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Prilagoditev modela vrednotenja merilne negotovosti pri kalibraciji dolžinskih etalonov na temelju avtomatizacije meritve

Modification of the Model for Measurement Evaluation in a Gauge-Block Calibration Based on Measurement Automation

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Prispevek obravnava modele za vrednotenje merilne negotovosti pri kalibraciji dolžinskih etalonov - vzporednih končnih meril po metodi mehanske primerjave dolžin. Prikazana je prilagoditev sedanjega modela, ki ga uporabljamo pri običajnem postopku kalibracije, za razmere meritve pri avtomatizirani meritvi. Z avtomatizacijo meritve je omogočen nadzor nad večino vhodnih veličin v matematičnem modelu meritve, zato je mogoče zmanjšati standardne negotovosti teh veličin in s tem tudi skupno merilno negotovost. Seveda pa ima lahko avtomatizacija tudi nekatere motilne vplive na rezultat kalibracije, zato je pomembno, da pri načrtovanju avtomatizacije vnaprej predpostavimo vse morebitne vplive na merilno negotovost in se na podlagi analize teh vplivov odločimo za ustrezno različico avtomatizacije.

(Ključne besede: etaloni, meritev dolžin, kalibriranje, negotovosti merilne, avtomatizacija)

This paper treats models for evaluating the uncertainty of measurement during the calibration of length standards — gauge blocks based on the mechanical comparative method. A modification of the existing model used in the classic calibration procedure for measurement conditions in the automated measurement is presented. Control over most input values of the mathematical model of the measurement is ensured by the automation, and as a consequence the standard uncertainties of these values and the combined uncertainty can be reduced. However, automation can also have some negative influences on the calibration result. Therefore it is very important that all possible influences on the uncertainty of the measurement are anticipated in advance when the automation is planned, and the method of automation is chosen after these influences are precisely analysed.

(Keywords: length standards, measurements, calibrations, uncertainty of measurements, automation)

0 UVOD

Nacionalni etalon za dolžino v R Sloveniji so vzporedna končna merila, ki so sledljiva na primarni etalon preko kalibracij v evropskih državnih laboratorijih. Etalone iz industrije in kalibracijskih laboratorijev kalibriramo po metodi mehanske primerjave dolžin z nacionalnim etalonom. Najboljša merilna zmogljivost, izražena z merilno negotovostjo, ni primerljiva z zmogljivostmi evropskih laboratorijev, ki kalibrirajo po metodi absolutne interferenčne meritve z laserjem, vendar je trenutno ustrezna glede na zahteve industrije. Naš cilj, ki temelji na predpostavljenem povečevanju zahtev industrije po točnosti, je zmanjšanje negotovosti kalibracij brez uvajanja interferenčnega sistema, ki bi bil za slovensko industrijo predrag. Raziskovalno delo na tem področju je usmerjeno v analizo kritičnih

0 INTRODUCTION

The national standard for length in Slovenia is realised with gauge blocks. These gauge blocks are traceable to the primary standard through calibrations in different European national laboratories. The standards from Slovenian industry and various calibration laboratories are calibrated by mechanical comparison with the national standard. Slovenia's best measurement capabilities are not comparable with those of other European national laboratories, which have interferometric calibration systems, but it is able to deal with the present industrial needs. Our aim is to reduce the uncertainty of length calibrations without having to resort to interferometric systems, which would be too expensive for industry. Our research work in this field is focused on critical uncertainty contributions like prispevkov k negotovosti, kakor so kalibracija opreme, pogoji okolice in vpliv merilnika.

Na podlagi raziskav smo se odločili, da bomo sistem za kalibracijo izboljšali z rekonstrukcijo merilne naprave in odlagalnih površin za temperaturno stabilizacijo etalonov in z avtomatizacijo merilnega procesa. Hkrati z uvajanjem teh izboljšav je treba tudi analizirati in spremeniti modele za vrednotenje merilne negotovosti zaradi optimiranja novega kalibracijskega postopka.

the calibration of the equipment, as well as environmental and human influences.

As a result of our research the calibration system will be improved by the reconstruction of the device and the surfaces for the thermal stabilisation of the gauge blocks and by the automation of the measurement process. In order to optimise the new calibration procedure, models for evaluating the uncertainty of measurements will be analysed and modified during the introduction of the improvements.

1 POSTOPEK VREDNOTENJA MERILNE NEGOTOVOSTI

1 PROCEDURE FOR EVALUATING THE MEASUREMENT UNCERTAINTY

Negotovost vrednotimo po postopku v [1], hkrati pa upoštevamo tudi priporočila EAL za evropske akreditirane laboratorije, ki so podana v [2]. Poglavitni koraki postopka so naslednji:

- Določimo matematični model meritve, ki predstavlja izhodno veličino meritve kot funkcijo vhodnih veličin. Funkcija f mora vsebovati vse veličine, vključno z vsemi povezavami in popravnimi faktorji, ki lahko prispevajo pomembno komponento negotovosti k merilnemu rezultatu. Pravilna določitev matematičnega modela meritve (1) je ključnega pomena za kakovost določitve negotovosti meritve:

The uncertainty is evaluated using the procedure in [1] and by considering the EAL guides for European accredited laboratories given in [2]. The procedure consists of the following basic steps:

- A mathematical model of the measurement, which represents the output value of the measurement as a function of input values, is defined. Function f comprises all the input values including all the corrections and correction factors that could significantly influence the uncertainty of the measurement result. The correct definition of the mathematical model (1) is of essential importance for the quality of the uncertainty evaluation:

$$y = f(x_1, x_2, ..., x_i, ..., x_N) \quad (1).$$

- Ovrednotimo standardne negotovosti vseh ocen vhodnih veličin $u(x_i)$. Če obstaja povezanost med dvema vhodnima veličinama (veličini med seboj nista neodvisni), moramo v skupni standardni negotovosti $u_c(y)$ upoštevati tudi člene, ki zajemajo kovariance ocen vhodnih veličin. Povezavo izrazimo z enačbo:

- Standard uncertainties $u(x_i)$ of all input values are evaluated. If there is a correlation between two input values (i.e. the values are not independent), parts including covariances of the input value estimations are considered in the combined standard uncertainty $u_c(y)$. The correlation is expressed by equation:

$$s(x_{i,k}, x_{j,k}) = \frac{1}{n-1}\sum_{k=1}^{n}(x_{i,k} - \bar{x}_i)(x_{j,k} - \bar{x}_j) \quad (2).$$

- Izračunamo standardno negotovost ocene izhodne veličine $u_c(y)$ po enačbi:

- The standard uncertainty of the output-value estimation $u_c(y)$ is evaluated using equation:

$$u_c^2(y) = \sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) \quad (3).$$

Če sta vhodni veličini X_i in X_j med seboj odvisni oz. sta v povezanosti, moramo v enačbi (3) upoštevati še njuno kovarianco. Enačba (3) dobi novo obliko:

If the input values X_i and X_j are dependent res. corelated, the covariance is included in equation (3). Equation (3) gets a new form:

$$u_c^2(y) = \sum_{i=1}^{N}\sum_{j=1}^{N}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}u(x_i, x_j) = \sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}u(x_i, x_j) \quad (4).$$

- Izračunamo razširjeno negotovost meritve:

- The expanded uncertainty of measurement is calculated:

$$U = ku_c(y) \quad (5).$$

- Faktor k izberemo v odvisnosti od zahtevanega nivoja zaupanja. Pri normalni porazdelitvi ustreza

- The coverage factor k is chosen with respect to the required level of confidence. In a normal distribution the faktor 2 nivoju zaupanja 95,45%, faktor 3 pa nivoju zaupanja 99,73%.

factor 2 corresponds to a level of confidence of 95.45% and the factor 3 to a level of confidence of 99.73%.

2 MODEL VREDNOTENJA NEGOTOVOSTI ZA SEDANJI POSTOPEK KALIBRACIJE

2 MODEL FOR THE MEASUREMENT UNCERTAINTY EVALUATION FOR THE EXISTING CALIBRATION PROCEDURE

2.1 Matematični model meritve

Meritev izvedemo tako, da najprej izmerimo referenčni etalon, nato pa še etalon, ki ga kalibriramo, in primerjamo med seboj izmerjeni vrednosti. Iz primerjave izmerjenih vrednosti izračunamo odstopek mere kalibriranega etalona. Ločljivost meritve je 10 nm. Postopek je opisan v [3] do [5]. Dolžina l končnega merila, ki ga kalibriramo, je podana z enačbo (6):

2.1 Mathematical model of measurement

The measurement is performed in such a way that the reference standard (gauge block) is measured first and then the standard to be calibrated is measured. The two measured values are compared and the deviation is calculated. The resolution of the measurement is 10 nm. The procedure is described in [3] to [5]. The length of the gauge block to be calibrated is calculated using equation (6):

$$l = l_e + \delta l - L \cdot (\delta\alpha \cdot \overline{\Delta t} + \overline{\alpha} \cdot \delta t) - \delta l_v \quad (6).$$

Ta enačba vsebuje vse veličine, ki pomembno vplivajo na rezultat meritve, vključno s popravki temperaturnih raztezkov in izsrednega tipanja končnega merila med meritvijo.

This equation contains all the values that significantly influence the measurement result including the thermal expansion and non-central gauge-block probing corrections.

2.2 Izračun koeficientov občutljivosti

Koeficienti občutljivosti za posamezne standardne negotovosti vhodnih veličin $u(x_i)$ povedo, kako močno bo določena negotovost vhodne veličine vplivala na skupno negotovost meritve. Izračunamo jih kot parcialne odvode funkcije f po posameznih vhodnih veličinah. V našem primeru moramo izračunati naslednje koeficiente občutljivosti [3]:

2.2 Sensitivity coefficient calculation

Sensitivity coefficients for single standard uncertainties of the input values $u(x_i)$ indicate the size of the influence of a particular input value's standard uncertainty on the total measurement uncertainty. These coefficients are calculated as partial derivatives of the function f over input values. In our case the following sensitivity coefficients are calculated [3]:

$$c_e = \partial l/\partial l_e = 1$$
$$c_{\delta l} = \partial l/\partial \delta l = 1$$
$$c_{\delta\alpha} = \partial \ell/\partial \delta\alpha = -L \cdot \overline{\Delta t}$$
$$c_{\overline{\Delta t}} = \partial \ell/\partial \overline{\Delta t} = -L \cdot \delta\alpha$$
$$c_{\overline{\alpha}} = \partial \ell/\partial \overline{\alpha} = -L \cdot \delta t$$
$$c_{\delta t} = \partial \ell/\partial \delta t = -L \cdot \overline{\alpha}$$
$$c_{\delta lv} = \partial l/\partial \delta l_v = 1$$

2.3 Ocene standardnih negotovosti vhodnih veličin in skupna standardna negotovost meritve

Standardne negotovosti vhodnih veličin smo ocenili na podlagi doseženih pogojev okolice, uporabljene merilne opreme, negotovosti kalibracije referenčnih etalonov in podatkov o lastnostih materialov etalonov. Pogoje okolice smo ovrednotili na podlagi meritev temperature v različnih točkah merilne prostornine, na mizi merilnega instrumenta in na etalonih pred kalibracijo in med njo. Podatke o lastnostih materialov (predvsem nas je zanimala linearna temperaturna razteznost α) smo dobili od nekaterih proizvajalcev končnih meril, podatke o

2.3 Standard uncertainty estimations of the input values and the total measurement uncertainty

The standard uncertainty estimations of the input values were based on the following: the environmental conditions; the measurement equipment used; the calibration uncertainties of the standard gauge blocks and the gauge-block comparator; and the material properties data. The environmental conditions were evaluated from temperature measurements at different points: in the measuring space, on the comparator table and on the gauge blocks, before and during the calibration. Material properties data (especially the linear thermal expansion coefficient α) were obtained from a negotovosti kalibracije referenčnih etalonov pa iz certifikata o kalibraciji. Negotovost zaradi izsrednega tipanja etalona smo ovrednotili na podlagi statistične analize več sto izmerjenih vrednosti.

V preglednici 1 so predstavljene ocene vrednosti posameznih vhodnih veličin, njihove standardne negotovosti, koeficienti občutljivosti, tip statistične porazdelitve za posamezno veličino in skupna standardna negotovost meritve (izračunana po enačbi (3)) za primer kalibracije etalona dolžine 100 mm.

number of gauge-block producers, while the uncertainties of the reference gauge-block calibration were obtained from the calibration certificates. The uncertainty of the non-central gauge-block probing was evaluated by a statistical analysis of many hundreds of measured values.

Estimated values of the input quantities, their standard uncertainties, sensitivity coefficients, type of statistical distributions for a single value, and the total standard uncertainty (calculated using equation (3)) for the case of the 100-mm gauge-block calibration are shown in Table 1.

Preglednica 1. *Standardne negotovosti ocen vhodnih veličin na zgornji meji merilnega območja (100 mm)*
Table 1. *Standard uncertainties of the input value estimations on the upper limit of the measurement range (100 mm)*

Veličina X_i Quantity X_i	Ocenjena vrednost Evaluated value	Standardna negotovost Standard uncertainty	Porazdelitev Distribution	Koeficient občutljivosti Sensitivity coefficient	Prispevek negotovosti Uncertainty contribution
l_e	100 mm	20 nm	normalna normal	1	20 nm
δ_l	0 nm	15,9 nm	normalna normal	1	15,9 nm
$\delta\alpha$	0 °C^{-1}	0,58·10^{-6} °C^{-1}	pravokotna rectangular	-3·10^{7} nm°C	-17,4 nm
$\overline{\Delta t}$	0 °C	0,08 °C	normalna normal	-200 nm°C^{-1}	-16 nm
$\overline{\alpha}$	11·10^{-6} °C^{-1}	0,40·10^{-6} °C^{-1}	pravokotna rectangular	-3·10^{7} nm°C	-12 nm
δ_t	0 °C	0,02 °C	pravokotna rectangular	-1200 nm°C^{-1}	24 nm
δ_{l_v}	0 nm	5 nm	normalna normal	1	5 nm
				Skupaj: Total:	44,2 nm

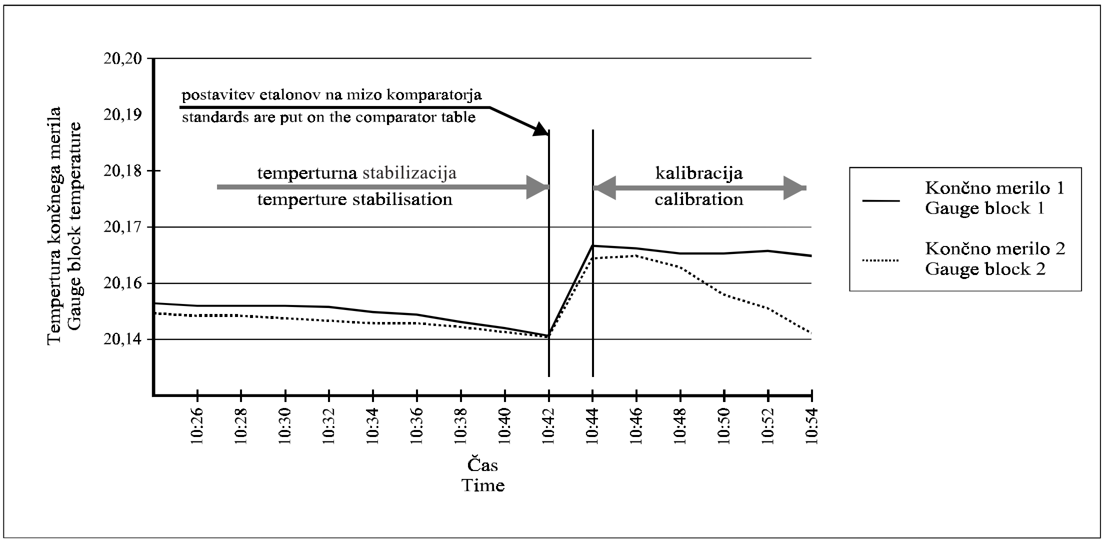
3 KRITIČNE KOMPONENTE NEGOTOVOSTI

Iz preglednice 1 vidimo, da poleg kalibracije etalonov in kompratorja (l_e, δl) bistveno vplivajo na negotovost še komponente δt, $\delta\alpha$ in $\overline{\Delta t}$. Če natančneje pogledamo komponento $\delta\alpha$, ugotovimo, da je prispevek negotovosti velik, ker je velik utežni koeficient $c_{\delta\alpha} = \partial\ell / \partial\delta\alpha = -L \cdot \overline{\Delta t}$, ta koeficient pa je odvisen od povprečnega odstopka temperature etalonov. Povzamemo lahko torej, da so bistveni vplivi na skupno negotovost kalibracije odstopek temperature etalonov, negotovost določitve temperaturnega odstopka, razlika med temperaturama referenčnega in kalibriranega etalona in negotovost določitve te razlike. Problem je predvsem v tem, da med kalibracijo ne moremo meriti temperatur posameznih etalonov, ampak merimo temperaturo mize komparatorja in predpostavljamo, da imata oba etalona enako temperaturo kakor miza. Dodatne težave povzroča

3 CRITICAL UNCERTAINTY COMPONENTS

As we can see in Table 1, besides the calibration of the standards and the comparator (l_e, δl) the components δt, $\delta\alpha$ and $\overline{\Delta t}$ significantly influence the total uncertainty. If we look closely at component $\delta\alpha$ we find that its contribution is significant because its sensitivity coefficient $c_{\delta\alpha} = \partial\ell / \partial\delta\alpha = -L \cdot \overline{\Delta t}$ is big. This coefficient depends on the average gauge-block temperature deviation. Indeed, we found that the significant influences on the total calibration uncertainty were the gauge-block temperature deviation, the uncertainty of temperature deviation evaluation, the temperature difference between the gauge blocks, and the uncertainty of the evaluation of this difference. One problem is that we are not able to measure the temperatures of both gauge blocks. However, we supposed that these temperatures are equal to the temperature of the comparator table, which is measured during the calibration. Additional problems nenaden porast temperature etalonov takoj po postavitvi na merilno mizo. Slika 1 prikazuje rezultate meritev temperature na dveh preskusnih etalonih med temperaturno stabilizacijo, postavitvijo na mizo komparatorja in med meritvijo.

are caused by a rapid gauge-block temperature rise after setting the gauge block on the comparator table. The results of temperature measurements on two test standards during: thermal stabilisation, placement on the table and measurement are shown in Figure 1.



Sl. 1. *Rezultati meritev temperature na etalonih pred kalibracijo in med njo*
Fig. 1. *Results of standard temperature measurements before and during the calibration*

Vidimo, da se pojavi kritični trenutek po postavitvi etalonov na mizo zaradi različnih toplotnih lastnosti materialov mize in površine za temperaturno stabilizacijo ter zaradi postavitve etalonov v navpično lego. Zaradi te temperaturne spremembe začnemo meritev približno tri minute po postavitvi etalonov na mizo komparatorja. Po nekaj minutah se pojavi nov problem. Temperaturi etalonov se začneta razhajati. Referenčni etalon, ki je postavljen bliže merilcu, ohranja temperaturo na približno isti ravni, medtem ko se kalibrirani etalon začne ohlajati. Po približno desetih minutah je razlika že 0,03 K, kar kritično vpliva na rezultat meritve.

It is easy to see that the critical moment is the placement of the standards on the comparator table. The temperature change is caused by the different thermal properties of the thermal stabilisation surface and the comparator table's surface and by turning the gauge blocks into the vertical position. In order to avoid the influence of this temperature change, the measurement begins approximately three minutes after the standards are placed on the table. However, a few minutes later a new problem arises. The gauge-block temperature difference increases. The reference gauge block that is closer to the operator maintains its temperature, while the gauge block being calibrated starts cooling. After about ten minutes the difference is already 0.03 K, large enough to have a critical influence on the measurement result.

4 SPREMEMBA MODELA VREDNOTENJA MERILNE NEGOTOVOSTI

4 MODIFICATION OF THE MODEL FOR MEASUREMENT UNCERTAINTY EVALUATION

V prejšnjem poglavju smo videli, da so kritični vplivi na negotovost predvsem negotovost kalibracije referenčnih etalonov in spremembe temperature etalonov pred kalibracijo in med njo. Na podlagi izkušenj v zadnjih petih letih, ko smo kalibrirali referenčne etalone v različnih evropskih državnih laboratorijih (PTB Nemčija, JV Norveška, BNM-LNE Francija) in smo natančno analizirali rezultate kalibracij, smo ugotovili, da pomeni pomemben prispevek k negotovosti tudi lezenje (drift) etalonov. Z leti se spreminjata dolžina in oblika etalonov, hkrati

In the previous section we have seen that the uncertainty of a calibration is critically influenced by the gauge-block calibration uncertainty and by the gauge-block temperature change before and during the calibration. However, our experience over the last five years, when calibrations of our reference standards have been performed in different European national laboratories (PTB Germany, JV Norway and BNM-LNE France) and when critical analyses of the calibration results have been performed, has shown that gauge-block drift also represents an important contribution to the uncertainty. Gauge-block length and geometry change over a period pa se zaradi uporabe obrabljajo. Zato moramo v matematični model (6) vnesti tudi popravek lezenja:

of a year as the surfaces get worn during application. For this reason the mathematical model (6) needs to be supplemented with a drift correction.

$$l = l_e + \delta l - L \cdot (\delta\alpha \cdot \overline{\Delta t} + \overline{\alpha} \cdot \delta t) - \delta l_v - d \quad (7).$$

Seveda je sprememba matematičnega modela samo prvi korak pri prilagoditvi modela vrednotenja negotovosti. Bistvene so dejavnosti, ki jih izvedemo na temelju analize kritičnih vplivov temperature.

Modification of the mathematical model is, however, only the first step in the modification of the uncertainty evaluation model. The activities that are performed on the basis of the analysis of critical temperature influences are very important.

4.1 Avtomatizacija postopka kalibracije

Nameni avtomatizacije postopka kalibracije so poleg časovne racionalizacije še naslednji:
- izključitev vplivov merilca na meritev (predvsem toplotno sevanje),
- postavitev etalonov v času temperaturne stabilizacije v enak položaj kakor med meritvijo,
- možnost zaščite etalonov pred nečistočami (teh v modelu vrednotenja negotovosti sicer nismo upoštevali, povzročajo pa naključne pogreške),
- manjša možnost mehanskih poškodb etalonov med meritvijo zaradi avtomatičnih pomikov merilne mize.

Avtomatiziran postopek bo potekal brez posegov merilca. Manipulator bo avtomatično postavljal etalone na merilno mizo, poseben krmilni mehanizem pa bo pomikal merilno mizo v položaje, ki jih določa merilni postopek.

Zasnova avtomatizacije, vključno z vsemi potrebnimi algoritmi in določitvijo mehanskih, pnevmatskih in elektronskih komponent, je že končana. V nasprotju s komercialnimi izvedbami avtomatizacije, ki jih ponujajo različni proizvajalci merilne opreme, smo se mi projekta lotili predvsem z vidika zmanjšanja merilne negotovosti in ne z vidika zmanjševanja merilnih časov. Izvedene so bile vse analize merilne negotovosti, ki so zajemale predvsem raziskave sprememb pogojev merjenja.

Z vidika merilne negotovosti je avtomatizacija pomembna zaradi zmanjšanja razlike med temperaturama referenčnega in kalibriranega etalona in zaradi zmanjšanja spremembe temperature po postavitvi etalonov na merilno mizo primerjalnika.

4.1 Automation of the calibration process

In addition to reducing the time of the calibration process the automation is designed to do the following:
- eliminate the operator influences on the measurement (especially thermal radiation),
- ensure the same position of the gauge blocks during the thermal stabilisation and the measurement,
- protect the gauge blocks from dirt (this was not considered in the uncertainty evaluation model, but it can cause random errors),
- decrease the possibility of mechanical damage during the measurement by introducing automated table movements.

The automated process will run without operator interventions. A manipulator will put standards on the measurement table, which will then be moved into specified positions by a special mechanism.

The design of the automated system including all the necessary algorithms and the determination of the necessary mechanical, pneumatic and electronic elements is already finished. In contrast to commercial automation systems offered by various producers of gauge-block comparators, the primary aim of our automation project is to reduce uncertainty rather than reducing the time and costs of calibration. All the uncertainty analyses relating to the change in measurement conditions have already been done.

Concerning measurement uncertainty, automation is important in order to decrease the temperature difference between the reference gauge block and the gauge block being calibrated, and to decrease the temperature change after placing the gauge blocks on the comparator table.

4.2 Merilna negotovost avtomatiziranega postopka

Analiza temperatur pred meritvijo in med njo, ki je temeljila na simuliranju avtomatiziranega merilnega postopka in je obsegala več sto meritev temperatur ob uporabi različnih materialov, virov osvetlitve in pogonskih agregatov (vključno z različnimi vrstami izolacije in odvoda toplotne energije), je pokazala, da se lahko temperaturne razmere znatno izboljšajo. Končni rezultati analize so predstavljeni v preglednici 2.

4.2 Measurement uncertainty of the automated process

A temperature analysis before and during the measurement based on a simulation of an automated process and containing hundreds more temperature measurements for different materials, illumination sources and driving aggregates (including different types of isolations and thermal energy flows) has shown that the thermal conditions can be significantly improved. The final analysis results are presented in Table 2.

Preglednica 2. *Standardne negotovosti ocen vhodnih veličin na zgornji meji merilnega obmoèja (100 mm) po spremembi kalibracijskega postopka*
Table 2. *Standard uncertainties of the input value estimations on the upper limit of the measurement range (100 mm) after modifying the calibration procedure*

Veličina X_i Quantity X_i	Ocenjena vrednost Evaluated value	Standardna negotovost Standard uncertainty	Porazdelitev Distribution	Koeficient občutljivosti Sensitivity coefficient	Prispevek negotovosti Uncertainty contribution
l_e	100 mm	20 nm	normalna normal	1	20 nm
δl	0 nm	15,9 nm	normalna normal	1	15,9 nm
$\delta\alpha$	0 °C^{-1}	0,58·10^{-6} °C^{-1}	pravokotna rectangular	-1·10^{7} nm°C	-5,8 nm
$\overline{\Delta t}$	0 °C	0,04 °C	normalna normal	-200 nm°C^{-1}	-8 nm
$\overline{\alpha}$	11·10^{-6} °C^{-1}	0,40·10^{-6} °C^{-1}	pravokotna rectangular	-1·10^{6} nm°C	-0,4 nm
δt	0 °C	0,01 °C	pravokotna rectangular	-1200 nm°C^{-1}	-12 nm
δl_v	0 nm	5 nm	normalna normal	1	5 nm
d	0 nm	7 nm	pravokotna rectangular	1	7 nm
				Skupaj: Total:	31,1 nm

5 SKLEP

Z avtomatizacijo postopka kalibracije končnih meril dosežemo stabilnejše pogoje merjenja in s tem zmanjšamo bistvene vplive na merilno negotovost. Na podlagi simuliranja postopka in analize pogojev (predvsem temperature) smo ugotovili, da se predvsem bistveno zmanjša razlika med temperaturama etalonov in sprememba temperature po postavitvi etalonov na merilno mizo. Skupna merilna negotovost se pri etalonu dolžine 100 mm zmanjša za približno 34%. S takšno negotovostjo kalibracije dosežemo raven najboljših svetovnih kalibracijskih laboratorijev, primerljivi pa postanemo tudi z nekaterimi laboratoriji, ki kalibrirajo po metodi absolutne interferenčne meritve z uporabo primarnega etalona.

5 CONCLUSION

An automated gauge-block calibration process ensures more stable measurement conditions and so the critical influences on measurement uncertainty are therefore minimised. The process simulation and conditions (temperature) analysis have shown that the temperature difference between the standards and the temperature change after placing the standards on the comparator table decrease significantly. The total uncertainty for the 100-mm standard decreases by about 34%. With such an uncertainty a level comparable with that of the world's best laboratories is achieved and the results can also be compared with some laboratories performing calibrations using the absolute interference method with an application of the primary standard of measurement.

6 SIMBOLI
6 SYMBOLS

ocena izhodne veličine meritve	y	measurement output value estimation
ocena vhodne veličine meritve	x_i	measurement input value estimation
standardna negotovost ocene vhodne veličine	$u(x_i)$	standard uncertainty of an input value estimation
skupna standardna negotovost meritve	$u_c(y)$	combined standard uncertainty of measurement
razširjena negotovost meritve	U	expanded uncertainty of measurement
faktor širitve negotovosti	k	coverage factor
kalibrirana dolžina končnega merila	l	calibrated gauge-block length

dolžina referenčnega končnega merila	l_e	reference gauge-block length
izmerjena razlika med referenčnim in kalibriranim končnim merilom	δl	measured difference between the reference and the calibrated gauge block
imenska dolžina končnega merila	L	nominal gauge-block length
povprečna razteznost končnih meril	$\bar{\alpha}$	average linear thermal expansion coefficient of two gauge blocks
razlika linearnih temperaturnih razteznosti končnih meril	$\delta\alpha$	difference between the linear thermal expansion coefficients of two gauge blocks
povprečni odstopek temperature končnih meril od 20 °C	$\overline{\Delta t}$	average temperature deviation of two gauge blocks from 20 °C
razlika temperatur končnih meril	$t\delta$	gauge-block temperature difference
odstopek zaradi izsrednega tipanja končnega merila	δl_v	deviation caused by non-central gauge-block probing
korekcija lezenja končnega merila	d	gauge-block drift correction

7 LITERATURA
7 REFERENCES

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