Metrology: Standardize and Automate!

Toward a Metrology Information Infrastucture

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Pantex Metrology

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Standards and Automation

- Standards
  - Standard vocabulary–VIM, ISO-IEC 80000, . . .
  - Standard measurement units–s, kg, m, V, K, . . .
  - Measurement standards–traceable artifacts, instruments, . . .
  - Quality standards–17025, Z540, . . .
  - Technical standards–ISO, IEC, IEEE, ANSI, ASTM, ASME, . . .
  - Standard measurement practices, . . .
- Automation
  - Measurements, measurements, . . .
  - Laboratory management software
  - Lowest lying fruit

Manual Tasks → Opportunities

- Search accreditation scopes and instrument specs
  - find suitable parameters, ranges, uncertainties
- Process paper or PDF calibration certificates
  - extract, interpret, transcribe and propagate content
- Create and maintain uncertainty budgets
  - hundreds per lab? thousands?
- Select calibration points

Shortcuts

We all look for the easiest or most effective way to meet our goals. Faced with tedious tasks, we take shortcuts that sacrifice quality for "close enough".

Metrology Made Easy (and Mediocre)

- Shortcuts, Avoided Work
  - Buy from familiar equipment and service vendors
  - Round off measurements and uncertainties
  - Choose easy uncertainty distributions (rectangular)
  - Interpret specs simply (all 95 % confidence)
  - Ignore correlation and degrees of freedom (DOF)
  - Generate "conservative" uncertainties
  - Test and report only at minimal points
  - Minimize the information on calibration certificates
- Herd Think
  - No standard: What does everyone else do?
  - Nervous–don't stray from the pack.
  - Regulators or assessors may pick you off.
- Mediocre Metrology

Why take shortcuts?

- Guidance Void–the community accepts simple approaches
  - Undefined instrument spec $\leftrightarrow$ uncertainty relation
  - Abbreviated traceability, arbitrary calibration point selection
- Solution: *Standardize*

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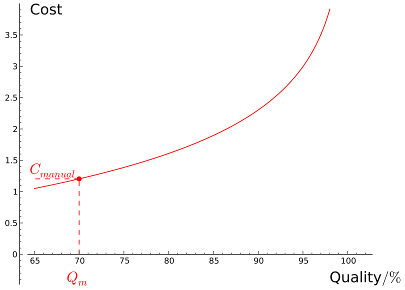
- Cost Tradeoff
  - Save resources



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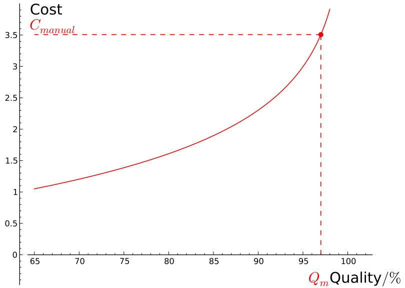
  - Avoid diminishing returns



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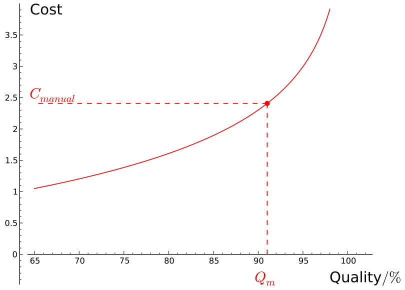

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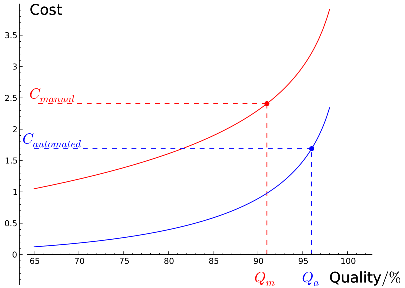
- Cost Tradeoff
  - Save resources
  - Avoid diminishing returns
- Solution
  - Change the process
  - Update technology
  - *Automate*



Metrology Information Infrastructure

- Standard machine-readable metrology documents
  - Accreditation Scopes
    - Embed parameters, ranges, uncertainties, admin data.
  - Calibration Certificates
    - Embed full precision data, uncertainties, correlations & DOF
    - Embed traceability to SI realizations & CODATA constants.
    - Embed cryptographic accreditor, lab, and personnel signatures.
  - Uncertainty Budget Template Repository
    - Embed uncertainty contributors and distribution types.
    - Chinese menu: UUT & measurement method
  - Instrument Specs
    - Functions, qualifiers, ranges, parameters, tolerance equations
    - Fully calculable specifications for all measurements
    - Internal time-dependent parameter uncertainties & correlation models
    - External measurands as functions of internal parameters
- Substance beneath the shine → Lower Cost, Higher Quality

Metrology Made Easy (and Correct)

- Have standards, will automate
  - Measurement requirements → compatible product lists
    - Suitable equipment and calibration services
    - Satisfaction or trust indicators
  - Validity & quality checks
  - Uncertainty propagation from vendors to customers
  - Accurate and valuable uncertainties
  - Product test enhancements
  - Calibration procedure test point selection
  - Accurate information at every customer measurement point
- → Valuable Metrology

Existing Technology for an MII

- ID codes: accredited measurements, uncertainty sources, etc.
  - URIs (Uniform Resource Identifiers)
  - GUIDs (Globally Unique IDentifiers)
- Data file formats
  - PDF, XML (eXtensible Markup Language), UnitsML, MathML
  - XSIL (eXtensible Scientific Interchange Language)
  - XBC (XML Binary Characterization)
  - HDF5 (Hierarchical Data Format)
  - Fast Infoset (an ISO spec)
- Semantic meaning for electronic data
  - The Semantic Web
  - OWL (Web Ontology Language)
  - RDF (Resource Description Framework)
- Data exchange and service advertisement & discovery
  - Web services, SOA (Service-Oriented Architecture)
  - UDDI (Universal Description Discovery and Integration), UBR (UDDI business registry)

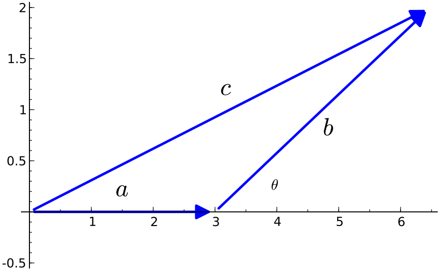
MII Research Topics

- Traceability Improvements
  - Top to bottom data in every certificate: SI to product test
  - Complete information: qualified quantities, uncertainties, correlations, DOF
  - All intervening measurement equations
  - Fundamental quantity identification
  - Applies to the GUM Uncertainty Framework and Monte Carlo
- Instrument Models
  - Common methodology for all instruments
  - Individual model creation & validation
  - Test point selection
  - Quality predictions for all measurement points

Geometric Uncertainty

Vector Analysis

Vector lengths and their relative orientations represent uncertainties and their correlations.



Computing uncertainties by the GUM equates to placing uncertainty vectors head-to-tail.

Geometric Uncertainty

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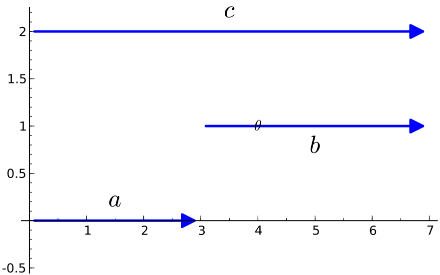

Uncertainty vectors for fully correlated errors point in the same direction and the lengths simply add.

Geometric Uncertainty

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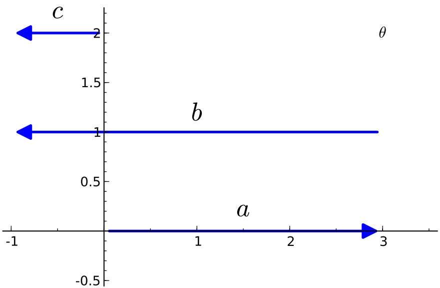
Vector lengths and their relative orientations represent uncertainties and their correlations.

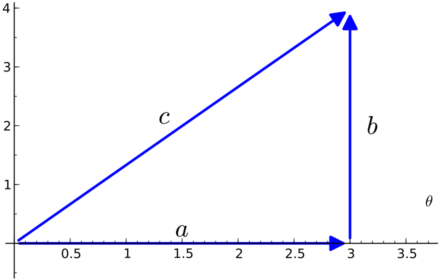


Uncertainty vectors for fully anti-correlated errors point in the opposite direction and the lengths cancel.

Geometric Uncertainty

Vector Analysis

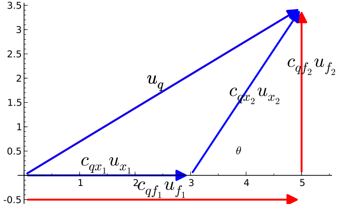
Vector lengths and their relative orientations represent uncertainties and their correlations.



Uncertainty vectors for independent errors lie perpendicularly. The lengths RSS.

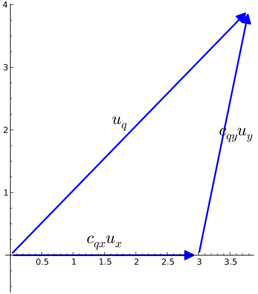
Traceability Information Loss

- All uncertainties have a reference frame (vector basis set).
- Unfortunately, we omit that information on reports.



Traceability Information Loss

- All uncertainties have a reference frame (vector basis set).
- Unfortunately, we omit that information on reports.
- Without a reference frame (the independent unc. sources)
  - We do not know how uncertainties from different sources relate.
  - Uncertainty calculations assume (incorrect) correlations.
  - DOF calculations become inconsistent.
  - Affects Monte Carlo also



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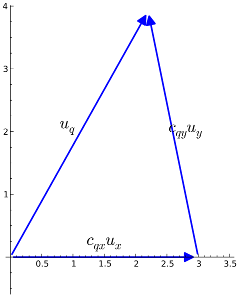

Lost in vector space!

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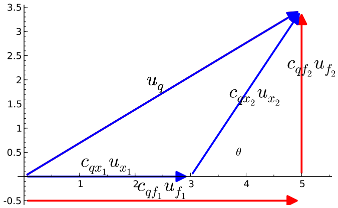

Burn data and sell the smoke!

GUM Example H.2.4

Laboratory Calibration Data

Quantity	Value	Unc.	DOF	95 % Conf.
$\|V\|$	4.9990 V	3.2 mV	4	±8.9 mV
$\|I\|$	19.6610 mA	9.5 μA	4	±26.3 μA
$\phi_V - \phi_I$	1.044 46 rad	0.75 mrad	4	±2.09 mrad
R (reported)	127.732 Ω	0.071 Ω	4.4	±0.190 Ω
X (reported)	219.847 Ω	0.296 Ω	5.1	±0.756 Ω
Z	254.260 Ω	0.236 Ω	6.0	±0.577 Ω

- Laboratory measures voltage, current and phase difference
- Laboratory calculates impedance, resistance and reactance
- Assume customer only requests resistance and reactance

GUM Example H.2.4

Unknown Laboratory Calibration Data

$\phi_V - \phi_I$	1.044 46 rad	0.75 mrad	4	±2.09 mrad
Z	254.260 Ω	0.236 Ω	6.0	±0.577 Ω

Customer: Calculations, No Correlation Information

$\phi_V - \phi_I$	1.044 46 rad ✓	1.41 mrad	9.4	±3.158 mrad
Z	254.260 Ω ✓	0.488 Ω	5.9	±1.201 Ω

GUM Example H.2.4

Unknown Laboratory Calibration Data

$\phi_V - \phi_I$	1.044 46 rad	0.75 mrad	4	±2.09 mrad
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$\phi_V - \phi_I$	1.044 46 rad ✓	1.41 mrad	9.4	±3.158 mrad
Z	254.260 Ω ✓	0.488 Ω	5.9	±1.201 Ω

Customer: Knows $\rho_{R,X} = -0.588$, but not the Reference Frame

$\phi_V - \phi_I$	1.044 46 rad ✓	0.75 mrad✓	5.6	±1.870 mrad
Z	254.260 Ω ✓	0.236 Ω ✓	5.3	±0.597 Ω

A Vector Uncertainty Data Model–Reference Frame

Quantity	ID	Uncertainty	DOF
Voltage, source and meter stability	GUID[f_1]	3.274 mV	4.0
Phase, component and meter repeatability	GUID[f_2]	379.1 µrad	0.6
Current, component and meter repeatability	GUID[f_3]	6.251 µA	−2.3

- The list of fundamental (independent) uncertainty contributors forms the reference frame, or vector basis set.
- Every succeeding measurement would add additional contributors.
- This (ad hoc) decomposition reflects the GUM example data.
- Uncertainty distributions and other detail not shown

A Vector Uncertainty Data Model–Traceable Quantities

Traceable Quantities & Sensitivities to Fundamental Quantities

ID	**GUID[f_1]**	**GUID[f_2]**	**GUID[f_3]**
GUID[V]	0.9799	0.1997 V/rad	2.209 mΩ
GUID[I]	−1.0726 S	16.32 mA/rad	-0.9999
GUID[ϕ]	0.1997 rad/V	-0.9797	−16.21 mrad/A
GUID[R]	11.90 A^{-1}	−114.4 Ω/rad	−6.499 kΩ A^{-1}
GUID[X]	−80.60 A^{-1}	298.9 Ω/rad	−11.18 kΩ A^{-1}
GUID[$\|Z\|$]	−63.71 A^{-1}	201.0 Ω/rad	−12.93 kΩ A^{-1}

- Traceable quantities and their sensitivities to the fundamental quantities
- This (ad hoc) decomposition reflects the GUM example data.
- Nominal values, quantity descriptors, and measurement equations not shown

Uncertainty Arithmetic: Multiply and Add!

To combine uncertainties, just linearly combine vectors.
No correlation worries, handled implicitly:

$$\boldsymbol{u_Z} = c_{Z,R}\begin{pmatrix} u_{R_1} \\ u_{R_2} \\ u_{R_3} \end{pmatrix} + c_{Z,X}\begin{pmatrix} u_{X_1} \\ u_{X_2} \\ u_{X_3} \end{pmatrix}$$

For uncertainty magnitude (as seen on certs),
$u = \|\boldsymbol{u}\| = \sqrt{\boldsymbol{u}^T\boldsymbol{u}} = \mathrm{RSS}(u_k)$

Correlations between two uncertainties (if desired):
$\rho_{i,j} = \frac{\boldsymbol{u}_i \cdot \boldsymbol{u}_j}{\|\boldsymbol{u}_i\|\|\boldsymbol{u}_j\|}$ (normalized dot product)

The paper has other useful relations.

Range Calibration

Metric	Pt 1	Pt 2
Location, % of FS	20 %	80 %
-	-	-

Range Calibration

Metric	**Pt 1**	**Pt 2**
Location, % of FS	20 %	80 %
TUR	4.2 : 1	4.1 : 1
-	-	-

Range Calibration

Metric	Pt 1	Pt 2
Location, % of FS	20 %	80 %
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Error, % of Tol	20.5 %	−61.6 %
-	-	-

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FAR, %	0.00 %	0.07 %
-	-	-

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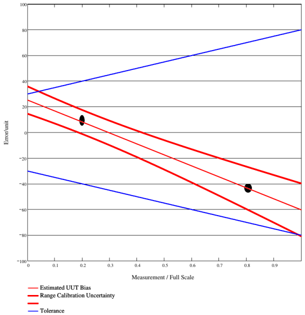

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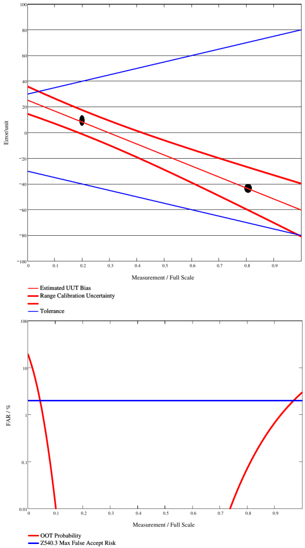
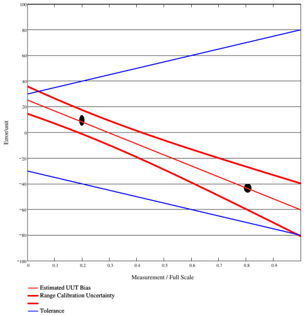
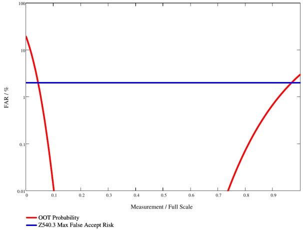


Range Calibration

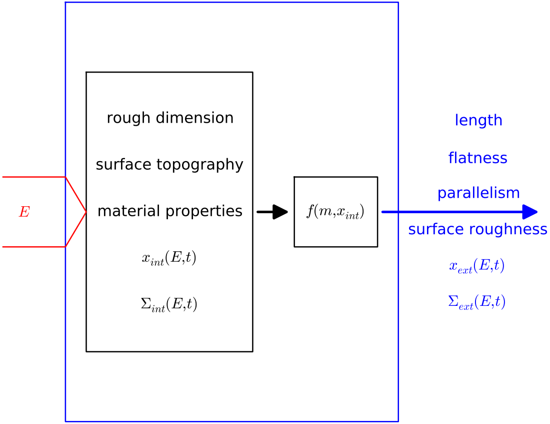
Metric	Pt 1	Pt 2
Location, % of FS	20 %	80 %
TUR	4.2 : 1	4.1 : 1
Error, % of Tol	20.5 %	−61.6 %
FAR, %	0.00 %	0.07 %
Location, % of FS	0 %	100 %
FAR, %	19.3 %	2.98 %
-	-	-

All test points meet their quality requirements but our myopic focus misses the instrument OOT.





Instrument Model



- Internal "black box" parameters determine external values
- The environment and time affect the internal parameters.

Model Development and Validation

- Model Development
  - Manufacturer takes a large role–part of the specifications
  - May reverse engineer through repeated measurement and decomposition: $(\boldsymbol{C}_{m,int}, \boldsymbol{\Sigma}_{int}, \boldsymbol{C}_{m,int}) = \mathrm{SVD}(\boldsymbol{\Sigma}_m)$
- Model Validation
  - Compute internal parameters from external measurements.
  - Predict other external values and uncertainties.

    $$\boldsymbol{x}_{ext} = \boldsymbol{f}\left(\boldsymbol{m}_{tst}, \boldsymbol{x}_{int}\right)$$
    $$\boldsymbol{C}_{ext,int} = \nabla \boldsymbol{f}(\boldsymbol{m}_{tst}, \boldsymbol{x}_{int})_{\overline{\boldsymbol{m}_{tst}, \boldsymbol{x}_{int}}}$$
    $$\boldsymbol{\Sigma}_{ext} = \boldsymbol{C}_{ext,int} \boldsymbol{\Sigma}_{int} \boldsymbol{C}_{ext,int}{}^{T}$$
  - Compare to further measurements.
- 1994 NIST study did essentially this
- Share and derive models
- Instrument *uncertainties*, finally!

Conclusion: MII Benefits and Recommendations

- An MII would
  - Eliminate cost and human performance barriers.
  - Obviate shortcuts, improve quality.
  - Create more value for customers.
  - Demonstrate value to management.
- Recommendations (practical approach)
  - Operate quality programs to the level automation supports.
  - Adapt automation to your quality program where practical.
  - Eliminate shortcuts as the corresponding automation arrives.
  - Join standardization groups.
  - Contribute uncertainty budgets and instrument models.
  - Define data structures, formats; write software libraries.
- Standardize and automate!

Questions

Acknowledgments

- Measurement Science Conference
- *Metrologist*, NCSL International
- Pantex Metrology
- Cherine-Marie Kuster

Thank You for your time! Questions?