). Nonconformances in the clinical diagnostic laboratory (CDL) are any defect that occurs in any part of the laboratory cycle, from order testing to reporting, interpretation, and response to results. Although they have traditionally been identified with analytical problems and measurement uncertainty, the literature suggests that the vast majority of them arise from the post-analytical activities of the overall testing process. Data from representative studies also show that pre-analytical inconsistencies are the first cause of variability in laboratory studies [2].

Issues of the quality of laboratory service (reduction of risk for patients, satisfaction with the quality of service, etc.) in modern medicine are now quite relevant for clinical laboratory research. The risk of a decision-maker using a certain strategy (technology) in uncertain conditions is the difference between the gain (result, performance indicator) that would have been obtained if the conditions were known and the gain that he would have received under conditions of uncertainty. So, there are two statements of the problem of choosing a solution, two possible scenarios: with one, we want to get the maximum profit, and with the other - the minimum risk [3]. The most obvious reasons are failures in individual activities related to attention, memory, knowledge, judgment, skill, and motivation. However, they are partly a result of the nature of medical work, such as the complexity of medical knowledge, the uncertainty of clinical prognoses, and the need to make timely decisions about treatment despite limited or uncertain knowledge. Inconsistencies are caused by systemic factors affecting working conditions. Although much attention has been focused on the harmful effects of errors on patients, it should be understood that these cases can be correspondingly unacceptable to physicians, causing shock and feelings of regret, guilt, anger, and fear. In addition, inconsistencies can provide essential learning experiences for physicians; however, difficulties in handling inconsistencies can hinder both learning and efforts to prevent future errors [4]. Obtaining analytically reliable and reproducible laboratory results in modern CDL is possible only if all elements of the research quality assurance system are implemented [5].

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THE ROLE OF MEASUREMENT UNCERTAINTY IN THE ACTIVITIES OF THE LIGHT INDUSTRY TESTING LABORATORY

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The DSTU EN ISO/IEC 17025:2019 [1] standard is identical to the international EN ISO/IEC 17025:2017 [2], which can help testing and calibration laboratories demonstrate their ability to provide reliable results. The testing laboratory of light industry of SE "UKRMETRTESTSTANDART" is responsible for the reliability of the results. One of the proofs of the reliability of test results is interlaboratory comparisons. For the testing laboratory of light industry, this means that it, as a participant or as a provider, participates in the tests. The organization, execution and evaluation of a test on the same or similar samples by two or more laboratories takes place according to predetermined conditions [1]. The obtained results are evaluated and a decision is made. When making a decision, a rule is used that describes how measurement uncertainty is taken into account when determining compliance with a certain requirement [1]. Based on the results of interlaboratory comparisons of results (MPR), a decision is made regarding the competence of the participants.

Proficiency testing through interlaboratory benchmarking is designed to determine the ability of participants (which may be laboratories, regulatory bodies, or individuals) to perform tests and to verify their performance. In the introduction to DSTU EN ISO/IEC 17043:2017 [3], the main tasks of the laboratory qualification check are given: determining the evaluation of the characteristics of the laboratory's functioning; establishing effectiveness and comparison of test or measurement methods; ensuring additional trust of customers in the laboratory; confirmation of the stated uncertainty; training of participating laboratories.

The testing laboratory of light industry of SE "UKRMETRTESTSTANDART" constantly participates in interlaboratory comparisons, as a participant, and also as a provider. Interlaboratory paper tests were organized by the testing laboratory. Thus, in the field of testing paper products, considerable attention should be paid to such components as climatic conditions and sample storage conditions, the number of samples and their handling, and test methods. Samples that were homogeneous, stable, and acceptable for the purposes of the proficiency testing program were submitted to five testing laboratories. Test methods are standardized and specified in the program of interlaboratory comparisons provider. It should be noted that each field of interlaboratory comparisons has its own specifics.

Test data obtained from five laboratories were analyzed in accordance with DSTU ISO 13528:2016 [4]. The score was based on an indicator that is calculated using the imputed value and standard deviation to assess proficiency. The assigned value was determined by calculating the average value of the results of all participants. The index z_i for the result of the qualification check x_i was calculated according to the formula:

$$z_i = (x_i - x_{pt}) / \sigma_{pt} \qquad (1)$$

where x_{pt} is assigned value; σ_{pt} is standard deviation for the proficiency score.

According to the results of the calculation $|z| \leq 2{,}0$, which is acceptable.

Conducting inter-laboratory comparisons confirms the ability of the light industry testing laboratory to obtain reliable results, and the measurement uncertainty assessment ensures the unity of measurements in accordance with the requirements of DSTU ISO/IEC 17025 [1] and other international regulatory documents.

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INFLUENCE OF THE SCINTILLATOR SURFACE EFFECTIVE SPECULARITY ON THE LIGHT COLLECTION COEFFICIENT SIMULATION UNCERTAINTY

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The influence of the effective specularity of a rough scintillator surface on the uncertainty of modeling processes light transfer in scintillators was evaluated. Light collection coefficients were obtained in program DETECT2000 [1, 2] by simulating the passage of light in scintillators. Fractions of light reflected specularly and diffusely from rough surface, modified using a surface model UNIFIED type.

The uncertainty $u_A(\tau)$ [3] of modeling the light collection coefficients τ in NaI(Tl), Ø40×40 mm, and BGO scintillators, Ø40×40 mm, was estimated when changing the given values of the coefficients: effective specularity p, optical transparency k and diffuse reflection k_{ref}. The number of emitted photons N_{emit} varied from 10^3 to 10^5. The results obtained for $N_{emit}=10^5$ photons are shown in Table 1.

Table 1.

Scintillator	k, cm^{-1}	k_{ref}, arb. un.	p, %					
			40		60		80	
			τ	$u_A(\tau)$, %	τ	$u_A(\tau)$, %	τ	$u_A(\tau)$, %
NaI(Tl)	0.005	0.95	0.649	0.124	0.635	0.140	0.599	0.052
		0.9	0.574	0.029	0.568	0.104	0.546	0.061
	0.01	0.95	0.582	0.133	0.571	0.052	0.538	0.137
		0.9	0.527	0.088	0.521	0.106	0.503	0.095
BGO	0.02	0.95	0.443	0.171	0.424	0.074	0.366	0.096
		0.9	0.415	0.129	0.402	0.089	0.366	0.106
	0.2	0.95	0.116	0.321	0.115	0.278	0.114	0.21
		0.9	0.115	0.253	0.115	0.233	0.113	0.446

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ANALYSIS OF THE STATUS AND TRANCEABILITY OF ELECTROMAGNETIC STANDARTDS OF UKRAINE, TAKING INTO ACCOUNT THE 2019 SI REFORM

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In 2019, a new SI (hereinafter SI-2019) came into force, which introduced a number of significant changes, in particular:

1) units of measurement are formulated in an implicit form - through "defining physical constants";

2) four of the seven basic units received fundamentally new definitions.

In particular, the basic unit of electricity is the ampere, which in the previous version of the SI was defined through the magnetic constant μ_0 and mechanical quantities, in the SI-2019 received a new basis - the elementary charge e, equal to 1.602 176 634 × 10^{-19} C exactly [1, 2].

The report discusses the traceability of quantum standards to constants (which seems obvious), discusses the sources of uncertainty in these standards, discusses the issue of "primacy and reference" of the thermal comparison method, on which all standards of the parameters of the intensity of electrical signals on alternating current, high and ultra-high frequencies.

It also analyzes the traceability to the defining constants of the standards of the parameters of the shape and spectrum of radio signals – the coefficients of amplitude modulation, harmonics, intermodulation, frequency deviation, the relationship of which with the constants is far from obvious.

The question of the interpretation of the traceability of the standard on the effect of nuclear magnetic resonance to a constant that is not among the determining ones is considered.

The question of the possibility of gradual decentralization of measurements due to traceability to constants is discussed, especially in hierarchical schemes headed by quantum standards [3].

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UNCERTAINTY EVALUATION OF MONITORING THE HUMAN SKIN CONDITION BY THE OPTICAL METHOD

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At present, the most acceptable method of comprehensive control of the condition of human skin is optical, which is absolutely non-invasive and does not affect the functional parameters of the skin. It is based on the measurement of the intensity of radiation reflected from the surface of the skin, based on information about the intensity of incident radiation, the total coefficient of diffuse reflection is obtained, which is a diagnostic criterion for a number of surface or systemic pathologies.

A control system has been developed, which consists of the following main components: a radiation source, an optical system, an object of measurement control (biotissue), an optical primary transducer, temperature sensors, fiber-optic waveguides, photodiodes, amplifiers, a microcontroller with a built-in ADC, and a power supply unit. An integrating sphere with a hole, which is installed on the examined surface of the skin, was used as the primary transducer. A mirror screen is installed inside the sphere to account the primary radiation [1].

The methodical uncertainty of the developed control system was evaluated based on the analysis of the components, which were determined by type B in percentages. The main component of uncertainty arises as a result of the physiological characteristics of the biotissue of various recipients and the instability of radiation transfer in the integrating sphere. The estimated value of this uncertainty is u_1=1.5%.

The estimated value of the uncertainty of the choice of the characteristic wavelength, at which the measurements were carried out, is no more than u_2=0.4%.

The methodical component of uncertainty should also include the uncertainty caused by edge effects in the working opening of the sphere, scattering effects of the radiation reflected from the mirror inside the sphere. It was experimentally established that this uncertainty is u_3=0.8%.

The mathematical model of making a diagnostic decision is based on the theory of fuzzy sets and is presented in the form of a tree of fuzzy logical conclusion. Therefore, the estimate of this uncertainty component is taken to be equal to u_4=1.4%.

Thus, the total methodological uncertainty is:

$$u_{method} = \sqrt{u_1^2 + u_2^2 + u_3^2 + u_4^2} = \sqrt{1,5^2 + 0,4^2 + 0,8^2 + 1,4^2} = 2,24\%$$

This metrological analysis testifies to the possibility of using this system to monitor the condition of the skin with acceptable methodical accuracy.

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INFLUENCE OF MEASUREMENT UNCERTAINTY ON INDICATORS OF GEOMETRIC PARAMETERS CONTROL

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The problem of rational choice of measuring means for monitoring the geometrical parameters of engineering products remains relevant. The main characteristic by which the assessment of the suitability of the device is carried out is its accuracy. The more accurately the measurement tool is chosen, the more reliable the control is, that is, the conclusion regarding the compliance of the product with the requirements of the drawing. But with an increase in the accuracy of the device, its cost increases significantly, which leads to an increase in the price of the company's products.

Analysis of literary sources and regulatory documentation showed that modern widespread methods and means of one-factor control of geometric parameters of engineering products give good results to identify cases of manufacturing parts whose dimensions do not meet the requirements of the drawing. But such results relate only to one-factor control.

Therefore, the task was set to analyze the influence of measurement uncertainty on the indicators of two-factor control of geometric parameters.

The research methodology included simulation modeling of the manufacture of a batch (sample) of shafts of a gear mechanism. Requirements for the geometric accuracy of the shaft neck met international standards. At the same time, the method of statistical modeling (Monte Carlo) reproduced an array of deviations from the nominal value of two geometric parameters. The following assumptions were accepted:

- the separation of deviations of the geometric parameter is uniform, the limits of the scattering interval from the lower to the upper deviation are selected with an increasing correction factor of 1.0027, which corresponds to the generally accepted level of technology accuracy in mechanical engineering;
- the basic array of random deviations of the geometric parameter of the product is modeled in the assumption of zero measurement error;

- arrays of random errors are generated with a uniform distribution when the interval limits consider the passport data of the device;
- the values of uncertainty parameters are calculated according to formulas known from regulatory documents.

The developed algorithmic model of numerical computer experiments involves in its composition modeling blocks of measuring and control procedures for two control parameters. That is, the combination of geometric parameters reflects a complex for two-factor passive tolerance control of the shaft neck.

Control procedures are modeled using logical formulas. The software implementation of the algorithmic model was carried out in Microsoft Excel. The sample size is 1000 parts, which is enough for acceptable accuracy of the research results.

The simulation was performed on the example of a specific sample of the gearbox shaft.

EXTENSION OF THE GUM-SUPPLEMENT 2 METHOD OF ESTIMATION UNCERTAINTIES OF INDIRECT MULTIVARIABLE MEASUREMENTS FOR THE PROCESSING FUNCTION WITH UNCERTAINTIES AND CORRELATIONS

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In this work discussed is the proposal for extending the method of estimation uncertainties of indirect multivariable measurement systems. The method given in the Supplement 2 of guide GUM is with the ideal multivariable processing function with negligible uncertainties, i.e.:

$$\boldsymbol{Y}=\boldsymbol{F}(\boldsymbol{X}). \qquad (1)$$

We extend this method for any type of measurement systems: hardware analogue and digital, and virtual, when the processing function of input multi-measurand $\boldsymbol{X}$ to the output multi-measurand $\boldsymbol{Y}$ is not the ideal formula (1), i.e.:

$$\boldsymbol{Y}=\boldsymbol{F_P}(\boldsymbol{P},\boldsymbol{X}) \qquad (2)$$

and all $\boldsymbol{X}$ and P of the function $\boldsymbol{F_P}(\cdot)$ has uncertainties and in general case – all possible correlations.

Even if the basic relation (2) is nonlinear, in the most cases, errors and uncertainties of X elements and $\boldsymbol{P}$ parameters are small, and linear relations (3)-(5) of covariance matrices describe propagation of absolute and relative variances:

$$\boldsymbol{U_Y} = \boldsymbol{U_Y}(\boldsymbol{X},\boldsymbol{P}) = \boldsymbol{S_{X,P}}\,\boldsymbol{U_{X,P}} = [\boldsymbol{S},\boldsymbol{S_p}]\begin{bmatrix}\boldsymbol{U_X} & \boldsymbol{U}\\ \boldsymbol{U^T} & \boldsymbol{U_p}\end{bmatrix}\begin{bmatrix}\boldsymbol{S^T}\\ \boldsymbol{S_P^T}\end{bmatrix} \qquad (3)$$

or

$$\boldsymbol{U_Y} = \boldsymbol{U_{YX}} + \boldsymbol{U_{YF}} = \boldsymbol{S_X U_X S_X^T} + \boldsymbol{U_{YF}}\,, \qquad (3a)$$

where

$$\boldsymbol{U_{YF}} = \boldsymbol{S_p U_p S_P^T} + \boldsymbol{S_X U S_P^T} + (\boldsymbol{S_X U S_P^T})^{\boldsymbol{T}} \equiv \boldsymbol{U_{YP}} + \boldsymbol{V} + \boldsymbol{V^T}; \quad \boldsymbol{V} \equiv \boldsymbol{S U S_P^T} \neq \boldsymbol{0}\,; \qquad (3b)$$

$$\boldsymbol{U_Y} = \begin{bmatrix} u_{y1}^2 & \cdots & \rho_{y1m}u_{y1}u_{ym} \\ \cdots & \cdots & \cdots \\ \rho_{y1m}u_{ym}u_{y1} & \cdots & u_{ym}^2 \end{bmatrix}, \tag{3c}$$

$$\boldsymbol{U_X} = \begin{bmatrix} u_{x1}^2 & \cdots & \rho_{x1n}u_{x1}u_{xn} \\ \cdots & \cdots & \cdots \\ \rho_{x1n}u_{xn}u_{x1} & \cdots & u_{xn}^2 \end{bmatrix}, \tag{3d}$$

$$\boldsymbol{U_p} = \begin{bmatrix} u_{p1}^2 & \cdots & \rho_{p1k}u_{p1}u_{pk} \\ \cdots & \cdots & \cdots \\ \rho_{p1k}u_{pk}u_{p1} & \cdots & u_{pk}^2 \end{bmatrix}, \tag{3e}$$

$$\boldsymbol{U} = \begin{bmatrix} \rho_{x1p1}u_{x1}u_{p1} & \cdots & \rho_{x1pk}u_{x1}u_{pk} \\ \cdots & \cdots & \cdots \\ \rho_{xnp1}u_{xn}u_{p1} & \cdots & \rho_{xnpk}u_{xn}u_{pk} \end{bmatrix}. \tag{3f}$$

Propagation of variances for $\boldsymbol{V} = 0$:
absolute uncertainties

$$\boldsymbol{U_Y = S\,U_X\,S^T + S_P U_P S_P^T}; \tag{4a}$$

relative uncertainties

$$\boldsymbol{U_{\delta(Y-Y_0)} = S_\delta U_{\delta(X-X_0)} S_\delta^T + S_{\delta P} U_{\delta P} S_{\delta P}^T}\,. \tag{4b}$$

Covariance matrices of type A and type B uncertainty components

$$\boldsymbol{U_Y = U_{YA} + U_{YB} = \left(SU_{XA}S^T + S_P U_{PA} S_P^T\right) + \left(SU_{XB}S^T + S_P U_{PB} S_P^T\right)}\,. \tag{5}$$

As the example, the indirect observation of the voltage U_2 and current I_2 of an inaccessible branch based on direct measurements of voltage U_1 and current I_1 on other pair of network terminals of a tested object. If this network is linear and passive then for the description, then one of structures of the equivalent circuit of the two-part of is used.

Formulas and calculations of the numerical example will be given with the discussion of different cases.

This presented method can be the basis for a new version of the guide GUM Supplement 2 or should be included in the new version of guide GUM 2. It will also allow the assessment of the accuracy of any multivariable instrumental measurement systems through uncertainties [1-3]. Partial methods of different multivariable measurements are discussed in few other authors publications or will be presented in future.

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COMPARISON OF ALTERNATIVE MEASUREMENT UNCERTAINTY MATRICES FOR PARAMETERS OF THE STRAIGHT-LINE CALIBRATION FUNCTION

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The main objective of this paper is to discuss various aspects and problems of straight-line calibration with errors in both variables. We present an alternative approach for parameter estimation and uncertainty matrix determination and explain the explicit relationship between the approximate uncertainty matrices based on ISO Technical Specification 28037:2010 [1] and the LPU based on JCGM 100:2008 (GUM) and its supplements [2-4].

We consider the concept of a linear comparison calibration model as presented in Technical Specification ISO 28037:2010 [1] and an iterative algorithm to obtain weighted total least squares (WTLS) estimates of the model parameters together with an uncertainty matrix for the parameters, which we refer to as the ISO uncertainty matrix.

In this paper we consider an alternative, albeit equivalent, approach in which the estimates of the model parameters together with their covariance matrix are determined under the assumption that the regression model of the errors in the variables is properly (iteratively) linearized and BLUE (the best linear unbiased estimates) of the model parameters together with their covariance matrix.

Finally, we compare the uncertainty matrix ISO with the LPU uncertainty matrix derived from the implicit measurement model according to [2-4] and establish a unique relationship between them.

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METROLOGICAL CONFORMITY OF OBGECTS CLASSIFICATION WITH ORDINAL AND NOMINAL PROPERTIES OBSERVATIONS

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Modern methods of data processing include information presented not only in numerical form, but, to a large extent, presented using categorized variables, which according to their individual properties were assigned to a certain group or category in ordinal or nominal scales.

To assess the reliability of the classification, it is necessary to have physical standards that would reproduce the categories of properties in accordance with their definition. Metrological conformity of classification results in the presence of such standards can be carried out by means of calibration or verification. Calibration, in most cases, is used as a training procedure for operators and, as for technical systems, is carried out before classification, which allows a priori to obtain classification reliability indicators that take into account the uncertainty of standards. Verification is used as a check of the obtained classification results. At the same time, it is necessary to combine the classification reliability indicators obtained during verification with the uncertainty characteristics of the standards.

In the paper, it is considered the verification of the classification by observing the manifestations of the nominal property. The result of the verification is the correspondence of the categories of nominal properties, to which their manifestations are classified according to observation, to the categories established according to the reference procedure.

To obtain classification reliability indicators, a stochastic classification matrix is formed, the components of which are the conditional probabilities of assigning manifestations of the nominal property to a certain category, while according to the reference procedure, these manifestations were assigned to the same or another category. The diagonals of the matrix correspond to the probability of correctly assigning manifestations of the nominal property to a certain category.

In order to establish metrological consistency, it is necessary to draw up a matrix of correspondence of the categories established according to the reference procedure to the true categories according to their definition. For an ideal reference procedure, full compliance is established, which is represented by units on the diagonal of the correspondence matrix.

If the reference procedure is not ideal, to take into account the uncertainty of the classification results according to the reference procedure, a matrix of the reference relation is created, the components of which are the conditional probabilities of correspondence of the categories established according to the reference procedure to the true categories according to their definition.

A method is proposed that allows you to take into account the non-ideality of the reference procedure using the combination of the ordinal variances of the verification matrices and the reference relation by rows with the subsequent assessment of conditional probabilities characterizing the reliability of the classification.

UNDERGROUND SODIUM CHLORIDE BRINES

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We have proposed previously the use of sonoluminescent spectroscopy for the determination of the main substance in sodium chloride underground brines (depth of occurrence is 250-350 m). Moreover, with an increase of the frequency of initiating sonoluminescence ultrasound, the metrological characteristics of the analysis results improved. At the same time, the use of initiating sonoluminescence ultrasound with a frequency of up to 5 MHz, S_r = 0.053-0.06, was studied for the obtained results of determination the basic substance in underground brines [1].

The purpose of this work is to study the use of sonoluminescence spectroscopy for the determination of the main substance in underground brines (300-450 g/l) using high-frequency ultrasound with a frequency of ≥ 5 MHz to initiate sonoluminescence.

The methodic of experiment was as follows. The sonoluminescent chamber was put into the well and 1000 ml of brine was pumped into a chamber with a capacity of 1200 ml, saturated with argon for 5 min, cooled to a certain temperature, cesium chloride was injected up to a concentration of approximately 30 g/l and exposed to ultrasound (US) with a frequency of 5-15 MHz, intensity from 17 to 20 W/cm^2. The sonoluminescent spectrometer was set up to the analytical sodium line and its content was determined. During the experiments, the gas supply was not stopped in order to avoid degassing of the solution [1].

With an increase in the frequency of ultrasound used to initiate sonoluminescence, the intensity of sonoluminescence changed (Table 1). The intensity of sodium sonoluminescence decreased with the transition of the US frequency from 5 MHz to 15 MHz, while a significant decrease in the intensity of sonoluminescence was observed when moving from 12 to 15 MHz (Table 1).

Table 1.

Determined component, concentration of solution (g/l)		Sonoluminescence intensity (relative units) at ultrasound frequency					
		5 MHz	8 MHz	10MHz	12 MHz	13 MHz	15 MHz
NaCl	400	12,2	10,0	9,5	8,1	0,9	0,4
	λ, nm	590,0	590,3	590,4	590,4	590,4	590,5

The averaged results of six experiments are given. The intensity of ultrasound is 20 W/cm2. Temperature of the solution is (20.0±0.5) °C.

As with the use of low US frequencies, the intensity of sodium sonoluminescence proportionally increased with an increase in the concentration of their salts (Table 1), which is explained by the same type of effect of high and low US frequencies on the intensity of sonoluminescence [1].

Thus, the possibility of using of high-frequency ultrasound in sonoluminescence spectroscopy to determine the main substance of underground sodium chloride brines has been shown. The methodic of analysis has been developed. The correctness of the methodic was confirmed by the “injected-found out” method, as well as by the analysis of the same samples by alternative methods: sonoluminescence spectroscopy using low-frequency ultrasound to initiate sonoluminescence, as well as gravimetric analysis and atomic absorption spectrometry (Table 2).

Table 2

The results of determination of the main substance in solutions of heat coolants and brines (n=6; P=0.95)

Sample	Injected, g/l	Found out, g/l							
		By sonoluminescent method				By gravimetric method [1]		By atomic absorption method [1]	
		US 22,0 кHz		US12,0 MHz					
		$\overline{C}$	S_r	$\overline{C}$	S_r	$\overline{C}$	S_r	$\overline{C}$	S_r
Brine	–	325	0,053	329	0,012	321	0,010	312	0,121
	50	369	0,060	375	0,012	360	0,012	329	0,11

Conclusions

The methodic for sodium determination in underground sodium chloride brines has been developed. It is shown that the value of the relative standard deviation of the results of sodium determination decreases with an increase in the frequency of ultrasound, which initiates sonoluminescence, up to an ultrasound frequency of 10-12 MHz at an intensity of 20 W/cm^2.

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ATOMIC EMISSION DETERMINATION OF CESIUM IN BRINES AND COOKING SALT USING CONCERTATION CO-PRECIPITATION

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Direct determination of cesium in brines and coooking salt using even such highly sensitive analysis method as flame atomic emission spectrometry is not possible due to its low content in the analyzed objects [1]. In this regard, preconcentration is used, for which it is most expedient to use coprecipitation on cobalt and copper (II) hexacyanoferrate, as well as on ammonium silica molybdate.

Cesium in cooking salt solutions and in brines is in a bound form, mainly with humic and fulvic acids, which makes it difficult to quantitatively concentrate it by coprecipitation [1]. For their destruction, we proposed to use the impact of ultrasound with a frequency of 18...44 kHz and an intensity of more than 7 W/cm^2 for more than 3 minutes. As follows from the experimental data (Table 1), ultrasonic treatment of salt solutions in optimal parameters ensures the destruction of up to 98% of organic cesium compounds.

Table 1

An influence of ultrasonic parameters on the degree of destruction of organic cesium compounds

US intensity, W/cm^2	Destruction degree of organic compounds of Cs, %	US frequency, MHz	Destruction degree of organic compounds of Cs, %	Time of US influence, min	Destruction degree of organic compounds of Cs, %,
4	67	15	95	0,5	84
5	85	18	98	1	93
6	94	20	98	2	96
7	98	44	98	3	98
8	98	45	96	4	98
9	98	47	94	5	98

We found out that under optimal conditions, the degree of coprecipitation when using bivalent copper hexacyanoferrate as a collector reaches 92%, cobalt hexacyanoferrate - 91% and ammonium silicon molybdate - 90% [1]. An increase in the amount of the collector and the contact time of the precipitate with the solution did not lead to positive results, and the use of ultrasound (US) to intensify the concentration by coprecipitation made it possible to bring the degree of cesium coprecipitation up to 98–99% (Table 2).

Table 2

An influence of ultrasonic parameters on the degree of coprecipitation of cesium

US intensity, W/cm2	Coprecipitation degree of organic compounds of Cs, %	US frequency, MHz	Destruction degree of organic compounds of Cs, %	Time of US influence, min	Coprecipitation degree of organic compounds of Cs, %,
0,5	36	15	80	10	76
1	88	18	92	15	80
2	98	20	99	20	83
4	98	44	99	25	90
5	99	45	90	30	92
6	98	47	87	35	98

The optimal parameters of ultrasound are: the frequency of 20-44 kHz, the intensity – more than 2 W/cm2, the exposure time - more than 30 s.

The cesium content was determined by the atomic emission method in an acetylene-air flame at a wavelength of 852 nm on an AAS-3 spectrometer (Germany). Thus, it has been shown that the use of ultrasound in sample preparation in the determination of cesium for the destruction of its organic compounds and the intensification of preconcentration by coprecipitation makes it possible to increase the expressiveness and improve the metrological characteristics of the results of analysis (Table 3).

Table 3

Results of the determination of cesium in cooking salt

Object of analysis	Injected $Cs \cdot 10^{-7}\%$	Found out $Cs \cdot 10^{-7}$, % / Sr ($p = 0,95$, $n = 6$)		
		*	**	***
PO "Artyomsol" R. one	0	–	–	–
	2,00	2,07 /0,03	1,76 /0,09	1,86 /0,06
Genic Salt factory	0	4,26 /0,03	8,97 /0,08	9,26 /0,05
	2,00	6,11 /0,04	10,45/0,09	11,19/0,06
Heroic Salt factory	0	4,88 /0,04	8,04 /0,09	8,76 /0,06
	2,00	7,01 /0,03	9,65 /0,08	11,01/0,07

Notes. The averaged results of six experiments are given.

*No destruction of organic compounds.

** With the destruction of organic compounds by boiling with ammonium persulfate in an acidic medium.

*** With the destruction of organic compounds by US exposure

EXAMPLES OF THE EXPANDED UNCERTAINTY EVALUATION BASED ON THE KURTOSIS METHOD

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A disadvantage of the Guide to the Expression of Uncertainty in Measurement (GUM) [1] is the independence of the expanded uncertainty from the probability density function (PDF) of the input quantities [2]. In documents EA-4/02 M:2022 [3] and M3003:2012 [4], it is proposed that the coverage factor should be selected based on an analysis of the budget of uncertainty obtained from the “most highly studied and most highly controlled statistical measurements” [1]. An algorithm for use in selecting the coverage factor, generalizing the approaches proposed in [3-4], is presented in [5]. It should be noted that the implementation of this algorithm has a low accuracy in determining the coverage factor and is poorly automated. We have proposed an approach based on the kurtosis method (KM), which allows us to automate the process of calculating the coverage factor [6]. The estimations of the expanded uncertainty will be close to the estimations obtained by the Monte-Carlo method (MCM) [7].

The report considers the use of KM [5, 7-8] for expanded uncertainty evaluation for the examples given in [3], Supplement 2. These examples were developed for situations in which one or two abnormal contributions to the measurement uncertainty are dominant.

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COMPONENT UNCERTAINTIES EVALUATION AT MANUFACTURE OF CALIBRATION STANDARD – CADMIUM SOLUTION IN HNO_3

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This paper discusses the preparation of a calibration solution for atomic absorption spectrometry based on the corresponding high-purity metal. A solution of 1000 mg of cadmium Cd in 1 liter of nitric acid HNO_3 is considered.

Almost all modern analytical measurements (in this case, atomic absorption spectrometry) are relative. Therefore, they require the use of a reference standard to ensure the traceability of the measuring instrument.

A calibration solution with a mass concentration of approximately 1000 mg/l is prepared from high-purity cadmium metal.

The measurement model:

$$C_{Cd} = 1000\frac{mP}{V},$$

where C_{Cd} is mass concentration of cadmium in solution, mg/l, 1000 is conversion factor from ml to l; m is high metal mass, mg; P is degree of purity of the metal, expressed as the mass fraction of cadmium; V is volume of calibration solution, ml.

The procedure for manufacturing a calibration solution includes 4 stages:

- Step 1: description,
- Step 2: identification and analysis of sources of uncertainty,
- Step 3: quantification of the components of uncertainty,
- Step 4: calculate the total standard uncertainty.

Sources of uncertainty are identified using the Ishikawa diagram. 12 sources have been identified. The analysis allowed us to identify 3 main ones:

- the degree of purity of the metal (Cd), indicated in the manufacturer's certificate;
- the mass of cadmium (was determined by weighing in containers);
- the volume of the solution in the measuring flask.

The latter is affected by three other main sources of uncertainty:

- uncertainty of the specified internal volume of the bulb;
- uncertainty of deviation when filling the bulb to the mark;
- the difference between the temperature of the bulb and the solution and the temperature at which the flask was calibrated.

The standard uncertainty from the influence of temperature is calculated from the assumption of a rectangular distribution.

The contribution related to the volume of the bulb is the largest; the contribution of the weighing procedure is of close importance. The uncertainty associated with the degree of purity of cadmium does not actually affect the overall uncertainty.

METHOD FOR CALIBRATION THE ATTITUDE OF THE OPTO-ELECTRONIC STATIONS DESIGNATED FOR THE TRAJECTORY MEASUREMENTS

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In this report there are considered the modern Opto-Electronic Stations (OES), which are used as measuring instruments for high-precision determination of the aerial vehicles (AV) trajectories for various purposes. Based on the results of measurements of the range and/or angles (azimuth and elevation) of one or more jointly functioning OES, the parameters of the AV trajectories in given rectangular or other Coordinate Systems (CS) are determined.

Usually, OES’s angle measurements refer to a rectangular instrumental CS (ICS), which is formed by the beginning of the CS (at a known focusing point of the received optical or infra-red signals) and the OES’s platform, which forms the horizontal and vertical planes of the device. However, to determine the parameters of the AV trajectories in a given external CS (for example, in the Earth-Centered Earth-Fixed Frame (ECEFF)) it is necessary to «relate» the ICS with the Topocentric Local Frame

(TLF), since the relationships between the coordinates in the ECEFF and in the TLF are known [1]. To recalculate the coordinates, it is necessary to know the coordinates (latitude, longitude and height) of the TLF beginning in the ECEFF and the geodetic azimuth of the TLF (direction of the OX axis) relative to the direction to the North [1].

The coordinates of the ICS beginning and the TLF beginning of the OES (usually they are superposed) are determined in the ECEFF using GNSS-technologies for precise positioning with errors of ~1–2 cm (RMS). Such errors can be neglected, since their contribution to the total errors of the OES angular measurements does not exceed ~1 angular second at distances of the AV from the OES up to ~5–20 km with the requirements of maintaining a level of 5–10 angular seconds (RMS). However, providing «leveling» of the ICS (for ICS-TLF-ECEFF recalculations) with the same level of errors (several angular seconds) is a very difficult task, which can be solved using expensive mechanical or laser gyroscopes. At the same time, it is also necessary to solve the additional problem of azimuthal referencing of the TLF/ICS of the OES with respect to the plane of the local meridian with the same accuracy. The solution to this problem is achieved using two geodetic-class GNSS-receivers and centimeter accuracy grade differential positioning technology. One of the receivers is located at the OES, the second – at a distance of 0.5–1 km. An accurate estimate of the azimuth of the direction that relates the phase centers of the antennas of two GNSS receivers, relative to the North direction, and a comparison of this estimate with the OES measurements of the azimuth of the remote GNSS-receiver, solve this problem.

The described approach to estimating the OES attitude parameters is expensive and rather difficult to implement. Another method proposed by the authors can serve as an alternative. Its essence is as follows.

1) At the initial stage, preliminary «leveling» and azimuthal referencing of the platform (ICS) of the OES are carried out using simple and inexpensive means and methods, which, however, do not provide sufficient accuracy of the angular referencing of the OES.

2) The implementation of high-precision calibration (refinement) of the angular orientation of the ICS in the TLF involves the use of two dual-frequency GNSS-receivers of the geodetic class. One of the receivers, as before, is installed on the OES and, using differential GNSS-positioning technology, makes it possible to determine the coordinates of the beginning of the ICS/TLF of the OES (in the ECEFF) with centimeter accuracy. The second GNSS-receiver is installed on board the unmanned aerial vehicle (UAV), which, during the calibration, circles the OES in such a way that the changes in the angles of the UAV relative to the OES lie within 0–360 degrees (azimuths) and 5–85 degrees (elevations) at the distances of the UAV from the OES ~3 -5 km. At the same time, the OES performs angular measurements of the position of a moving UAV in the ICS.

3) After the completion of all measurements, as a result of kinematic high-precision differential GNSS-positioning, the estimates of the trajectory parameters (coordinates) of the UAV geometric center are formed (with errors of ~3–5 cm (RMS)). Based on the results of determining these high-precision coordinates, the reference values of azimuths and elevations of the UAV are calculated as a function of

time in the TLF of the OES with errors of ~2–5 angle seconds (RMS). Significant redundancy of observations and their smoothing make it possible to reduce the errors of angle estimates by at least 2–3 times.

4) The differences between time-synchronized smoothed OES observations of azimuths and elevations of the UAV (in the ICS of the OES) and their high-precision calculated values (in the TLF of the OES) can be used as either corrections to the results of the OES angular measurements in the course of standard test range measurements, or as initial data for determining the parameters of mutual angular orientation (three Euler's angles) of ICS and TLF.

In the first case, it is necessary to perform spatial interpolation of corrections as functions of azimuths and elevations. In the second case, the estimates of the angular orientation parameters of the OES platform in the TLF should be used to calculate the corrections for measurements of the OES performed in the ICS and the subsequent determination of the azimuths and elevations of the observed AVs in the TLFof the OES.

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