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Traceability ensuring by organizing the Metrological Measurements Network

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ABSTRACT
A new scheme for the traceability ensuring, called the Metrological Measurements Network, was proposed. It is not an alternative to the existing scheme but is only another form of implementation of the traceability scheme. It is about the main principle of construction of the Metrological Measurements Network and its advantages over the existing scheme. The main reason is that each laboratory calibrates its own object for measurement using its measurement standard and sends it for calibration to a laboratory-participant and, almost simultaneously, receives a similar object from another laboratory-participant that calibrated it. If each participant, at the same time as the others, makes at least four such calibrations and transfers between laboratories-participants, it will form a common and very precise Metrological Measurement Network in a very short time. It can cover hundreds and even thousands of laboratories in a short period of time. The joint processing of a large number of such measurements will help to define the additive and/or multiplicative biases of each measurement standards. Moreover, the reference conditions are imposed that the sum of additive and, separately, the sum of multiplicative biases for all measurement standards is equal to zero regardless of the number of network participants.

Section: RESEARCH PAPER

Keywords: Metrology Measurements Network; traceability; comparisons of measurement standards; interlaboratory comparisons calibration; measurement uncertainty

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1. INTRODUCTION

Science, industry, trade, medicine, ecology, and other fields of human activity have a demand for increasing number of measurements and requirements for increasing their accuracy. Finding ways to solve these issues is crucial and will increase over the years. At the same time, it is very important to ensure metrological measurements traceability to SI units in the sense given in [1]. Traceability is based on establishing the equivalence of measurement standards [2], which implement units of measurement during international comparisons. It is built according to the hierarchical principle and includes three levels of comparisons: International Bureau of Weights and Measures (BIPM) key – regional key – additional comparisons [2], [3]. Further, traceability goes on with continuous chains of calibrations [1], [4] and ends with measurements that meet the needs of society.

International comparisons are organized according to [3] using a radial or circular scheme (Figure 1 [3]) and are completed by recognition of the measuring capabilities of national metrological or designated institutes according to [4]. Traceability chains have a tree structure during calibrations. Accreditation according to ISO 17025 [5] aims to build reliable quality systems for calibration or testing laboratories to meet the needs of society in traceability and measurement accuracy. One of the effective mechanisms for confirming the competence of laboratories is the interlaboratory comparisons (ILCs) of measurement results according to ISO 17043 [6]. One of the components of successful participation in ILCs is the assurance of the laboratory's traceability of measurements [7].

Let's call the traceability scheme, mentioned above, classic. It has well-known disadvantages. In short, they can include:

- restrictions on the number of comparison participants;
- absence of the necessary number of comparisons;
- too long terms that required to conduct comparisons according to a circular or radial scheme, when a limited number of the objects for measurement is used;

- weak and imperfect linking of comparisons on different levels: BIPM – regional – additional;
- the lack of direct horizontal connection between different regional comparisons, both between themselves and with additional comparisons (Figure 1 [3]);
- uncontrollability of traceability chains during calibrations, because they do not intersect in any way;

difficulties with the formation of a common reference due to the lack of the possibility to organize traceability to SI units for some types of measurements.

The collection of evidence of competence of laboratories and compliance of their quality systems with the requirements of ISO 17025 [5] is not automated enough. This creates a large bureaucratic burden during the preparation of laboratories for accreditations and audits. Maintaining the laboratory's calibration capabilities according to this standard is very expensive for them, for calibration customers, and for society as a whole. Of course, compliance with the requirements of ISO 17025 reduces the probability of errors and latent (undetected or uncounted) uncertainty, but it is far from reducing these probabilities to zero.

To solve this problem and to reduce the above-mentioned disadvantages, we propose to increase the number of independently monitored measurements according to the scheme of the Metrological Measurements Network, and to provide the automation of the work in it as much as possible. This will reduce the amount of bureaucratic procedures in favour of increasing the number of measurements during international comparisons and ILCs.

2. ANALYSIS OF SOURCES DEVOTED TO THE TRACEABILITY ENSURING THROUGH METROLOGICAL MEASUREMENTS NETWORK

The idea of a Metrological Measurements Network (MMN) is based on a well-developed mathematical apparatus for processing combinations of measurements by the least squares method (LSM). In the field of metrology, this mathematical apparatus has been addressed, for example, in [8]-[13] for processing the results of comparisons. According to Cox [9], during comparisons at the highest level, the reference, as a reference data (basis) for comparison, is formed as an average or weighted average of all measurement results at the point of the scale at which these measurements were performed. This average or weighted average has an appropriate name - the reference value. Degrees of equivalence of measurement standards are defined as deviations of values measured by standards from the reference value. The result is considered positive when the degree of equivalence of the measurement standards is less than the uncertainty calculated by the participant and declared by him during comparisons.

The analysis of the sources shows that there is no meaning that, on the one hand, connects all components of the metrological system mathematically, structurally (schematically) and organizationally, but, on the other hand, does not contradict the guiding documents [2]-[4] and the existing practice. The consequence of this is that, for instance, Koo et al. [12] made an attempt to process combinations of measurements by LSM resulted in the incorrectly composed system of linear equations in the example given there. As a result, the system of linear equations cannot be solved there. In general, the correct approach given by Koo et al. in [12] received an incorrect implementation due to the lack of a general idea: How, Why and What precisely have to be done during the organization of measurements, execution of measurements and processing of measurements according to LSM?

In the researches provided by Sutton [14] and Elster et al. [15], the issue of linking several comparisons to others is solved as a local one. There is no general solution when multiple comparisons link with several in any complex combination; when multiple comparisons ground on one or more other comparisons. The proposed MMN solve all these and the following problems and disadvantages, both structurally and organizationally, as well as computationally.

MMN are mentioned in the plural because they are created separately for each sub-field of measurements. For example, separately for weights, gauge blocks or accelerometers.

In our opinion, the perspective idea of organizing traceability as a Metrological Measurements Network, unfortunately, has not yet found support in the Metrological community. A small group of authors participated in its development. An improved mathematical basis, compared to the sources mentioned above, for processing the results of measurements by LSM in Metrological Measurements Networks was presented by Kuzmenko et al. [16], [17]. This term "Metrological Network" appeared in Samoilenko study [18] in relation to the software created on the basis of [16], [17]. Samoilenko also expanded the idea [19] not only as a mathematical apparatus and computer software, but also as an organizational structure with a view to its implementation in the future. Several of the most common measurement models, which can be used to build Metrological Measurements Networks, are considered in Kuzmenko et al. [20]; Samoilenko et al. [21]; Samoilenko et al. [22] studies.

It should be emphasized that comparisons organized according to a radial or circular scheme form the simplest MMN, moreover if they have several loops or use several measures or their sets. Processing of all the results of measurements of the magnitude and phase of the complex sensitivity of accelerometers according to the Metrological Measurements Network methodology, previously published in Samoilenko et al. [23], and obtained during key comparisons of the BIPM Bruns et al. [24], resulted in unexpectedly large estimations of the systematic error components of the measurement standards in comparison with the random component. For EURAMET.L-K1 [25], it was possible to combine two comparisons loops with two sets of gauge blocks in each, thanks to the fact that three organizations performed measurements on two loops [18]. Estimations of the systematic error components of the measurement standards in comparison with the random component of these comparisons are also significant.

The study reported in this paper aims to draw attention of Metrological community to discuss the ways of the Metrological Measurements Network implementation and its further modernization. Whereas from a philosophical point of view, the future of humanity is not based on purely hierarchical schemes, but on automated network of schemes with a large number of horizontal connections, in which the hierarchy will be built according to the results of work within the Network.

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3. JUSTIFICATION OF THE IDEA OF METROLOGICAL MEASUREMENTS NETWORK CREATING

The network scheme is proposed not as an alternative to the classic scheme, but as one of the forms of traceability ensuring.

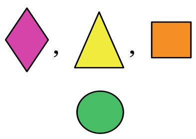

Figure 1. Subjects and objects for measurements.

The necessity of its implementation is to reduce of the negative consequences mentioned above for those types and subtypes of measurements for which it is appropriate.

In this publication we tried to demonstrate the advantages of the network scheme, distribution of traceability over the classic one. In other words, here we prove the right to existence of the network scheme along with the classic one. We do not propose to completely replace classic schemes with network ones, but implement them only where it is technically possible and economically justified. Network scheme will probably not be efficient where the objects for measurements are too expensive and enormous.

Rhombuses, triangles and squares in Figure 1, Figure 2 and Figure 3 are subjects for measurements (standards, instruments or laboratories), and circles are transfer objects for measurements (measures or their sets, standards, reference materials, gas mixtures, etc.).

Figure 2 shows a simplified classic scheme of the traceability ensuring similar to scheme on Figure 1 from [3].

Figure 3 shows a simplified proposed MMN. Perhaps, it can also be called a Comprehensive Measurement Traceability Network [19]. The correct name of the proposed network scheme is still open for discussion.

The building concept of classic traceability scheme and MMN is based on the principle of constancy of metrological characteristics of the subjects for measurements, and the parameters of subjects and objects for measurements:

- random and systematic components of measurement errors by the subjects for measurement (standards and instruments) that are constant over a certain period of time;

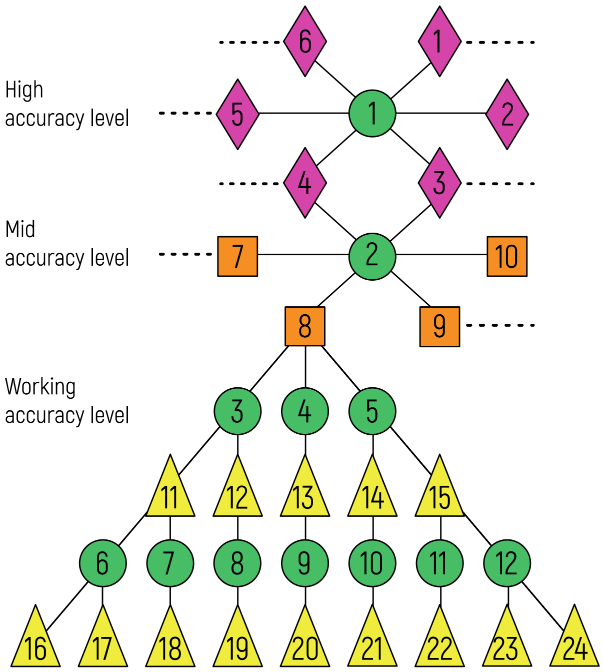

Figure 2. Classic scheme of traceability ensuring.

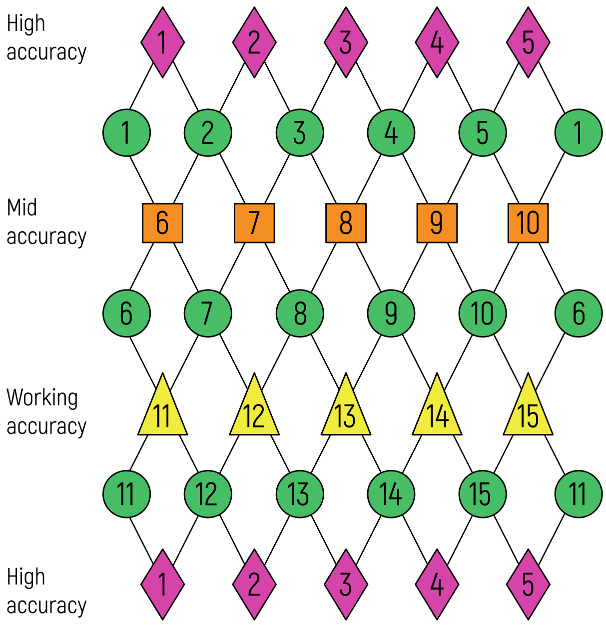

Figure 3. Network scheme of traceability ensuring.

values of a quantity, which are stored by the objects for measurements, are constant over a certain period of time.

We can detect the significant instability of the characteristics and parameters of the subjects for measurements (standards and instruments), as well as instability of the parameters of the objects for measurements (quantity values). Instability may be included in measurement models as time drift, but are not considered right now.

Metrological Measurements Networks theoretically does not have restrictions on:

- total number of measurements in the network;
- number of measurements in the network that are performed almost simultaneously;
- number of the subjects for measurements (standards or instruments) that are used to perform measurements in the network;
- the number of the objects for measurement (for example, transfer measures), the values for which are defined;
- the number and complexity of connections that can be formed by measurements in the network;
- the number of hierarchical levels formed from the objects and subjects for measurements.

There are also practical limitations of the Network, but that is not the subject of this paper.

To implement the network scheme for the traceability ensuring, it is necessary to have a sufficiently large number of transfer objects for measurements. Theoretically, the optimal way is having their number equal to the number of laboratories participating in the network, but it may be more or less. For example, there is no difficulty if each laboratory puts into use one or two accelerometers in the Metrological Measurements Network, one set of gauge blocks or weights from 4 to 8 pieces, etc.

A Guideline for the Network Operation should be developed and adopted by Metrological Community. The Community should also establish a Network Administration and Support Service which will provide the correct operation of the Network considering the adopted principles and rules.

The Network Administration and Support Service shall provide a high level of confidence, impartiality, and automation of the measurements (comparison) organization and the measurement results processing, reporting, and publication as well.

Some general functions of the Network Administration and Support Service are detailed in [19].

In order to understand the essence of Metrological Measurements Networks, we will present a typical simplified sequence of their creation:

1) The parameters of each object for measurements are measured almost simultaneously by each laboratory-participant of the Metrological Measurements Network. Measurement results are sent to the Network Administration and Support Service with no right of return for changes and corrections;
2) According to the logistic scheme, which no one except the Network Administration and Support Service knows in advance, the objects for measurements are sent to laboratories-participants almost simultaneously. As a result, each laboratory will receive the object for measurements from a neighbouring laboratory to measure the parameters. After measurements, the results are also sent to the Network Administration and Support Service with no right of return for changes and corrections. A neighbouring laboratory is not only a geographically close laboratory. It may be a laboratory from any point of the Earth;
3) To build such a strict Metrological Measurements Network, it's enough to complete minimum 4 such cycles of measuring parameters and data transfer, which will be performed by each laboratory-participant. However, the more such cycles, the better. Consequently, upon achieving a high level of automation of all processes, the work of the Metrological Measurements Network may acquire a permanent character;
4) The Network Administration and Support Service performs joint processing of all measurement results submitted by all participants for a certain period with special software [18], [23] according to the LSM and then publishes the results.

Thanks to the exchange of the objects for measurements between laboratories, classic metrological traceability chains [1] are interwoven into a continuous MMN (maybe it called Traceability Measurements Network).

The measurement correctness control, with the uncertainty declared by the laboratories, is entrusted to the qualification test rounds according to ISO 17043 [6]. Dealing with network schemes, it is possible to decrease the local character of the rounds by combining the efforts of thousands of laboratories in calibration or test. In this case, each laboratory is identified as a subject for measurements.

The common practice is to use reference materials when conducting ILC rounds that are not referred to SI units. The reference material reproduces the measured parameters of the object for measurements with an uncertainty that is meant to be better than the measurement uncertainty declared by the laboratories. Different manufacturers or suppliers identify different reference materials by different average values and different standard deviations. Each laboratory does irreparable damage to its sample of reference material during measurements and it cannot be measured by another laboratory anyway.

There is a real problem of how to organize traceability in this case. For instance, a common reference for all, as a reference data for comparison, may not be available, and traceability cannot be organized to SI units. This problem can be solved by the creation of a Global Metrological Measurements Network, which will involve many laboratories and manufacturers of reference materials, and will be based on the references obtained by the following methodology.

4. MEASUREMENT MODEL FOR METROLOGICAL MEASUREMENTS NETWORK

Among all the possible parameters of the subjects for measurements, we propose to determine the most simple and widespread ones by the LSM. They are estimates of additive and/or multiplicative systematic components of the error measured by subjects. These estimates are usually called biases. For the objects for measurements, as already mentioned above, the parameters are defined quantity values. They are also evaluated during the adjustment. Uncertainties of quantity values for parameters must be evaluated strictly according to the LSM using statistical data of all measurements. It fully corresponds JCGM 100 [26].

The best way to reveal the essence of the Metrological Measurements Network is to consider the simplest and most common model of measurements - the model of direct measurements of quantity values (were also considered in [8], [10], [12], [16]-[20], [23]):

$$x_{ij} = y_i + d_j + x_{ij} \cdot b_j \, , \tag{1}$$

where x_{ij} is the quantity value measured with subject for measurement (measurement standard), y_i is the defined unknown quantity value stored by the object for measurement by number$i = 1 ... i ... n$, d_j is the defined unknown additive bias of the subject for measurement (for example, measurement standard) with number$j = 1 ... j ... k$, b_j is the defined unknown multiplicative bias of the subject for measurements (for example, measurement standard) with number$j = 1 ... j ... k$.

Additive biases of measurements d_j and multiplicative biases of measurements b_j can be calculated separately or simultaneously if necessary.

The other five common measurement models that are suitable for use in the Metrological Measurements Network are discussed in [20]. The application of two models from [20] for processing specific measurement results during ILC are given in [21], [22].

There cannot be a correct solution based on the system of equations (1) in case of the absence of at least one such precisely known (reference) quantity value. Therefore, during the adjustment of the Metrological Measurements Network, additional reference conditions must be added to the system of equations (1)

$$\sum_{j=1}^{k} d_j = 0, \sum_{j=1}^{k} b_j = 0 \, . \tag{2}$$

Usually, there are no measurements in the Network that can be taken as a reference. This means that there are no measurement results with uncertainty much smaller than the uncertainty of other measurement results. In this case, if no other conditions are taken into account, the determinant of the system of linear equations will be close to zero and as a consequence, there will be no correct solution by the LSM. However, by adding an additional condition in the form of equations (2) to the system of linear equations the determinant of the matrix will no longer be equal to zero and allow for a correct matrix solution to be found.

According to [1] "2.42 Metrological traceability chain – is a sequence of measurement standards and calibrations that is used to relate a measurement result to a reference". The reference here is understood as a generalized concept of the quantity value, which is taken as a reference data for comparison. Equations (2) precisely create this reference at the highest level of the traceability hierarchy for the entire Metrological Measurements Network, in the absence of reference quantity values taken as a reference data for comparison. Hence, the reference data for comparison is the additive and/or multiplicative biases of standards that correspond to these equations regardless of the size and complexity of the Metrological Measurements Network structure.

The first equation (2) shows averaging the zero of the all scale standards that participated in the comparisons in relation to which all additive biases of measurements d_j are calculated for each standard. The second equation (2) shows averaging the measurement unit, which is implemented by all the standards that participated in the comparisons in relation to which the multiplicative biases of measurements b_j are calculated for each standard. Moreover, equations (2) can be used both when the measurements during comparisons were performed according to the classic scheme or according to the Metrological Measurements Network scheme.

If we remove the additive and multiplicative components from equation (1), we will obtain $x_{ij} = y_i$. Then, the degrees of standards equivalence we identify as deviations from the average or weighted average of all measurements performed at the measurement point $d_{ij} = x_{ij} - y_i$ according to [9]. Consequently, the generally accepted method of processing the results of comparisons according to [9] is a partial case of equations (1) and (2), for which the first of equations (2) is fulfilled.

We present equations (1) and (2) in the form of the following generalized system of equations

$$x = \begin{bmatrix} A_y & A_d & A_b \\ 0 & A_{\Sigma d} & 0 \\ 0 & 0 & A_{\Sigma b} \end{bmatrix} \cdot \begin{bmatrix} y \\ d \\ b \end{bmatrix} = A \cdot \beta \,, \tag{3}$$

where x is the vector of measured quantity values, y is the vector of quantity values stored by the objects for measurements, d is the vector of additive biases of the subject for measurements (for example, measurement standards), b is the vector of multiplicative biases of the subject for measurements (for example, measurement standards), A_y is equations coefficient matrix (1) for quantity values, A_d is equations coefficient matrix (1) for additive bias, A_b is equations coefficient matrix (1) for multiplicative bias, $A_{\Sigma d} = [1 \quad 1 \quad \dots \quad 1]$ - vector of reference equations coefficient (2) for additive bias, $A_{\Sigma b} = [1 \quad 1 \quad \dots \quad 1]$ - vector of reference equations coefficient (2) for multiplicative bias.

Through the measurement models (1) and [20] we connect defined quantity values that stored by the objects for measurements with additive and multiplicative biases of the subjects for measurements.

To generalize our research, we use the simplest and well-known measurements results processing according to LSM.

Normal equations based on equations (3)

$$A^T W_x A \cdot \beta + A^T W_x x = 0 \text{ or } N_\beta \cdot \beta + L = 0 \,, \tag{4}$$

where W_x is matrix of weights of measurement results, $N_\beta = A^T\, W_x\, A$ is coefficient matrix of normal equations, $L = A^T\, W_x\, x$ is the vector of constant term of normal equations.

The solution of normal equations for identifying the defined parameters is

$$\beta = -N_\beta^+ \cdot L = -Q_\beta \cdot L \,, \tag{5}$$

where $N_\beta^+ = Q_\beta$ is pseudo inverse matrix to the normal equations matrix.

Estimation of the standard deviation of a unit of weight, that is, the standard deviation of a measurement, the weight of which is taken as a unit

$$S = \sqrt{\frac{\sum_{j=1}^{k} \sum_{i=1}^{n} w_{ij} \cdot \delta x_{ij}^2}{v}} \,, \tag{6}$$

where $\delta x_{ij} = \hat{y}_i + \hat{d}_j + x_{ij} \cdot \hat{b}_j - x_{ij}$ is the differences between the measured and adjusted (estimated) quantity values, $v = n - k$ is the number of degrees of freedom.

The covariance matrix is

$$K = S^2 \cdot Q_\beta \,. \tag{7}$$

Evaluation of standard deviations of determined parameters - quantity values that are stored by the objects for measurements, additive and multiplicative bias

$$S_{\beta_{jj}} = S \cdot \sqrt{Q_{\beta_{jj}}} \,, \tag{8}$$

where $Q_{\beta_{jj}}$is diagonal terms of matrix that is pseudo inverse to the normal equations matrix.

During the adjustment, the covariance matrix (7) for the classic scheme (Figure 2) has an almost diagonal form, but for the MMN (Figure 3) - the solid form. Mathematically, this forms a tight network where all measurements and parameters become directly or indirectly interconnected.

The disadvantages of the classic scheme include rather long breaks between the traceability confirmation through comparison. The traceability ensuring through the Metrological Measurements Network can be permanent (continuous). Laboratories will once a year, half year or quarter send their object for measurements to a neighbouring laboratory and receive an object for measurement from another neighbouring laboratory to measure.

Moreover, nowadays we are facing a problem of mathematically strict relation of different comparisons with each other, as, for example, between different regional and additional comparisons, as well as between comparisons spread over time. Permanent Metrological Measurements Network shall also solve this problem.

Without delving into the organizational and mathematical details, we note that the above-mentioned relation problems can be solved by composing equation (1) and using the weight matrix that has the following structure

$$W = \begin{bmatrix} W_x & 0 & 0 & 0 \\ 0 & W_y & 0 & 0 \\ 0 & 0 & W_d & 0 \\ 0 & 0 & 0 & W_b \end{bmatrix} , \tag{9}$$

where W_x is weight matrix of measurement results, W_y is weight matrix for quantity values stored by the objects for measurements, W_d is weight matrix of additive biases, W_b is weight matrix of multiplicative biases.

At the initial stage of creating the Metrological Measurements Network matrix (9) $W_y = 0$, $W_d = 0$ and $W_b = 0$. That is, before adjustment the parameters of all subjects and the objects for measurement are defined as unknown quantities. Therefore, it is necessary to join the system of equations (1) with the reference equations (2), which will create the reference.

Afterwards, at the following exploitation stages of Metrological Measurements Network, real weights can be assigned to the obtained quantity value and the obtained additive and multiplicative bias, according to the estimation results of their uncertainties in the Metrological Measurements Network. Parameters that have a weight become the reference ones, but they can change the value inversely proportional to the weight, so they can be defined more precisely. For some reason, some parameters can be assigned such large weights that they will remain unchanged during adjustment and will be a reference for comparison. All other parameters are assigned weights equal to zero. They will be defined parameters with regard to the reference ones. The values of all defined and corrected parameters will be mathematically strictly linked to all reference values for any complex measurement scheme. Following this, there will be no need to add reference equations (2) to the system of equations. Uncertainties of all determined parameters are estimated taking into account the uncertainties of all reference values and the uncertainties of all measurements.

To conclude, here is a brief vision of the answers to the question: What? How? Why?

5. COMPARATIVE ANALYSIS OF THE ORGANIZATION OF MEASUREMENTS ACCORDING TO THE CLASSIC SCHEME AND THE METROLOGY MEASUREMENTS NETWORK SCHEME

The advantages of the network scheme over the classic one can be shown on a simple example. For instance, according to the classic scheme 20 laboratories measured the parameters of one object according to the radial scheme at the BIPM level of key international calibrations. Then, five groups of 20 laboratories measured according to the radial scheme one object at the level of key comparisons of international regional metrological organizations. It means that the parameters of only 6 objects were measured. In each group, 4 organizations took part in key BIPM comparisons. Mentioned above is similar to scheme on Figure 1 from [3]. The main indicators of such comparisons are given in Table 1, Column 2.

According to the Metrology Network scheme, 100 laboratories measured the parameters of 100 objects simultaneously. Then, at the same time, the objects were moved to neighbouring laboratories. Subsequently, they again made the cycle of simultaneous measurements and again moving. Such cycles are performed at least 4 times, so that no combination of objects in different cycles in different laboratories is repeated (Figure 3). Whereas Table 1, Columns 3 and 4 is show two versions of comparisons. The first is shown as described above, and the second (shown in Table 1, Column 4) as when the parameters of only 20 objects were measured. The total measurement time is given in conventional units, for example, it can be a month.

Table 1. Main indicators of international comparisons.

Name of indicators	Main indicators of international comparisons		
	Classic scheme	Metrology Network scheme (version 1)	Metrology Network scheme (version 2)
1	2	3	4
Number of the subjects for measurements (participants of comparisons)	100	100	100
Number of the objects for measurements	6	100	20
Number of measurement quantities	120	400	400
Total time of measurements	40	4	20
Number of the unknown parameters	106	200	120
Number of the degrees of freedom	14	200	280

Table 1 shows the number of unknowns and degrees of freedom that are given for the case when only the additive biases by the measurement standards are defined. According to the classic scheme, degrees of equivalence in the sense given in [9] are additive biases for the use of one transfer object for measurements, which stores one nominal value. If the objects for measurements are unambiguous measures of different nominal values, and the logistic scheme of the circulation of measures is built so that there were measures of different nominal values in the laboratories, then it is possible to estimate multiplicative bias. This is a clear advantage of the network scheme in comparison with the classic one, because it is not generally accepted to calculate multiplicative biases according to the classic one.

The greater number of degrees of freedom according to the network scheme in Table 1 indicates that the uncertainties of the parameters of the subjects for measurement estimated according to it will be smaller than according to the classic scheme. This is another advantage – a larger number of measurements in a shorter time allows to reduce the measurement uncertainty in general and makes it more confident for the entire Metrological Measurements Network.

According to the network scheme, the time of comparisons can be significantly reduced. If the number of objects for measurements involved in the comparisons is equal to the number of laboratories, then the measurement time can be, theoretically, reduced by 10 times (Table 1, Column 3). Even if the number of objects for measurements is 5 times less than the number of laboratories, the measurement time will be reduced by half (Table 1, Column 4).

When comparisons according to the network scheme are permanent the new measurements are added to the old ones. The weight of the old measurements should decrease over time. At the same time, additive and multiplicative biases of the subjects for measurements (standards or laboratories) and their uncertainties are corrected.

One of the main advantage of the network scheme over the classic one is that, according to the classic scheme, the regional level of comparisons is interconnected exclusively through laboratories that participated in the BIPM level of comparisons. According to the network scheme, even indirectly, all participants are interconnected through horizontal connections.

According to the simulation results, we conclude that for the classic and network scheme of traceability ensuring, the defined parameters differ from each other within the estimated uncertainty [18], [23].

6. THE RESULTS OF COMPARISONS PROCESSING EXPERIENCE AS A METROLOGICAL MEASUREMENTS NETWORK

It was developed the special software 'Metrology Network' [18], [23], which implements the above-mentioned measurement results processing methodology according to [16] for any complexity of the network scheme. With this software, it is also possible to process the measurement results obtained according to the classic scheme during comparisons, as they have features of the simple network. With 'Metrology Network' software were processed the measurement results obtained during:

- Key comparison EURAMET.L-K1 'Measurement of gage blocks by interferometer' [25];
- Key comparison CCAUV.V-K5 'Measurement magnitude and phase of the complex sensitivity of the accelerometers' [24].

The results of CCAUV.V-K5 [23] processing, as a Metrological Measurements Network helped to reveal for the first time a very significant multiplicative biases of the magnitude measurements and a phase of the complex sensitivity of accelerometers in comparison with their estimated expanded uncertainties and uncertainties estimated by participants.

Furthermore, CCAUV.V-K5 participants have very large differences between the multiplicative biases estimated for two different accelerometers. They reach up to 13 % with an estimated standard uncertainty of 0.7 % to 1.5 % [23] and a declared expanded uncertainty of 1 % to 3 % [24]. This indicates a great dependence of the measurement results on the measurement standards from characteristics and properties of specific accelerometers. When few accelerometers are involved in comparisons, their unpredictable systematic influence is transferred to the standards.

During the CCAUV.V-K5 comparison, the multiplicative biases were not evaluated [24]. Instead, the degrees of equivalence were assessed by determining the biases from the weighted mean in each measurement point, which is a well-known procedure described in [9]. Each participant carried out measurements on two accelerometers in 62 points within the frequency range of 10 to 20000 Hz, as per the comparison technical protocol. The procedure of the evaluation of the measurement results in [9] and [24] does not involve the estimation of systematic errors. Therefore, each participant's biases for each accelerometer over the mentioned frequency range were approximated using a linear function (1), following the method described in paragraph 4 (which is explained in more detail in [16]-[23]). This approach allowed us to detect significant multiplicative biases for this kind of measurement for the first time. These biases, which also serve as estimates of systematic error, were found to vary significantly (up to 13 %) across different accelerometers.

If the number of accelerometers used in network scheme comparisons is increased, their overall unpredictable systematic effect on establishing the equivalence of standards can be significantly reduced. Using a large number of accelerometers, the systematic effect of each will turn into a random effect of all. For example, the Metrological Measurements Network can simultaneously include 100 leading laboratories in the field of vibration measurements and from 100 to 200 accelerometers of different manufacturers. This will reduce the influence of each accelerometer on the final comparison results and provide a lot of statistical data for analysis.

Using the real measurement results obtained during CCAUV.V-K5 [24] and EURAMET.L-K1 [25], there were simulated the measurement results during comparisons 5-6 times larger than real comparisons (120 participants). Processing the results of real and simulated measurements using the 'Metrology Network' software according to the network scheme demonstrated a very good convergence, but this is not the scope of this paper. Thus, the technique given in [15], [16], implemented in "Metrology Network" software [18], has shown its ability to solve such complex and voluminous, in terms of the number of calculations, problems.

7. CONCLUSIONS

1) According to the advantages of using a traceability ensuring scheme as a Metrological Measurements Network over a classic scheme, the following principles were formulated:

- the number of subjects and objects for measurements and the measurements performed in the network is almost unlimited;
- significantly more measurements will be performed per unit of time, which will increase reliability and reduce the uncertainty of the parameters of the subjects and objects for measurements;
- the problem of connection, directly or indirectly, of parameters of all subjects and objects for measurements is solved in the most general form;
- the measurement scheme can be of any complexity;
- measurements can be permanent, which will allow any laboratory to join the measurement process at any time, based on its needs and capabilities;
- the measurement interconnections can be regulated by the weights for measurements, and with the accumulation of certain statistical information, by the weights of the quantity values of their parameters.

2) The parameters of all objects and subjects for measurements and their uncertainties will be evaluated according to the statistical data of the joint processing of measurements, which have been accumulated over a certain period for the entire Metrological Measurements Network. These subjects and objects for measurements will be considered calibrated, and the results of this calibration will be considered traceable. The calibration, measurement or testing methodology of the laboratories will be considered validated, and the measuring capabilities of the laboratories and the professional level of their personnel will be confirmed.

Therefore, for accreditation bodies in the Metrological Measurements Network, an irrefutable evidence base of laboratory compliance with some ISO 17025 requirements will be collected. That in the future may allow providing a presumption of conformity with such requirements. The reliability of measurement results during calibrations and tests will be increased by increasing the number of training measurements in the Metrological Measurements Network.

3) The Metrological Measurements Network is able to provide a transition from the declarative form of Calibration and Measurement Capabilities (CMCs), followed by its confirmation through comparisons, to the consistently maintained CMCs through the continuous accumulation of statistical data of measurements processed according to LSM.

4) In the future, it is possible that the Metrological Measurements Network, upon achieving a high level of automation of its use, will allow transforming the traceability to SI units into the permanent maintenance of SI units and other units that are not traceable to them.

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