DETERMINATION OF MEASUREMENT UNCERTAINTY ON CMM SIOS NNM-1

JAN SRAMEK, ROBERT JANKOVYCH
Brno University of Technology
Faculty of Mechanical Engineering
Brno, Czech Republic
DOI : 10.17973/MMSJ.2018_03_201796
e-mail: jsramek@cmi.cz

This paper focuses on determination of uncertainty and individual contributions to the measurement uncertainty on the nano-CCM NNM-1 instrument fitted with the touch-probe scanning system Gannen XP. Ruby ball diameters with various nominal diameters are used as the measured objects. Two main methods to determine the measurement uncertainty, the substitution and multi-position methods are addressed in detail. The paper also summarizes and specifies calculation methods to determine the measurement uncertainty, and provides results of representative sets of measurements, including determination of the expanded measurement uncertainty, in a new, unpublished way.

KEYWORDS
ruby ball, measurement uncertainty, length measurement, multi-position method, substitution method, nanometrology, coordinate measuring machine

1 INTRODUCTION

This paper focuses on two methods used to determine the measurement uncertainty with a touch probe CMM (Coordinate Measuring Machine) SIOS NNM-1 (Nanopositioning and Nanomeasuring Machine).

It also includes methodology for the calculation of the measurement uncertainty, and builds on the previous work of the authors [Sramek, Jankovych 2016].

There have been a growing demand for the assessment and determination of the measurement precision in very accurate measuring instruments, and this tendency can also be seen in the area of nanometrology and length measurements [Jaeger 2012]. The manufacturer SIOS [SIOS 2012] has adopted a specific approach to determine the measurement accuracy and the measurement uncertainty in nano-CMM NNM-1 (Figure 1).

Figure 1. Overall view on the nano-CMM NNM-1 [SIOS 2012]

This specific approach of the manufacturer is especially apparent in the stated measurement uncertainty of the instrument, where the uncertainty is specified only for the measuring instrument, which is He-Ne laser interferometer, and for the resolution of the measured value, therefore not for the nano-CMM NNM-1 instrument as whole. This situation is caused by the specificity of these instruments that are custom designed, meeting specific requirements, and fitted with various scanning systems for their intended use [Pernikar 2015].

This paper has been compiled due to the necessity to quantify the measurement accuracy in metrology using the nano-CMM NNM-1 device under controlled conditions in the Czech Metrology Institute Laboratory in Brno, especially when using the Gannen XP nano-series touch probe.

2 MATERIALS AND METHODS

CMM is a measuring instrument and it is also classified as a measuring system because it contains 3 and more gauges with their own indications, and usually also heat sensors and other accessories, depending on the CMM construction. In nanometrology, there are even higher demands on the measurement precision. There are employed coordinate measuring machines - nano-CMMs. Generally, CMMs use the same calibration methods, standards and standardized methods to determine the measurement accuracy. Nevertheless, construction differences of nano-CMM instruments, their smaller size and required greater precision place very different and high demands on the measurement process. In nanometrology, these demands cannot be met using the standard CMM standards and calibration methods.

Furthermore, there can be a problem with missing adequately exact standard or calibrated standard with a sufficiently low value of the measurement uncertainty. Another significant factor concerning the nano-CMM is a relatively wide range of scanning systems, unlike in standard CMMs, where there are mostly touch-probe scanning systems, sometimes complemented with CMMs employing optical scanning or multi-sensor devices. Nano-CMMs are often fitted with scanning systems like AFM microscopes, laser-focus sensors and interferometric sensors.

Implementation of these non-contact scanning methods does not automatically mean that it is a real 3D space measurement.

In these cases, the *x*- and *y*-axis shift is often used only to achieve the target point or area of the "nano" measurement.

A real 3D space measurement is used in case, where a contact scanning system fitted with a miniature ball, i.e. a touch-probe, is employed. When calibrating these devices, it is necessary to consider the potential of nano-CMM manufacturers and users, who often do not have the necessary technical equipment, knowledge or finances to adjust the nano-CMM device construction or edit its software.

Therefore, when calibrating nano-CMMs, it is necessary to use special standards suitable for nano scanning. If such standards are not available, it is necessary to choose a suitable method to determine the measurement uncertainty or the nano-CMM measurement precision. In compliance with standards [CSN EN ISO 17025:2005, ISO 15530-3:2004, EA 4/02 M: 2013 and TNI 01 0115:2009] and scientific publications [Sladek 2016, Seggelen 2007], two methods suitable to determine the measurement accuracy have been chosen: the multi-position and substitution method.

This paper also addresses individual contributions to the measurement uncertainty. The measurement methods are further developed and accommodated to the nano-CMM NNM-1 system, in particular to touchless nano-probe Gannen XP-1 measurements.

The expanded measurement uncertainty has been used to quantify the measurement precision in nano-CMM.

2.1 Multi-position method to determine the CMM measurement uncertainty

This method uses a non-calibrated object (standard) for the measurement. The corrected nano-CMM indication provides the measurement result.

This method implements a set of measurements of the object in various positions and orientations within the nano-CMM measuring range (Figure 2). Results are analyzed through the evaluation of standard deviations of the monitored CMM parameter or the measured object, which influences the determination of the measurement uncertainty.

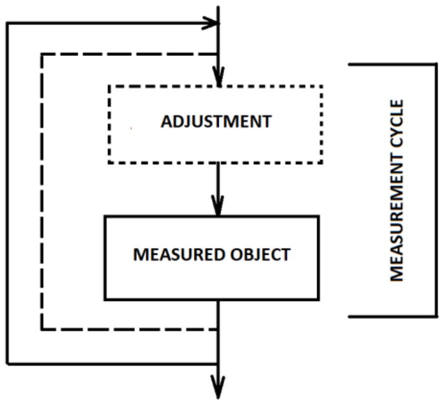

Figure 2. Scheme of the multi-position method [Sladek 2016]

The multi-position method [Sladek 2016, Seggelen 2007] has been chosen due to a common lack of suitable and sufficiently accurate calibration method ensuring the metrological traceability of the used standard. It yields adequate accuracy of the calibration measurement and sufficiently low uncertainty values for the standard calibration. However, it is necessary to realize that in nanometrology, length measurements are in the range of nanometers, which is for a vast majority of implemented methods beyond their physical limitations. Therefore, the authors aimed to create methodology to determine the measurement accuracy in nano-CMM NNM-1 by a non-substitution method.

2.2 Substitution method to determine the CMM measurement uncertainty

This method uses a calibrated object (standard) for the measurement (Figure 3). The uncorrected CMM indication provides the measurement result.

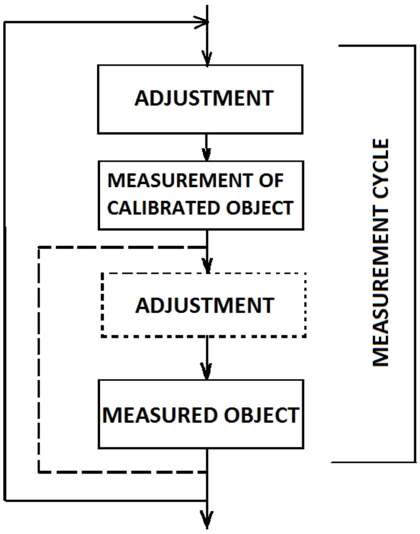

Figure 3. Scheme of the substitution method [Sladek 2016]

The substitution method differs from the previous one especially by the fact that in the nano-CMM NNM-1 calibration process, suitable length standards are used – ruby balls (ball plate) that have calibration protocols with the measured values and the expanded measurement uncertainty. Obtained values do not have to be corrected by the systematic error caused by the use of a non-calibrated object. Length standards can also be used for usual nano-CMM NNM-1 measurement, therefore they have an irreplaceable impact on the determination of the measurement accuracy of this instrument.

3 PROPOSED SOLUTION

The newly developed method to determine the measurement accuracy in nano-CMM NNM-1, and to quantify it by the measurement uncertainty draws on standards [ISO 15530-3:2004] and published scientific works [Sladek 2016, Seggelen 2007] that are commonly implemented on standard CMSs (Coordinate Measuring Systems). However, this method is further developed and accommodated to the nano-CMM NNM-1 system, in particular to the touchless nano-probe Gannen XP-1 measurement (Figure 4). Two methods to determine the CMM measurement accuracy have been used and compared.

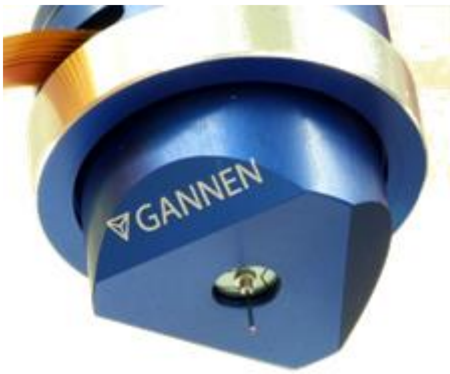

Figure 4. Touch probe Gannen XP - detail [Gannen 2011]

3.1 CMM measurement uncertainty when using the multi-position method

3.1.1 Determining the corrected value of the measured object

The developed method regards the true value of a measured object's characteristic (ruby ball diameter) as the average of all measurements of a particular ruby ball's characteristic decreased by the average length measurement error of the used standard E_L by laser interferometer XL 80, and the correction value for the ruby ball diameter measurement E_D. The corrected value of the measured object is calculated by the following relationship [Sladek 2016]:

$$y_{corr} = y - E_L - E_D, \tag{1}$$

where:

y is the average value of all measurements of a particular characteristic,

E_D is correction for the ruby ball size measurement,

E_L is average length measurement error obtained with laser interferometer XL80 is calculated by the following relationship:

$$E_L = \frac{1}{n_3} \sum_{i=1}^{n_3} \frac{L_{meas std} - L_{cal std}}{L_{cal std}}, \tag{2}$$

where:
n_3 is total number of standard ball measurements with laser interferometer XL80,
L_{calstd} is length of the measured object obtained during its calibration,
$L_{measstd}$ is average length value of the object obtained during its measurement.

3.1.2 Calculation definition for the determination of the measurement uncertainty

Definition of the relationship used to calculate the expanded measurement uncertainty in nano-CMM NNM-1 has been made in compliance with generally used practice and described in international documentation [CSN EN ISO 17025:2005, ISO 15530-3:2004, EA 4/02 M: 2013, TNI 01 0115:2009], CMI Brno internal documentation, technical standards and scientific publications [Sladek 2016, Seggelen 2007]:

$$U = |E_D| + |E_L| + \\ + k\sqrt{u_{rep}^2 + u_{geo}^2 + u_{corrL}^2 + u_{temp}^2 + u_{prob}^2}, \tag{3}$$

where:
E_D is correction for the measurement of the ruby ball,
E_L is average error of measurement of ruby ball diameter by laser interferometer XL80,
k is expansion coefficient,
u_{rep} is standard measurement uncertainty caused by repeatability of nano-CMM,
u_{geo} is standard measurement uncertainty caused by geometric error of nano-CMM,
u_{corrL} is standard measurement uncertainty of ruby ball diameter by laser interferometer XL80,
u_{temp} is standard measurement uncertainty caused by the impact of temperature during the measurement,
u_{prob} is standard measurement uncertainty caused by touch-probe scanning system Gannen XP.
The above definition was adapted to the general practice and rules of the CMI Brno accredited calibration laboratory. This alteration reflects the chosen measuring method and respects the main sources of the measurement uncertainty that were determined during a large set of measurements. The expanded measurement uncertainty does not include corrections eliminating the systematic error caused by the use of a non-calibrated object. Their impact is reflected in standard deviation, pursuant to European accreditation documents [EA 4/02:2013]:

$$U_{mult} = k\sqrt{u_{rep}^2 + u_{geo}^2 + u_{corrL}^2 + u_{temp}^2 + u_{prob}^2 + u_L^2}, \tag{4}$$

where:
u_L is standard measurement uncertainty determining correction for the measurement of a non-calibrated object in nano-CMM.

3.1.3 Determining the measurement uncertainty contribution u_{rep}

Standard measurement uncertainty caused by the nano-CMM repeatability is defined as follows [Sladek 2016]:

$$u_{rep} = \sqrt{\frac{1}{n_2}\sum_{j=1}^{n_2} s_j^2}, \tag{5}$$

where s_j is standard deviation calculated for every position of the ruby ball, expressed as follows:

$$s_j = \sqrt{\frac{1}{(n_2 - 1)}\sum_{i=1}^{n_2}(y_{ij} - \bar{y}_j)^2}, \tag{6}$$

where s_j is standard deviation calculated for every position of the ruby ball.

3.1.4 Determining the measurement uncertainty contribution u_{geo}

Standard measurement uncertainty caused by nano-CMM geometric errors is defined as follows [Sladek 2016]:

$$u_{geo} = \frac{1}{\sqrt{n_2}}\sqrt{\frac{1}{(n_2 - 1)}\sum_{j=1}^{n_2}(\bar{y}_j - y)^2}, \tag{7}$$

where y is mean of all measurements that can be calculated by the following equation:

$$y = \frac{1}{n_1 n_2}\sum_{j=1}^{n_2}\sum_{i=1}^{n_1} y_{ij}, \tag{8}$$

where:
n_1 is the total number of the ball diameter measurements and n_2 is the total number of ball positions during the measurement.

3.1.5 *Determining the measurement uncertainty contribution u_{corrL}*

Standard uncertainty of the measurement correction of the ruby ball diameter provided by laser interferometer XL80 is defined by the relationship pursuant to international documents [GUM, EA4/02] and is based on the value of expanded uncertainty of the measurement of ruby balls obtained by the CMI Brno accredited calibration procedure:

$$U_{RUB} = (0.02 + 0.4L)[\mu m], \tag{9}$$

where L is measuring length in meters. Standard measurement uncertainty caused by the measurement correction of the ruby ball diameter provided by XL 80 is defined as follows:

$$u_{corrL} = \frac{U_{RUB}}{k}, \tag{10}$$

where k is expansion coefficient.

3.1.6 Determining the measurement uncertainty contribution u_{temp}

Standard measurement uncertainty caused by the impact of temperature on the measurement is defined as follows [Sladek 2016]:

$$u_{temp} = L\sqrt{\begin{aligned}&(u_t^2 + u_{cal}^2)\alpha_{mo}^2 + (u_t^2 + u_{cal}^2)\alpha_{cmm}^2 + \\ &(u_{\alpha mo}(T_{mo} - 20)) + (u_{\alpha cmm}(T_{cmm} - 20))\end{aligned}}, \tag{11}$$

where:
T_{mo} id average temperature of ruby balls during the measurement [°C],
T_{cmm} is average temperature of the nano-CMM NNM-1 body during the measurement [°C],
$u_{\alpha mo}$ is standard uncertainty for the thermal expansion coefficient of the ruby ball material
$u_{\alpha cmm}$ is standard uncertainty for the thermal expansion coeficient of the nano-CMM NNM-1 body material,
α_{mo} is length expansion coefficient of the ruby ball material,

α_{cmm} is length expansion coefficient of the nano-CMM NNM-1 body material,
u_t is standard measurement uncertainty of the thermometer used during the measurement,
u_{cal} is standard calibration uncertainty of the used thermometer.

3.1.7 Determining the measurement uncertainty contribution u_{prob}

According to the manufacturer's data for Gannen XP probing system [Gannen 2011], the expanded measurement uncertainty of this touch probe is: U_{prob} = 45nm. Where expansion coefficient k = 2. Therefore, to determine the contribution to the standard measurement uncertainty caused by the probe's touch, the following equation is used:

$$u_{prob} = \frac{U_{prob}}{k}, \tag{12}$$

where k is expansion coefficient and U_{prob} expanded measurement uncertainty of the sensor stated by the manufacturer.

3.1.8 Determining the measurement uncertainty contribution u_L

Standard measurement uncertainty of determining the correction when measuring a non-calibrated object with nano-CMM NNM-1 is defined by the equation. For this value, we expect equal (rectangular) probability distribution with a coefficient typical for the given type of distribution $k = \sqrt{3}$. The following equation is used to determine the contribution to the standard measurement uncertainty caused by the probe's touch:

$$u_L = \frac{E_L}{\sqrt{3}}. \tag{13}$$

3.2 CMM measurement uncertainty when using the substitution method

3.2.1 Definition of the measurement uncertainty calculation

Definition of the relationship for calculation of the expanded measurement uncertainty in nano-CMM NNM-1 is also created in compliance with generally acknowledged practice described in international documents [CSN EN ISO 17025:2005, ISO 15530-3:2004, EA 4/02 M: 2013 and TNI 01 0115:2009] and latest scientific publications [Sladek 2016, Seggelen 2007].

$$U = k\sqrt{u_e^2 + u_p^2 + u_w^2 + u_b^2}, \tag{14}$$

where:
k is expansion coefficient,
u_e is standard measurement uncertainty caused by the used standard,
u_p is standard measurement uncertainty evaluated by the A method (see EA 4/02 M),
u_w is standard measurement uncertainty caused by accidental material changes of the measured object and by influences during its manufacturing, it also depends on the measurement strategy,
u_b is standard measurement uncertainty associated with determination of the systematic measurement error of the standard's dimension.

The given definition was closely specified based on experience with measurements and standard practice and rules of the CMI Brno accredited calibration laboratory. This modification reflects the chosen measurement method and main sources of the measurement uncertainty that have been identified and analyzed during a large set of measurements:

- Resolution of the measuring system nano-CMM;
- Impact of the Gannen XP probe's touch;
- Standard deviation from repeated measurements;
- Calibration uncertainty of the used standard;
- Uncertainty of knowledge of thermal expansion of the measured object;
- Uncertainty of knowledge of thermal expansion of the nano-CMM body material;
- Calibration uncertainty of the used thermometer;
- Measurement uncertainty of the real temperature of the nano-CMM working area;
- Impact of cleaning of the measured object;
- Impact of fixing of the used standard.

Based on this analysis, the better specified formula for calculation of the expanded measurement uncertainty by the substitution method is as follows:

$$U_{subs} = k\sqrt{u_r^2 + u_{prob}^2 + u_a^2 + u_e^2 + u_{temp}^2 + u_{cl}^2}, \tag{15}$$

where:
u_r is standard measurement uncertainty caused by the impact of the nano-CMM resolution,
u_a is standard measurement uncertainty evaluated by the A method,
u_{cl} is standard measurement uncertainty caused by the impact of impurity of the measured object,
u_{temp} is standard measurement uncertainty caused by the impact of temperature on the measurement.

3.2.2 Determining the measurement uncertainty contribution u_r

Standard measurement uncertainty caused by the impact of resolution of the nano-CMM gauge is derived from the nano-CMM manufacturer's data, who stated the value of 0.1 nm. In this value, we expect even probability distribution. Calculation of standard uncertainty caused by the impact of nano-CMM resolution uses the following relationship:

$$u_r = \frac{D}{\chi}, \tag{16}$$

where:
D is value of resolution of the nano-CMM measuring system,
χ is coefficient for even distribution.

3.2.3 Determining the measurement uncertainty contribution u_{prob}

According to the data stated by the manufacturer of the probing system Gannen XP [Gannen 2011], the expanded measurement uncertainty of this touch probe is U_{prob} = 45nm with the expansion coefficient k = 2. To determine the contribution to the standard measurement uncertainty caused by equation (12).

3.2.4 Determining the standard measurement uncertainty u_a

Standard measurement uncertainty evaluated by the A method is defined by the relationship [EA4/02:2013], where the standard deviation for every position of the ruby ball is expressed as follows:

$$u_{rep} = u_a = \sqrt{\frac{1}{(n_1 - 1)} \sum_{i=1}^{n1} (y_i - \bar{y})^2}, \tag{17}$$

where:
y_i is a result of the *i*- measurement,
$\bar{y}$ is arithmetic mean of the measurement results.

3.2.5 Determining the measurement uncertainty contribution u_e

Standard measurement uncertainty caused by the used standard - laser interferometer XL80 - is based on the value of the expanded measurement uncertainty obtained during calibration of the device using the accredited calibration method of Primary Metrology Laboratories at CMI Brno. The expanded measurement uncertainty stated in the calibration protocol is:

$$U_{las} = (0.02 + 0.4L)[\mu m], \tag{18}$$

where *L* is the measured length in *m*. Standard measurement uncertainty caused by the used standard - laser interferometer XL80 is defined by the following relationship:

$$u_e = \frac{U_{las}}{k}, \tag{19}$$

where *k* is expansion coefficient.

3.2.6 Determining the measurement uncertainty contribution u_{temp}

Standard measurement uncertainty caused by the impact of temperature on the measurement is defined by the following relationship (11).

3.2.7 Determining the measurement uncertainty contribution u_{cl}

Based on the results of the measurement of number of solid particles in the laboratory air, the upper limits of the dust particle size can be estimated Δp = 150nm [Sramek 2016]. To determine the standard uncertainty contribution caused by the impurity of the measured object, the following relationship is used:

$$u_{cl} = \frac{\Delta p}{\chi}, \tag{20}$$

where:
Δp is the value of the upper limit of the dust particle size,
χ is coefficient for even distribution.

4 COMPARISON OF RESULTS OF BOTH METHODS

To determine the accuracy of the nano-CMM NNM-1 measurements, expanded measurement uncertainty was determined by the multi-position method for all diameters of the measured ruby balls. This solution ensured covering of the whole measuring range of the nano-CMM NNM-1 instrument. Overview Table 1 summarizes all values of combined measurement uncertainties for individual ruby ball diameters.

St. unc.	*d* = 1mm	*d* = 2mm	*d* = 3mm	*d* = 4mm	*d* = 5mm
u_{rep1-5}	21.5	6.4	4.3	3.9	4.1
u_{geo1-5}	17.8	1.6	1.5	2.5	3.4
$u_{corrL1-5}$	10.2	10.4	10.6	10.8	1.,0
$u_{temp1-5}$	0.6	1.3	1.9	2.5	3.2
$u_{prob1-5}$	22.5	22.5	22.5	22.5	22.5
u_{L1-5}	11.7	6.7	10.8	9.2	11.3
u_{c1-5}	39.0	26.6	27.6	27.1	28.2

Table 1. Comparison of individual measurement uncertainty contributions determined by the multi-position method [*nm*]

The result provides expanded measurement uncertainty determined by the multi-position method for the whole measuring range of nano-CMM NNM-1 in Table 3.
Evaluation of the measurement uncertainty was based on determination of the total measurement uncertainty determined by the substitution method for all diameters of the measured ruby balls. Table 2 summarizes individual contributions to standard measurement uncertainties that were calculated for all diameters of the used ruby balls (1 – 5) mm. The result provides expanded measurement uncertainty determined by the substitution method in Table 3.

St. unc.	*d* = 1mm	*d* = 2mm	*d* = 3mm	*d* = 4mm	*d* = 5mm
u_{r1-5}	0.1	0.1	0.1	0.1	0.1
$u_{prob1-5}$	22.5	22.5	22.5	22.5	22.5
u_{a1-5}	2.2	1.1	0.5	0.4	0.6
u_{e1-5}	10.2	10.4	10.6	10.8	11.0
$u_{temp1-5}$	0.6	1.3	1.9	2.5	3.2
u_{cl1-5}	14.4	14.4	14.4	14.4	14.4
u_{c1-5}	28.7	28.7	28.8	28.9	29.1

Table 2. Comparison of individual measurement uncertainty contributions determined by the substitution method [*nm*]

Table 3 summarizes individual contributions to the expanded measurement uncertainty determined by both methods for all ruby ball diameters (1-5mm). Figure 5 shows line diagram of the obtained results.

Ex. unc.	*d* = 1mm	*d* = 2mm	*d* = 3mm	*d* = 4mm	*d* = 5mm
$U_{mult1-5}$	78.1	53.2	55.2	54.3	56.4
$U_{subst1-5}$	57.4	57.5	57.7	57.9	58.2

Table 3. Values of the expanded measurement uncertainty determined by the substitution and multi-position methods [*nm*]

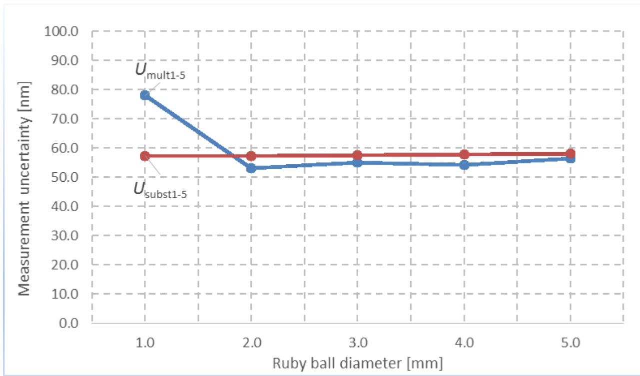

Figure 5. Line diagram of expanded measurement uncertainty of ruby balls with nominal diameters *d* = (1-5) mm.

Expanded measurement uncertainty of the ruby ball diameter *d* = 1mm determined by the multi-position method is after rounding: U_{mult1} = 78.1 nm. Expanded measurement uncertainty of the ruby ball diameter *d* = 1mm determined by the substitution method is after rounding: U_{subs} = 57.4 nm.

5 DISCUSSION

This article has briefly addressed the current situation in the area of defining the measurement accuracy in nanometrology using the machine nano-CMM NNM-1. This precise coordinate measuring machine constitutes an upgrade to measuring instruments standardly used in metrology, especially multi-axial and multi-purpose measuring instruments that, due to their functional principle and construction, cannot yield measurements as precise as provided by nanotechnologies.

The paper presents the original solution procedure, which replaces the simplified method of determining the uncertainty of measurement specified by the manufacturer of instrument. This solution has not yet been implemented in the Czech Republic or in other EU countries.

6 CONCLUSIONS

The evaluation of representative sets of the measured data shows that both measuring methods facilitate very accurate length measurements in nanometrology.

The machine nano-CMM NMM-1 could play a key role in the area of primary standardization within the system of metrological traceability, especially in the calibration laboratory at the Czech Metrology Institute in Brno. However, due to the range and characteristics of individual factors influencing the measurement uncertainty, this field is so complex that this overview article cannot describe all aspect of nano-CMM NMM-1 used as an accurate measurement standard in detail.

The authors are currently working on an accredited calibration procedure for measuring on the nano-CMM NNM-1 according to the Czech Institute for Accreditation standards.

REFERENCES

[CSN EN ISO 17025:2015] General requirements for the competence of testing and calibration laboratories. Geneva: International Organization for Standardization. (In Czech). CNI 2015.

[EA 4/02 M: 2013] Evaluation of the Uncertainty of Measurement in Calibration. EA 4/02 M:2013. European Accreditation. 2013.

[Gannen 2011] Gannen XP and XM – User manual and installation guide, Version 1.8, Xpress Precision Engineering, Eindhoven, Netherlands, 2011.

[ISO 15530-3:2004] Geometrical product specification (GPS) – Coordinate measuring machines (CMM): techniques for evaluation uncertainty of measurement – part3 : use of calibration workpieces. Geneva: International Organization for Standardization, CNI 2004.

[Jaeger 2012] Jaeger, G. Challenges and Limitations of Nanomeasuring Technology. Germany, Ilmenau: Ilmenau University of Technology 2012.

[Pernikar 2015] Pernikar, J. and Pospisil, M. Accuracy measurement determination in engineering praxis. (In Czech). Journal Metrologie 4/2015, pp. 12-18. ISSN: 1210- 3543.

[Seggelen 2007] Van Seggelen, J. A. 3D coordinate Measuring Machine with low moving mass for measuring small products in array with nanometer uncertainty. Eindhoven University of Technology. 2007. ISBN-10:90-386-2629-0.

[SIOS 2012] SIOS. Design and Operation of the Nanomeasuring Machine / Part B Probe system. Operational Handbook. SIOS Messtechnik GmbH. Ilmenau. Germany 2012.

[Sladek 2016] Sladek, A. J. Coordinate Metrology Accuracy of systems and Measurements. Springer tractsin Mechanical Engineering, 2016, ISBN 978-3-662-48463-0.

[Sramek 2016] Sramek, J, Sperka, J and Jankovych, R. The Measurement System for the Calibration of Particle Counters. Conferencion Mechatronika 2016, Czech Technical University in Prag, 2016.

[Sramek, Jankovych 2016] Sramek, J. and Jankovych, R. Accuracy of Measurement in Nanometrology. MM Science Journal, 2016, No. 5, pp. 1643-1647. ISSN: 1803-1269.
DOI : 10.17973/MMSJ.2016_12_2016203

[TNI 01 0115:2009] International vocabulary of metrology – Basic and general concepts and associated terms (VIM). TNI 01 0115:2009. Geneva: International Organization for Standardization, 2009.

CONTACTS:

Ing. Jan Sramek
Czech Metrology Institute
Regional Inspektorate Brno
Okruzni 31. Brno, 638 00. Czech Republic
Tel.: +420 737 292 042
e-mail: jsramek@cmi.cz
www.cmi.cz

doc. Ing. Robert Jankovych, CSc.
Brno University of Technology
Faculty of Mechanical Engineering
Institute of Production Machines, Systems and Robotics
Technicka 2896/2. Brno, 616 69. Czech Republic
Tel.: +420 605 440 420
e-mail: jankovych@fme.vutbr.cz