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Metrological Data Completeness for Digital Transformation

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Topics

1. MII and Data Completeness

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2. Traceability Completeness

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1. MII and Data Completeness
2. Traceability Completeness
3. Modeling Completeness

Topics

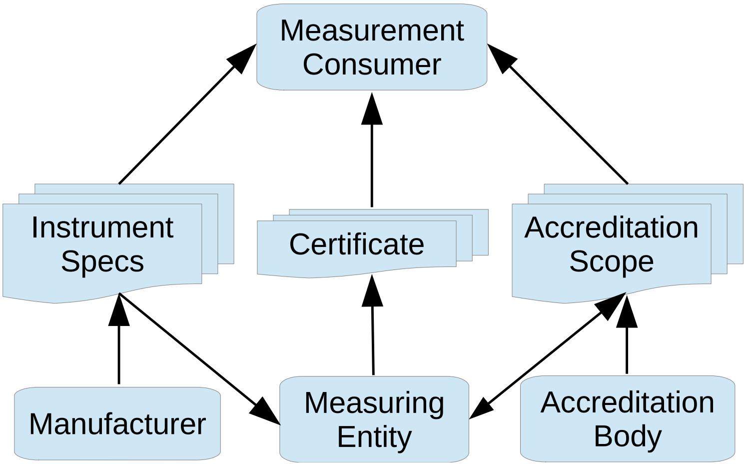
Acronyms, Symbols

- MII—measurement information infrastructure
- CMC—calibration and measurement capability
- MPE—maximum permissible error
- MQM—measurement-quality metric
- MathML—math markup language
- q—arbitrary quantity
- $\boldsymbol{q}_{\mathrm{inp}}$, $\boldsymbol{q}_{\mathrm{inf}}$—input and influence quantity vectors

Section 1

MII and Data Completeness

Partial Metrology Information Flow



Small excerpt from a vast network

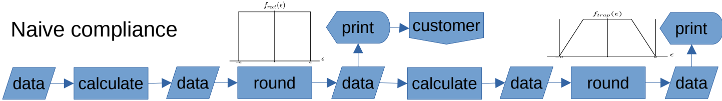
Data Completeness

- Principle: To increase quality and decrease cost, digital documents should retain all measurement data.
  - BECAUSE automation increases quality, decreases cost,
  - AND data completeness allows more automation.

- One of seven MII document design requirements
  - Digital transformation, not just digitalizing current practice
  - Applies to upstream traceability data, correlations, Monte Carlo outputs, optimal specifications and CMCs, measurement models, instrument models, full numeric precision, . . .

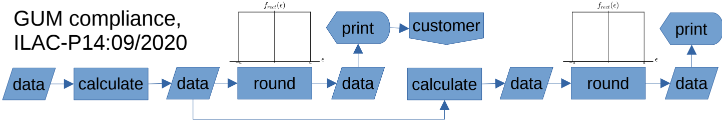
Numeric Rounding—Stop!

Naive compliance



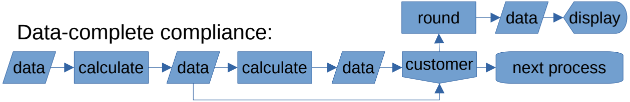
Works well for a slide rule, abacus, or back-of-the-napkin calculation!

GUM compliance, ILAC-P14:09/2020



Still a bit silly, but okay for analog documents.

Data-complete compliance:



Suitable for live views or printing; less effort, confusion, and (correct) uncertainty; fewer software bugs

Section 2

Traceability Completeness

GUM Recommendation

Quoting from GUM §7.1.4:

> *Although . . . the amount of information . . . to document a measurement result depends on its intended use, the basic principle . . . remains unchanged: when reporting the result . . . err on the side of providing too much information rather than too little.*

And further. . .

> *include measurement results and uncertainty calculation methods, the full uncertainty budget and derivation, sufficient information to duplicate the results, and all corrections, constants, and their sources.*

Digitalization offers the opportunity to track detailed traceability, even for multi-function instruments with hundreds of measurands.

Minimal Traceability Representation

Key elements:

- Uniquely identified orthogonal base quantities (BQs)
- Sensitivity coefficient list (SCL) with respect to the BQs for each measurand
- Registry for common BQs, e.g., uncertain constants and functions

Example Calibration Process

BQ ID	SCL A	SCL B	SCL N
1	$c_{A,1}$		$c_{N,1}$
2	$c_{A,2}$	$c_{B,2}$	$c_{N,2}$
3		$c_{B,3}$	$c_{N,3}$
(4)			$c_{N,4}$

$$c_{N,i} = c_{NA} * c_{A,i} + c_{NB} * c_{B,i}$$

Features:

- Streamlined storage and computation
- Welch-Satterthwaite equation works without compromise
- Hall-METAS system already in use, Kuster variant also

Traceability Extensions

"err on the side of providing too much information"

- Measurement functions
- Full uncertainty budgets and derivation
- Calibration functions
- Alternative uncertainty calculation methods
- Redundancy for quality verification and refinement opportunities

Extensible data structures

- Indicate substitute schemas via "case" or "switch" data elements.
- Facilitate minimum viable products
- Retain power for future applications
- Incur negligible cost to information producers and consumers

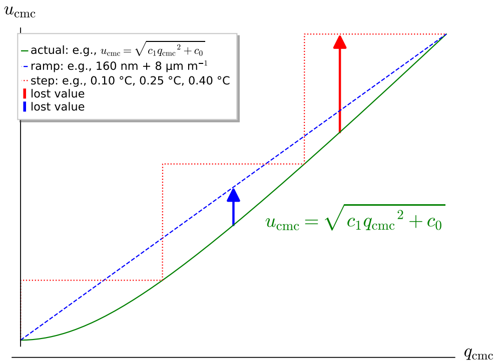
Section 3

Modeling Completeness

Measurement-Data Models

- Digital accreditation scopes
  - Live CMC uncertainty calculation; lab search & comparison
- Digital instrument specifications
  - Live MPE calculation; instrument search & comparison
  - Instrument behavior models
- Digital certificates
  - Bias correction functions (parameterized models)
  - Measurement functions and models (traceability)

CMC Uncertainties, MPE Specs



Value trade-off okay for paper

Hardly acceptable digitally

In general, we would like arbitrary calculable expressions:

$$u_{\mathrm{cmc}} = f_{\mathrm{cmc}}\left(q_{\mathrm{cmc}}, \boldsymbol{q}_{\mathrm{inp}}, \boldsymbol{q}_{\mathrm{inf}}\right)$$
$$h_{\mathrm{cmc}}\left(u_{\mathrm{cmc}}, q_{\mathrm{cmc}}, \boldsymbol{q}_{\mathrm{inp}}, \boldsymbol{q}_{\mathrm{inf}}\right) = 0$$

Similarly, for instrument MPEs:

$$\epsilon_{\mathrm{mp}} = f_{\mathrm{mpe}}\left(q, \boldsymbol{q}_{\mathrm{inp}}, \boldsymbol{q}_{\mathrm{inf}}\right)$$
$$h_{\mathrm{mpe}}\left(\epsilon_{\mathrm{mp}}, q, \boldsymbol{q}_{\mathrm{inp}}, \boldsymbol{q}_{\mathrm{inf}}\right) = 0$$

Instrument Models $\rightarrow$ Calibration Functions

- Bias correction functions that predict instrument performance over its measurement space from a finite calibration point set
  - ITS-90 range and subrange functions for PRTs
  - Quadratic or cubic curve fits for force transducers
  - Applicable to any measuring instrument
  - Nominal-valued model parameters determined at calibration
  - Digitalizes physical adjustments
  - Facilitates digital twins and smart instruments

Instrument Model Examples

General time-dependent model for corrected measurement q_{c}, indication q, parameter vector $\boldsymbol{\theta}$, and time t:

$$q_{\mathrm{c}} = f_c\left(q, \boldsymbol{q}_{\mathrm{inp}}, \boldsymbol{q}_{\mathrm{inf}}, \boldsymbol{\theta}, t\right)$$

$$h_c\left(q_{\mathrm{c}}, q, \boldsymbol{q}_{\mathrm{inp}}, \boldsymbol{q}_{\mathrm{inf}}, \boldsymbol{\theta}, t\right) = 0$$

Linear resistance range (time-independent):

$$q_{\mathrm{c}} = q\theta_1 + \theta_0$$

$$\boldsymbol{\theta}_{\mathrm{nom}} = \left(1\,\Omega\,\Omega^{-1}, 0\,\mu\Omega\right)$$

Length standard (time-independent): reference temperature and expansion coefficients

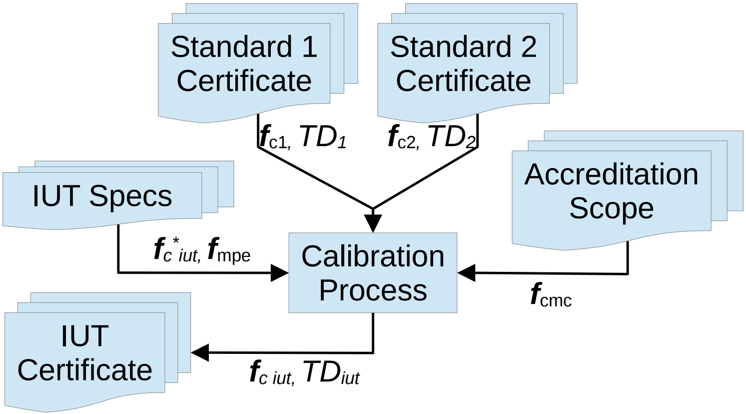
$$q_{\mathrm{c}} = \left((T-\theta_0)^2\theta_2 + (T-\theta_0)\theta_1 + 1\right)q$$

$$\boldsymbol{\theta}_{\mathrm{nom}} = (T_{\mathrm{o}}, \alpha_{\mathrm{nom}}, \beta_{\mathrm{nom}})$$

time-of-use gage temperature

$$\boldsymbol{q}_{\mathrm{inp}} = (T)$$

Example Data Flow for Calibration



*uncalibrated (nominal) parameter values. TD: traceability data. IUT: instrument under test.

Implementation

- Encoding via MathML, e.g.
  - Arbitrary math expressions and rich function set
  - Parameter metadata, symbols and known values
  - Quantity symbols and metadata to identify free variables
- Human Interface—transparency for decision makers
  - Static views: render equations, computed results, or graphic visualizations
  - Interactive live views
    - Should become more prevalent.
    - Optimize for user preferences based on user parameter and configuration choices.
    - Plot two competing labs' CMCs or instruments' MPEs together, e.g.

Section 4

Conclusion

Summary

- Data completeness will allow:
  - Optimized CMC and MPE statements
  - Intelligent laboratory and instrument search and comparison
  - CMC-informed and restrained uncertainty calculation
  - Transparent instrument adjustment and bias correction
  - Full measurement-space uncertainty and MQM prediction
  - Complete SI-traceability chain for every measurement
  - More full calibrations and fewer verifications
  - Recaptured value from pragmatic simplifications
- Plan for data completeness up front!

Acknowledgments

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And Thank You for your time!

Questions?

Collaboration opportunities?