Estimation of Measurement Uncertainty (Firearms)

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1. Introduction

The ASCLD/LAB-*International* accreditation program accredits forensic science laboratories to the ISO/IEC 17025:2005 and the 2011 ASCLD/LAB-*International* Supplemental Requirements. Section 5.4.6 of the ISO/IEC 17025 accreditation document contains requirements for estimating the uncertainty of measurements, specifically:

Clause 5.4.6.2: Testing laboratories shall have and shall apply procedures for estimating uncertainty of measurement. In certain cases the nature of the test method may preclude rigorous, metrological and statistically valid, calculation of uncertainty of measurement. In these cases the laboratory shall at least attempt to identify all the components of uncertainty and make a reasonable estimation, and shall ensure that the form of reporting of the result does not give a wrong impression of the uncertainty. Reasonable estimation shall be based on knowledge of the performance of the method and on the measurement scope and shall make use of, for example, previous experience and validation data.

The ASCLD/LAB-*International* "Policy on Measurement Uncertainty" requires laboratories accredited by ASCLD/LAB-*International* to estimate the measurement uncertainty for any area of testing or calibration where the customer makes a request or the jurisdiction or statute requires such. At a minimum, ASCLD/LAB requires the laboratory to assess the measurement uncertainty when quantitative values are reported for: 1. the quantity (mass or volume) of a controlled substance, or the presence of a controlled substance when it is reported as a percentage (mass or volume) of the whole sample; 2) the concentration (mass or volume fraction) of a drug in a toxicology sample, including values reported for blood alcohol; 3) the barrel length of a firearm and/or the overall length of a firearm; and 4) the calibration of breath alcohol measuring instruments and calibration of breath alcohol reference materials.

2. Scope

This document sets forth the process used to determine the measurement uncertainty for the barrel length of a firearm and/or the overall length of a firearm for the SCDL Firearm Discipline; useful terms, definitions, and equations; an overview of measurement uncertainty; procedure employed by the Firearm Discipline to estimate the measurement uncertainty; analysis of uncertainty with calculations; and summary with estimated measurement uncertainties for the Firearm Discipline.

3. Measurements Requiring Estimation of Uncertainty (Firearm Discipline)

The measurements requiring estimation of uncertainty being reported by the SCDL Firearm Discipline as established by the SCDL "Firearms/Toolmarks" (FTM) and "Firearm and Toolmark Work Instructions" (FTMWI) Manuals include the barrel and overall firearm lengths for state and federal penalty thresholds.

The state and federal thresholds are:

- Barrel length
  - Less than 18 inches for shotguns
  - Less than 16 inches for rifles
- Overall length – Less than 26 inches for both shotguns and rifles

4. Terms, Definitions, and Equations

Combined uncertainty – (Uc) of the measurement result when that result is obtained from the values of a number of other quantities, equal to the positive square root of a sum of terms, the terms being the weighted variances of the individual uncertainty components:

$$U_c = \sqrt{a^2 + b^2 + c^2 + \cdots}$$

Coverage factor – numerical factor (k) used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty. A coverage factor of k = 2 yields a level of confidence of 95%; k = 3 yields a level of confidence of 99.7%.

Expanded interval – interval centered on the sample mean within which the measurand is expected to lie with a specified coverage probability. The end-points of the interval define the limits of the estimated uncertainty of the measurand (EUM):

$$EUM = \bar{x} \pm U$$

Expanded uncertainty – quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand. The expanded uncertainty (U) is determined by multiplying the combined uncertainty by the coverage factor:

$$U = u_c \times k$$

Level of confidence (coverage probability) – the degree of certainty expressed as a percentage that the true value of the measurand falls within the expanded interval.

Measurand – quantity intended to be measured (e.g. the length of a firearm barrel).

Measurement – process of experimentally obtaining information about the magnitude of a quantity.

Measurement result – information about the magnitude of a quantity, obtained experimentally.

Measurement uncertainty – parameter that characterizes the dispersion of the quantity values that are being attributed to a measurand, based on the measurement information.

Normal distribution – a distribution in which the values of the measurand are more likely to fall nearer the mean than further away resulting in a "bell" shaped curve, also called a *Gaussian* distribution.

Repeatability – closeness of the agreement between the results of successive measurements of the same measureand carried out under the same conditions of measurement.

Reproducibility – closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement.

Root sum square (RSS) formula – combines independent components by squaring the components, summing the squares, and taking the square root of the sum.

$$\text{RSS} = \sqrt{a^2 + b^2 + c^2 + \cdots}$$

Sample mean – the sum of the sample data points divided by the number of data points, mathematically:

$$x = \frac{\sum_{1}^{n} x_i}{n}$$

Sample size (n) – number of measurements performed.

Standard Deviation – a measure of the dispersion of the data points about the sample mean. For the normal distribution:

$$s = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}}$$

Standard Uncertainty – measurement uncertainty expressed as a margin equivalent to plus or minus one standard deviation.

Uniform (Rectangular) distribution – a distribution in which the values of the measurand are uniformly distributed over a range from "a" to "b". Its standard uncertainty is the half width between the upper and lower limits divided by the square root of three,

$\frac{\frac{1}{2}(a-b)}{\sqrt{3}}$; it's variance is the square of the standard uncertainty.

Variance-A measure of the degree of spread of a set of values about their mean value equal to the square of the standard deviation or the square of the standard uncertainty.

5. **Measurement Uncertainty**

5.1 Introduction

When a measurement is made, there exists some question or uncertainty as to how the measured value relates to the true value of the measurand. The measuring system, measurement procedure, operator skill, environment, or other factors may introduce random and/or systematic errors into the measuring process. In general, any series of replicated measurements (or sample) will result in a dispersion or distribution of measured values with the true value of the measurand lying somewhere within the limits of the measurement results.

For a normally or uniformly distributed sample of replicate measurements, the best estimate of the true value of the measurand is given by the sample mean or average. The best estimate of the dispersion of the measurements is given by the standard deviation of the sample.

A generally accepted approach to estimating the measurement uncertainty involves calculating an expanded interval with an associated coverage probability. The expanded interval is determined by:

- calculating or estimating the variances of the sources of uncertainty
- calculating the combined uncertainty using the root sum square method
- selecting a coverage factor and multiplying the combined uncertainty to obtain an expanded uncertainty
- adding and subtracting the expanded uncertainty to the mean (or measured value) of the measurand to yield, respectively, the upper and lower limits of the expanded interval
- determining the level of confidence of the expanded interval based upon the coverage factor. For example, a coverage factor of 3 yields a level of confidence of approximately 99.7% that the measurand is included within the expanded interval.

5.2 Overall Length and Barrel Length

5.2.1 <u>Specify the measurement process</u>

Measurand:

<u>Overall length of a firearm</u> is measured using 48 and 12 inch calibrated steel rulers, with 0.1 inch scale markings. The range of measurements is up to 51 inches.

<u>Barrel length of a firearm</u> is measured using 48 and 12 inch calibrated steel rulers, with 0.1 inch scale markings. The range of measurements is up to 30 inches.

Current test method: The procedure for this measurement process is described in the current SCDL Manual: Firearm and Toolmark Work Instructions.

Overall length: A measured line that is parallel to the axis of the bore from a perpendicular tangential line that touches the rearmost point of the butt-plate to the muzzle.

Barrel length: A measured line that is the distance from the breech end of the barrel to the muzzle.

The overall length or barrel length can be expressed by the following equation:

$$Y = y + b \pm U$$

Where,

y is the best estimate of the measurand Y from the test method and is expressed by:

$y = f(X_{1,} X_{2,} \ldots, X_n)$

y is a function to the components of uncertainty

b = bias; in this example, the calibrated scale error is a systematic bias in the measurement

U = Expanded uncertainty

5.2.2 Identify the uncertainty components

Traceability is established for this measurement through the every third year calibration of the rulers used to make the measurement.

External calibration of the 48” and 12” steel digital rulers is performed by a calibration laboratory- Certified Measurements, Inc. that meets Section 3.2.3 of the ASCLD/Lab Policy on Measurement Traceability.

List of Uncertainty Components Considered:

Measuring Equipment

- Length scale readability
- Length scale resolution
- Calibration uncertainty
- Calibrated scale error
- Proper use, storage and handling

Staff

- Multiple analysts

- Training
- Experience
- Visual acuity
- Time of day, day of week, interruptions, workload

Test Method

- The same test method is used to measure the length of all types of firearms
- Differences in establishing parallel and perpendicular between analysts
- Analyst must position measuring equipment at both the zero point at the butt end of the firearm and at the end of the barrel

Facility

- Temperature variation of laboratory and difference from that during calibration
  Impact on the coefficient of expansion of the measuring equipment
- Lighting
- Space

5.2.3 <u>Quantify the uncertainty components</u>

Data has been collected during a laboratory study performed to evaluate variation in the measurement process across the two analysts. The study performed during method validation utilized firearms from the laboratory's reference collection. The firearms included in the study covered the range of overall lengths up to 51.0" and the range of barrel lengths up to 30.0". The study covered the measuring device used for the test, different days and different times of day (twice a day for three days in each of two weeks, by each analyst), different types and ages of lighting and normal variations in laboratory temperature. The study will be repeated for one week (3 days, twice a day) quarterly during the next calendar year for a final calculation of measurement uncertainty in December of 2016.

The laboratory has standard operating procedures for use, storage, handling, and calibration checks for the digital rulers.

The table below lists each uncertainty component considered and how it will be evaluated.

Uncertainty Component	Method of Evaluation
Measuring Equipment: 12" digital ruler – Only one 12" ruler in discipline 48" digital ruler – Only one 48" ruler in discipline	
Length scale readability	Type B Evaluation
Length scale resolution	Type B Evaluation
Calibration uncertainty	Type B Evaluation
Calibrated scale error	Type B Evaluation
Proper use, storage and handling	Covered in Type A Evaluation of process reproducibility data
Staff	
Multiple analysts	Covered in Type A Evaluation of process reproducibility data
Training	Covered in Type A Evaluation of process reproducibility data
Experience	Covered in Type A Evaluation of process reproducibility data
Visual acuity	Covered in Type A Evaluation of process reproducibility data
Time of day, day of week, interruptions, workload	Covered in Type A Evaluation of process reproducibility data
Test Method	
Differences in establishing parallel and perpendicular between analysts	Covered in Type A Evaluation of process reproducibility data
Analyst positioning of measuring equipment	Covered in Type A Evaluation of process reproducibility data
Facility	
Temperature coefficient of expansion for measuring equipment	Type B Evaluation
Lighting	Covered in Type A Evaluation of process reproducibility data
Space	Covered in Type A Evaluation of process reproducibility data

Type A Evaluation of uncertainty components:

Measurement Process Reproducibility

The number of measurements from the study and on-going measurement assurance is greater than 100.

Because the length varied with each firearm measured, the data of interest is not the nominal length but the variation of each measurement from the mean of the measurements made by all analysts on a single measurand.

The variation data was evaluated and appears to have a normal distribution.

The statistic that will be calculated is the standard deviation. Standard deviation (Sample):

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

The standard deviation of the reproducibility data for overall length is = 0 inches.

The standard deviation of the reproducibility data for barrel length is = 0 inches.

Type B Evaluation of uncertainty components:

Length scale readability: Equal to 1/10" = 0.1 inch
Readability is defined as the smallest increment that can be detected by the measuring equipment.

The measurement procedure requires interpretation at both the "zero" and the muzzle; therefore, the uncertainty budget will have two entries using this standard uncertainty.

Length scale resolution: Per laboratory procedure, no resolution will be done. The measurement will be taken to the nearest 0.1 inch scale mark.

Calibration Uncertainty: A review of all calibration certificates indicates that the largest expanded uncertainty is: $\pm$ (1000 + 30L)µ" at K=2, where L = Length in inches or (1000 + 30(26")) micro inches = 0.00178 inch (the legal limit for overall length is 26 inches).

Calibrated Scale Error: A review of all calibration certificates indicates that the largest scale error is 0.005 inches at 60 inches (the legal limit for overall length is 26 inches).

Coefficient of Linear Thermal Expansion for Stainless Steel 316: The coefficient of linear thermal expansion for stainless steel 316 = 0.0000089 per °F. The laboratory temperature does not vary enough for this component to be significant.

5.2.4 Convert Quantities to Standard Uncertainties

Type A Evaluation Components:

Reproducibility data: This data is in the correct measurement unit (inch), and is in decimal inches as the measurement is in the nearest 0.1" for calculations. It is expressed as one standard deviation.

The standard deviation of the reproducibility data for overall length is = 0 inches.

The standard deviation of the reproducibility data for barrel length is = 0 inches.

Type B Evaluation Components:

Length Scale Readability: This component is evaluated using a rectangular distribution. For a rectangular distribution, the standard uncertainty is equal to half of the possible range of values divided by the square root of 3.

Standard uncertainty = ½ (2a)/$\sqrt{3}$

Where a = readability = 0.1 inch

Standard uncertainty = 0.057735

The measurement procedure has to interpret both the zero and the muzzle; therefore, the uncertainty calculation will have two entries using this standard uncertainty.

Calibration Uncertainty: A review of the calibration certificates indicates that the largest expanded uncertainty is 0.00178 inch.

The certificate indicates this expanded uncertainty uses a coverage factor of K=2 and a coverage probability of approximately 95%. The uncertainty on the calibration certificate will be divided by the coverage factor to obtain the standard uncertainty.

Standard uncertainty = 0.00178 inch/2 = 0.00089 inch

Calibrated Scale Error: This component is evaluated using a rectangular distribution. For a rectangular distribution, the standard uncertainty is equal to half of the possible range of values divided by the square root of 3.

Standard uncertainty = ½ (2a)/$\sqrt{3}$

Where a = scale error = 0.005 inches

Standard uncertainty = 0.005 inches /$\sqrt{3}$ = 0.002887 inches

5.2.5 <u>Calculate the Combined Standard Uncertainty</u>

The combined standard uncertainty is the positive square root of the sum of the component variances. Variance is equal to the square of the standard deviation.

$$U_c = \sqrt{0^2_{process} + 0.057735^2_{read\ zero} + 0.057735^2_{read\ end} + 0.00089^2_{calibration} + 0.002887^2_{scale\ error}}$$

$$u_C = \sqrt{0.006676}$$

$$u_C = 0.081705$$

5.2.6 Expand the Combined Standard Uncertainty

To expand the uncertainty to a 99.7% coverage probability the coverage factor k=3 will be used.

K=3 U = 3 X 0.081705 inch = 0.245116 or rounded = 0.2 inch

To expand the uncertainty to a 95% coverage probability the coverage factor k=2 will be used.

K = 2 U = 2 X 0.081705 inch = 0.163411 or rounded = 0.2 inch

5.2.7 Evaluate and Report the Expanded Uncertainty

Since measured lengths are reported in 1/10" increments, the expanded uncertainty will be rounded to the nearest larger 1/10" increment for reporting purposes.

The expanded uncertainty is expressed in increments of 1/10":

The reported uncertainty is:

K = 3 U = 0.2 X $\frac{\frac{1}{10} inch}{0.100}$ = 0.2 of an inch

Example report statement:

The overall length of item 1 was found to be 25.1" $\pm$ 0.2 (K=3, 99.7%)

The barrel length of item 2 was found to be 12"$\pm$ 0.2 (K=3, 99.7%)

6. Data Collection Procedure

The following procedure was used to collect data to estimate Measurement Uncertainty when measuring the overall and barrel lengths of firearms:

- Uncertainty components which are of importance in the measurement of the overall and barrel lengths of a firearm were taken into account. (See ISO/IEC 17025, Clause 5.4.6.3; and 7).
- The Firearm Supervisor prepared data slips for the Estimation of Measurement Uncertainty (EMU) exercise. The two firearm examiners used the same digital rulers (48" and 12") measuring to 0.1".
- The three guns listed below were selected from the Laboratory firearm reference collection for measurement of barrel and overall lengths. The weapons were selected due to the nearness of barrel and overall lengths to the state and federal penalty thresholds and to utilize both rulers in the measurement process.
    - Mossberg Model 500A 12 Gage #R867055
    - Remington Model 522 #3085912
    - Winchester model 1400 MK II #403909
- The two firearm analysts were instructed to make two measurements a day (one measurement being made near the beginning and one near the end of each work day) for six days over two calendar weeks of both the barrel and overall lengths of the three guns, resulting in 24 repeats of each measurement.
- The analysts were instructed to follow the measuring method set forth in the current Firearm Protocol Manuals.
- Completed data slips were returned to the Firearm Supervisor for tabulation and calculation.
- Excel spreadsheets were used to perform the calculations.

7. Summary and Estimation of Measurement Uncertainty (EMU)

An approach to establish an Estimation of Measurement Uncertainty, as required by ASCLD/LAB-*International* accreditation program, for firearm barrel and overall lengths for the Alaska Scientific Crime Detection Laboratory Firearm/Toolmark discipline was developed and administered to all analysts. Replicate measurements of the barrel length and overall length of the representative guns were made using NIST traceable rulers.

Standard deviations of the measurements were calculated. Reasonable estimates, using suitable distributions were also established for other factors that might affect the uncertainty of measurement. The estimates were combined using the RSS method to yield a combined uncertainty for barrel and for overall length.

The resulting estimation of measurement uncertainty, coverage factors, and level of confidence were:

- Overall firearm length (EMU^{oal}) = $\pm$ 0.2 inch (coverage factor [k] = 3; level of confidence = 99.7%)
- Barrel length (EMU^{bbl}) = $\pm$ 0.2 inch (coverage factor [k] = 3; level of confidence = 99.7 %)

- Overall firearm length (EMU^{oal}) = $\pm$ 0.2 inch (coverage factor [k] = 2; level of confidence = 95%)
- Barrel length (EMU^{bbl}) = $\pm$ 0.2 inch (coverage factor [k] = 2; level of confidence = 95 %)

The rounded calculations for coverage factors at 95% and 99.7% were both equal to 0.2 inch, therefore it was determined that the higher coverage factor would be reported.

8. Update and Continuing Evaluation of the Estimation of Measurement Uncertainty (EMU)

- Continuing evaluation of the EMU data will be collected monthly for 12 months by each firearm examiner, on the one gun (Winchester model 1400 MK II #403909) that utilizes the two digital rulers (12" and 48") that measure to 0.1 inch. Each analyst will take the overall and barrel length of the gun one time on one day in the month for the twelve months. Data will be continually added to the excel spreadsheet by the Supervisor. (Data sheets are provided to the examiners by the Supervisor.)
- The measurement uncertainty budgets will be updated annually with the accumulated data. The result is a continually updated measurement uncertainty budget.
- The measurement process reproducibility study and EMU will be reevaluated if a different method of measuring is implemented.