MEASUREMENT UNCERTAINTY OF LENGTH MEASUREMENTS ACCORDING TO THE NEW VERSION OF SRPS / ISO STANDARD

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Summary: *Internationally recognized standards, which change over time, are used to calibrate electro-optical distance meters. Such is the case with SRPS/ISO standard 17123-4. The new version of the standard differs from the previous one in calculating the measurement uncertainty which is given in a new way. The paper presents the procedure for calculating the uncertainty of measuring lengths with electro-optical distance meters according to the old and to the new standard.*

Keywords: *Uncertainty, electro-optical distance meter, standards*

1. INTRODUCTION

For the purpose of global acceptance of the European measurement results and calibration, a coherent transfer of measurement capacities is required. The coherent transfer is achieved by expressing the measurement uncertainty according to the rules and documents of the International Laboratory Accreditation Cooperation - ILAC [8]. Adherence to these rules and documents is aimed at assisting the national accreditation body (ATS) in the process of calibration laboratories' accreditation. The calibration laboratories are obligated to provide the documented evidence on the measurement uncertainty estimation performed during the evaluation and verification of their competences. The measurement uncertainty estimation is required for all calibrations and measurements within the Scope of Accreditation. When performing evaluation and accreditation of calibration laboratories, the ATS applies the provisions and instructions stipulated in the following documents:

- ISO/IEC 17025: General requirements for the competence of testing and calibration laboratories.
- EA-4/02 M: Evaluation of the Uncertainty of Measurement in Calibration.

The existence and application of the document for estimating the measurement uncertainty is accepted as the proof of meeting the requirements of the SRPS ISO/IEC 17025:2017 standard. That document shall be produced in accordance with the requirements of the above standard, while noting as an example the result of the measurement uncertainty

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estimation performed for a particular case of calibration. In the event of multiple existing methods of calibration, the measurement uncertainty estimate shall be done for each individual method, i.e. for each measurement type.
The measurement uncertainty estimate shall be performed in accordance with the document EA-4/02 M:2013. The laboratories are obligated to determine and document the Calibration and Measurement Capability (CMC) they may achieve for their particular accreditation scope in accordance with this document and method of the measurement uncertainty estimation [1].

2. MEASUREMENT UNCERTAINTY

The measurement uncertainty evaluation determines the Calibration and Measurement Capability - CMC. The Calibration and Measurement Capability is expressed against:

- reference equipment;
- method of calibration and type of the instrument to be calibrated;
- measurement range and auxiliary parameters;
- measurement uncertainty.

"The uncertainty of measurement is a non negative parameter, associated with the result of a measurement that characterises the dispersion of the values that could reasonably be attributed to the measure." [2].
Regarding the expression of the Calibration and Measurement Capability (CMC), the particular attention needs to be paid on the application of a single or multiple methods of its expression. Regarding the manner in which the value of the unit to be calibrated and its measurement uncertainty are being determined, the input values are divided into three categories:

- Values directly determined at the moment of measurement. Those may also contain certain corrections due to the working conditions (such as: environment temperature, barometric pressure or humidity);
- Values that are entered into measurement from the external sources, such as the values related to the data obtained from manuals and instructions;
- Values that are determined indirectly, as the functions of measured values.

Calculation of the standard measurement uncertainty of values directly determined at the moment of measurement $X\left(x_1,\ x_2,...x_n\right)$ is performed based on:

- Verification of the reference equipment calibration. Reading the extended measurement uncertainty *U*, for the coverage factor *k*=2 and confidence level of 95%:

$$u_{X_C} = \frac{U}{2} \tag{1}$$

- Resolution reading *r* of the reference equipment. The orthogonal distribution is taken as an assumption, thus the standard measurement uncertainty is calculated as:

$$u_{X_r} = \frac{\frac{r}{2}}{\sqrt{3}} \tag{2}$$

- The sample $X\left(x_1,\ x_2,...x_n\right)$:

$$u_{X_m}=\frac{\sigma_X}{\sqrt{n}} \tag{3}$$

where: $\sigma_X=\sqrt{\frac{\sum_{i=1}^{n}\left(x-\overline{x}\right)^2}{n-1}}$; x - measurement result ; $\overline{x}$ - mean measurement result, and n number of measurements.

The standard uncertainty of measurand is:

$$u_X=\sqrt{\left(u_{X_C}\right)^2+\left(u_{X_r}\right)^2+\left(u_{X_m}\right)^2} \tag{4}$$

Measurement uncertainty of the measurand function $F=f\left(x,\ y,\ ...z\right)$ is determined by the application of the law on errors transference in the form of the expression:

$$\left(u_f\right)^2=\left(\frac{\partial F}{\partial x}\right)^2u_x^2+\left(\frac{\partial F}{\partial y}\right)^2u_y^2+\ ...\left(\frac{\partial F}{\partial z}\right)^2u_z^2=c_i^2u_i^2,\quad i=x,\ y,\ ...z \tag{5}$$

where: c_i - the sensitivity coefficient.

Within EA it has been decided that calibration laboratories accredited by members of the EA shall state an expanded uncertainty of measurement *U*, obtained by multiplying the standard uncertainty $u\left(y\right)$ of the output estimate *z* by a coverage factor *k*=2 shall be used. The assigned expanded uncertainty corresponds to a coverage probability of approximately 95% [2].

The measurement uncertainty is estimated for two types: "type A" or "type B".

- The type A is a method of uncertainty valuation by the means of statistical sample analysis. In this case, standard measurement uncertainty is the experi-mental standard deviation of the sample mean or the appropriate analysis using the least squares method.
- The type B is a method of uncertainty valuation in a different manner, which is not based on the statistical sample analysis and is founded in scientific knowledge and experience instead.

The measurement uncertainty calculation procedure:

- Define the values that are being directly determined at the moment of measurement, sample: $X\left(x_1,\ x_2,...x_n\right)$;
- Enter the corrections in the measurement results Δ_i;
- Define the function linking the measured values: $F=f\left(X_1,\ X_2,\ ...X_n\right)$;
- Apply the law of errors propagation for all measurement uncertainties;
- Determine the standard measurement uncertainty of the sample: $X\left(x_1,\ x_2,...x_n\right)$ - for type A;
- Determine the standard measurement uncertainty from the available literature based on scientific knowledge and experience - for type B;
- Determine the total measurement uncertainty for the measured value: *u*;
- Calculate the extended measurement uncertainty: *U* with the coverage factor *k*=2.

The measurement result includes the measured value $X(x_1, x_2,...x_n)$ and the associated extended measurement uncertainty *U*. The measurement result should be presented as $x \pm U$, with associated units for x, U. The measurement results in table format may also be used, as well as the relative extended measurement uncertainty $\frac{U}{x}$. The verification on calibration needs to stipulate the coverage probability and the coverage factor.

3. MEASUREMENT UNCERTAINTY BUDGET

The measurement uncertainty budget is formed in the event of non-fitted quantities included in the total measurement uncertainty calculation. Use of the schematic contribution to the total measurement uncertainty is recommended for any calibration method, Table 1.

Table 1. Schematic of an ordered arrangement of the quantities, estimates, standard uncertainties, sensitivity coefficients and uncertainty contributions used in the uncertainty analysis of a measurement.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Contribution to the standard uncertainty $u_i(y)$
X_1	x_1	$u(x_1)$		c_1	$u_1(y)$
X_2	x_2	$u(x_2)$		c_2	$u_2(y)$
:	:	:		:	:
X_N	x_N	$u(x_N)$		c_N	$u_N(y)$
F	f				$u(f)$

4. CALIBRATION OF ELECTRO-OPTICAL DISTANCE METERS

In the methods used for calibration of distance meters, the measurement uncertainty is being expressed over the values directly determined at the moment of measurement (with the parameters used for determining the measurement uncertainty) and measured value unit.

The SRPS ISO 17123-4:2014 document describes the standard method for calibration of distance meters. The standard (chapter: 5 Simplified test procedure; 5.1 Configuration of the test field) shows a polygon, measurement procedure and the procedures to be adop-ted for determination and evaluation of precision (repeatability) of the EDM instrument, together with the equipment when used for geodetic measurements. These tests are predominantly aimed at verifying if a certain instrument is appropriate for the task at hand.

Polygon for short distances consists of a single permanently stabilized pillar for moun-ting the instrument and four permanently placed pillars for mounting the prism. This polygon is used for the addition constant value determination.
The multiplication constant is determined by measuring a single, long distance to the signal prism mounted on a distance greater than 200 m.

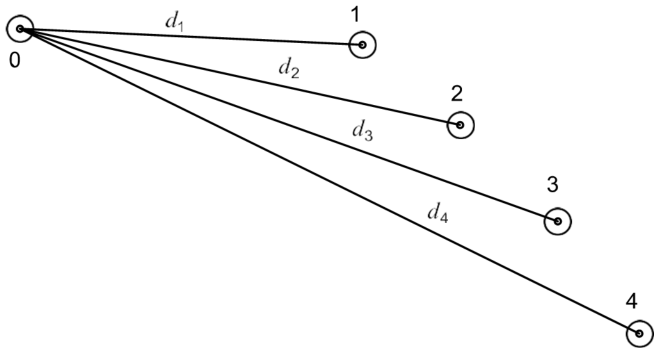

Figure 1. Configuration of the test field

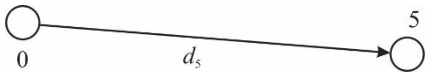

Figure 2. Configuration of the test field

5. MEASUREMENT UNCERTAINTY

The total standard measurement uncertainty is obtained as the sum of two measurement uncertainties (u_a - for short and u_b - for long distances):

$$u_D = u_a + u_b \tag{6}$$

The extended measurement uncertainty is calculated by multiplying coefficients u_a and u_b in the expression (6) with the coverage factor *k*=2:

$$U_D = 2u_a + 2u_b \tag{7}$$

5.1. SHORT DISTANCE MEASUREMENT UNCERTAINTY

The result of measurements in the short distance polygon contains:

- Component covering the measured distance in the polygon D_m and
- Component based on the experiences and scientific knowledge regarding the equipment and tools used for the measurement.

The components that are directly related to the equipment and tools are the error of centering distance meter and prism (ΔD_{cd}, ΔD_{cp}) as well as the rounding error (ΔD_{gc}). The result (D_a) of short distance measurement is given by the following expression:

$$D_a = D_m + \Delta D_{cd} + \Delta D_{cp} + \Delta D_{gc} \tag{8}$$

where:

D_a - distance value ("accurate" result of measurement),

D_m - measured distance value (result of measurement),

ΔD_{cd} - error of centering distance meter,

ΔD_{cp} - error of centering prism,

ΔD_{gc} - error of rounding reading.

The short distance measurement uncertainty pursuant to EA-4/02 is:

$$u_a^2 = u_{(D_a)}^2 = c_{D_m}^2 \cdot u_{(D_m)}^2 + c_{D_{vd}}^2 \cdot u_{(D_{cd})}^2 + c_{D_{cp}}^2 \cdot u_{(D_{cp})}^2 + c_{D_{gc}}^2 \cdot u_{(D_{gc})}^2 \quad (9)$$

where c_i are sensitivity coefficients, i.e. partial derivatives of the function (8) per individual significant values.

5.2. LONG DISTANCE MEASUREMENT UNCERTAINTY

The result of measurements in the long distance polygon contains:

- Component covering the measured distance in the polygon D_m together with the addition constant *a* and
- Component based on the experiences and scientific knowledge regarding the equipment and tools used for the measurement.

The result D_b of long distance measurement is given by the following expression:

$$D_b = D_m + a + \Delta f_D + \Delta D_t + \Delta D_p + \Delta D_h + \Delta D_{cd} + \Delta D_{cp} + \Delta D_{gc} \quad (10)$$

where:

D_b - distance value ("accurate" result of measurement),

D_m - measured distance value (result of measurement),

a - addition constant,

Δf_D - correction for frequency (multiplication constant),

ΔD_t - correction for measurement temperature deviation from normal value,

ΔD_p - correction for measurement pressure deviation from normal value,

ΔD_h - correction for measurement humidity deviation from normal value,

ΔD_{cd} - error of centering distance meter,

ΔD_{cp} - error of centering prism,

ΔD_{gc} - error of rounding reading.

The long distance measurement uncertainty pursuant to EA-4/02 is:

$$\begin{aligned} u_b^2 = u_{(D_b)}^2 &= c_{D_m}^2 \cdot u_{(D_m)}^2 + c_a^2 \cdot u_a^2 + c_{\Delta f_D}^2 \cdot u_{(D_{\Delta f_D})}^2 + c_{D_t}^2 \cdot u_{(D_t)}^2 + c_{D_p}^2 \cdot u_{(D_p)}^2 \\ &+ c_{D_h}^2 \cdot u_{(D_h)}^2 + c_{D_{vd}}^2 \cdot u_{(D_{cd})}^2 + c_{D_{cp}}^2 \cdot u_{(D_{cp})}^2 + c_{D_{gc}}^2 \cdot u_{(D_{gc})}^2 \end{aligned} \quad (11)$$

where c_i are sensitivity coefficients, i.e. partial derivatives of the function (10) per individual significant values.

6. MEASUREMENT UNCERTAINTY BUDGET

The measurement uncertainty budget is determined by the sum of two measurement uncertainties: for short u_a and long distances u_b .

6.1. SHORT DISTANCE MEASUREMENT UNCERTAINTY BUDGET

Values of the individual coefficients for the short distances measurement uncertainty (9) are provided in Table 2, together with all other values required for calculating the least possible measurement uncertainty budget. Standard uncertainties of the input value impacts for calibration are calculated (evaluated) for the equipment used and assumed measurement conditions.

Table 2: Least possible short distance measurement uncertainty budget

Input value X_i	Value / unit x_i	Std. meas. uncert. u_i	Distribution	Sensitivity coefficient c_i	Impact on meas. unc. $c_i^2 \cdot u_{(x_i)}^2$ mm²	Measurement uncertainty type and source
D_m	5.4 m	0.3 mm	Normal	1	0.090	*A*, measured distance error, from polygon adjustment
ΔD_{cd}	0	0.2 mm	Orthogonal	1	0.040	*B*, distance meter centering, *u* from experience
ΔD_{cp}	0	0.2 mm	Orthogonal	1	0.040	*B*, prism centering, *u* from experience
ΔD_{gc}	0.1	0.029 mm	Orthogonal	1	0.001	*B*, error of rounding reading, *u* per formula: $u = \text{div.}/(2 \cdot \sqrt{3})$
			Square root of sum:		0.41	Mm

6.2. LONG DISTANCE MEASUREMENT UNCERTAINTY BUDGET

Values of the individual coefficients for the long distances measurement uncertainty (11) are provided in Table 3, together with all other values required for calculating the least possible measurement uncertainty budget. Standard uncertainties of the input value impacts for calibration are calculated (evaluated) for the equipment used and assumed measurement conditions.

Table 3: Least possible short distance measurement uncertainty budget

Input value X_i	Value/unit x_i	Std. meas. uncert. u_i	Distribution	Sensitivity coefficient c_i	Impact on meas. unc. $c_i^2 \cdot u_{(x_i)}^2$ mm²/230m	Measurement uncertainty type and source
D_m	230.213 m	1.3 mm	Normal	1	1.513	*B*, meas. dist. error per manufacturers' error limit
a	0.0 mm	0.3 mm	Normal	1	0.090	*A*, addition constant, from polygon adjustment
Δf_D	0	0.5 ppm	Normal	D_m	0.013	*B*, DM frequency modulation, *u* from experience
ΔD_t	$\Delta t = 0°C$ 0 mm	1.0 °C	Normal	$1 \cdot 10^{-6} \cdot D_m$	0.053	*B*, temperature deviation from nominal value, *u* from experience
ΔD_p	$\Delta p = 0$hPa 0 mm	2 hPa	Normal	$0{,}3 \cdot 10^{-6} \cdot D_m$	0.019	*B*, pressure deviation from nominal value, *u* from experience
ΔD_h	$\Delta h = 0\%$ 0 mm	20 %	Normal	$0{,}005 \cdot 10^{-6} \cdot D_m$	0.001	*B*, humidity deviation from nominal value, *u* from experience
ΔD_{cd}	0	0.2 mm	Orthogonal	1	0.040	*B*, DM centering, *u* from experience
ΔD_{cp}	0	0.2 mm	Orthogonal	1	0.040	*B*, prism centering, *u* from experience
ΔD_{gc}	0.1	0.029 mm	Orthogonal	1	0.001	*B*, error of reading rounding, *u* per formula: $u = \text{div.}/\left(2 \cdot \sqrt{3}\right)$
Sum	230.213 m			Square root of sum:	1.33	Mm

The total standard measurement uncertainty of the distance measurement is obtained as the sum of two measurement uncertainties (for short and long distances):

$$u_D = u_a + u_b \tag{12}$$

Extended measurement uncertainty is calculated by multiplying coefficients u_a and u_b in the expression (12) by the coverage factor k=2:

$$U_D = 2 \cdot u_a + 2 \cdot u_b \tag{13}$$

i.e.:

$$U_D = 0{,}82\ \text{mm} + 2{,}66\ \text{mm/km} \tag{14}$$

The numeric value of the extended measurement uncertainty is expressed with the maximum of two significant figures. Similarly, the numeric value of the measurement result is usually rounded to the decimal place of the least significant figure of the extended measurement uncertainty value.

7. CONCLUSIONS AND DISCUSSION

The concept of the distance meter possibility of measurement and calibration has been examined in detail in the present paper. The result of the measurement uncertainty estimate performed for a particular case of calibration is in line with the rules and guidelines of the international and national accreditation bodies. The research is the result of the documented measurements performed using the reference equipment that meets the requirements for the accreditation scope: $U_D = 0{,}82\ \text{mm} + 2{,}66\ \text{mm/km}$.

The purpose of expressing the accreditation scope is to:

- Determine the fields of activity of the calibration laboratory verified by the Accreditation body of Serbia;
- Provide the users of the services with the overview of the capacities of measurement and calibration achieved by the accredited calibration laboratories.

In accordance with the requirements of the SRPS ISO/IEC 17025:2017 standard, all equipment used for the establishment of the calibration polygons (Figure 1, Figure 2) including the equipment for auxiliary measurements - environment conditions, is calibrated prior to the commissioning. Calibration and Measurement Capability is calculated in the paper for the reference equipment used in the calibration polygon, which is available to the service users under the regular circumstances.

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МЕРЕНА НЕСИГУРНОСТ МЕРЕЊА ДУЖИНА ПРЕМА НОВОЈ ВЕРЗИЈИ SRPS/ISO СТАНДАРДА

Резиме: *За еталонирање електрооптичких даљиномера користе се међународно признати стандарди који се временом мењају. Такав је случај и са SRPS/ISO стандардом 17123-4. Нова верзија стандарда се у односу на претходну разликује у рачунању мерне несигурности која је дата на нов начин. У раду је представљен поступак рачунања мерне несигурности код мерења дужина електрооптичким даљиномерима према срaром и новом стандарду.*

Кључне речи: *Мерна несигурност, електрооптички даљиномер, стандарди*