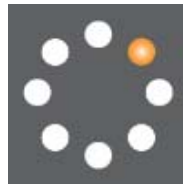


CMM Measurement Uncertainties: Applications & Case Studies



Kim D. Summerhays
Technical Director
MetroSage

Topics

- Task-Specific Measurement Uncertainty
- Gauge R&R vs. Measurement Uncertainty
- Ways to Assess Measurement Uncertainty
- An Automotive Case Study
- CMM Measurement Traceability
- Optimizing Tolerance Schemes
- Economics of Measurement Uncertainty

Task-Specific CMM

Measurement Uncertainty

- Specific to a particular measurand.
- Specific to a particular level of confidence.
- **Sample Statement:** *“The uncertainty of the diameter of this nominal 10-mm diameter hole, measured with this particular CMM under these specific conditions is ± 0.004 mm at 95% confidence.”*

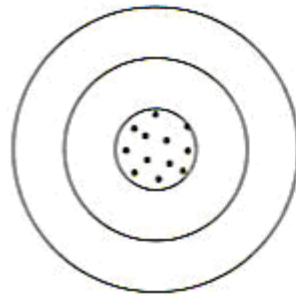


Topics

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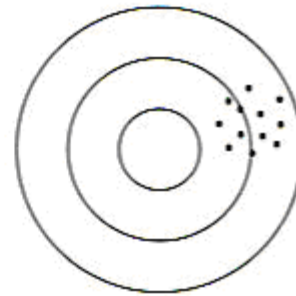
Reproducibility vs. Accuracy

Commonly
Encountered
Textbook
Graphic



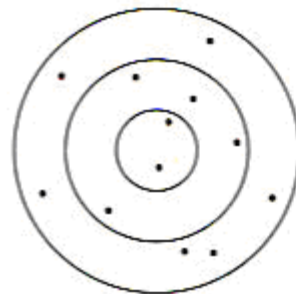
High Reproducibility
High Accuracy

(a)



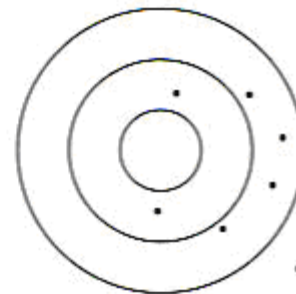
High Reproducibility
Low Accuracy

(b)



Low Reproducibility
High Accuracy

(c)



Low Reproducibility
Low Accuracy

(d)



Reproducibility vs. Accuracy

Reality



High Reproducibility
Accuracy ???

(a)



High Reproducibility
Accuracy ???

(b)



Low Reproducibility
Accuracy ???

(c)



Low Reproducibility
Accuracy ???

(d)



Gauge Repeatability & Reproducibility (GR&R)

“A concept to insure stable measurements where a single person gets the exact same results each and every time they measure and/or collect data measurements.”

- Six Sigma SPC's Quality Control Dictionary and Glossary



Gauge Repeatability & Reproducibility (GR&R)

Assesses Reproducibility, but not Accuracy:

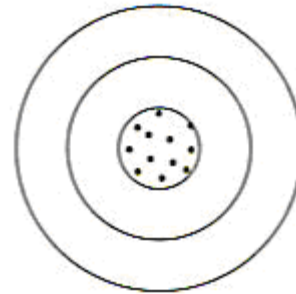
Distinguishes



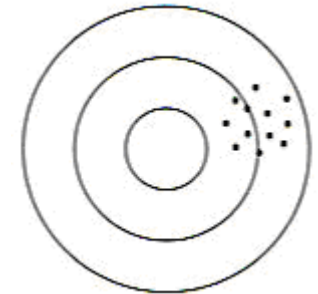
from



but cannot distinguish



from



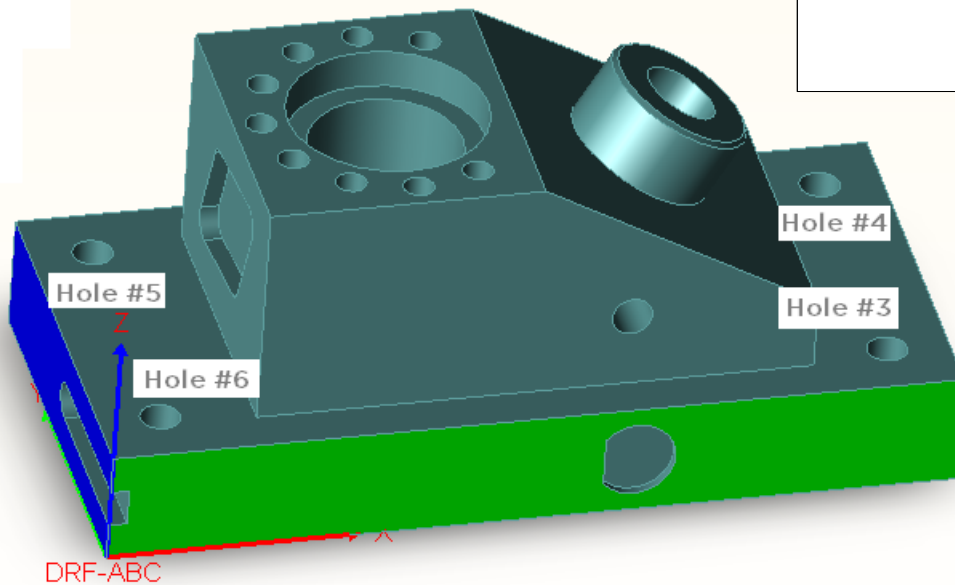
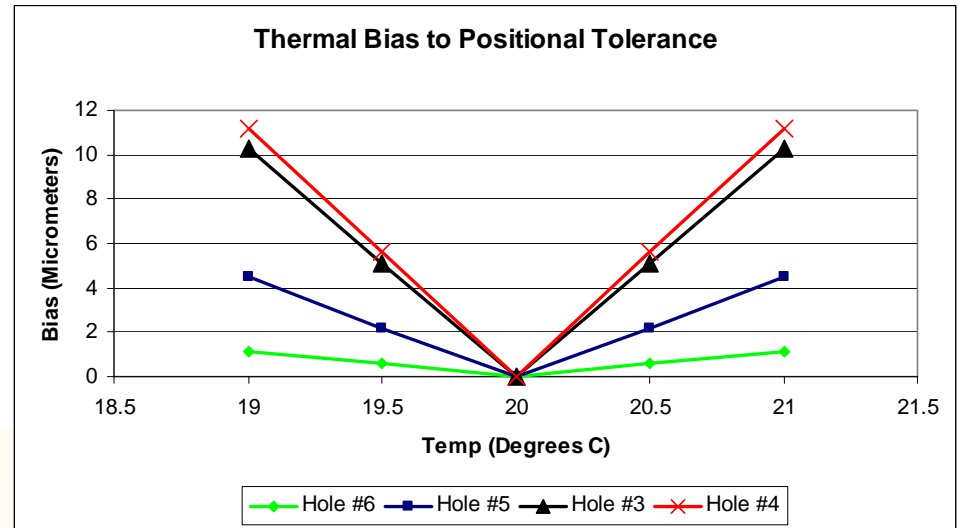
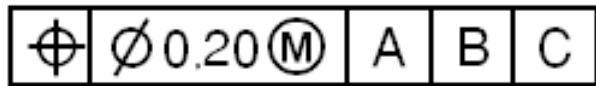
Bias in CMM Measurements

Some Sources:

- Repeatable Geometric Errors of CMM Axes
- Repeatable Probe Errors (e.g. Over-travel)
- Uncorrected Thermal Expansion of Scales
- Uncorrected Thermal Expansion of Part
- Sampling Strategy Inadequacies
- Wrong Point-Fitting Algorithm



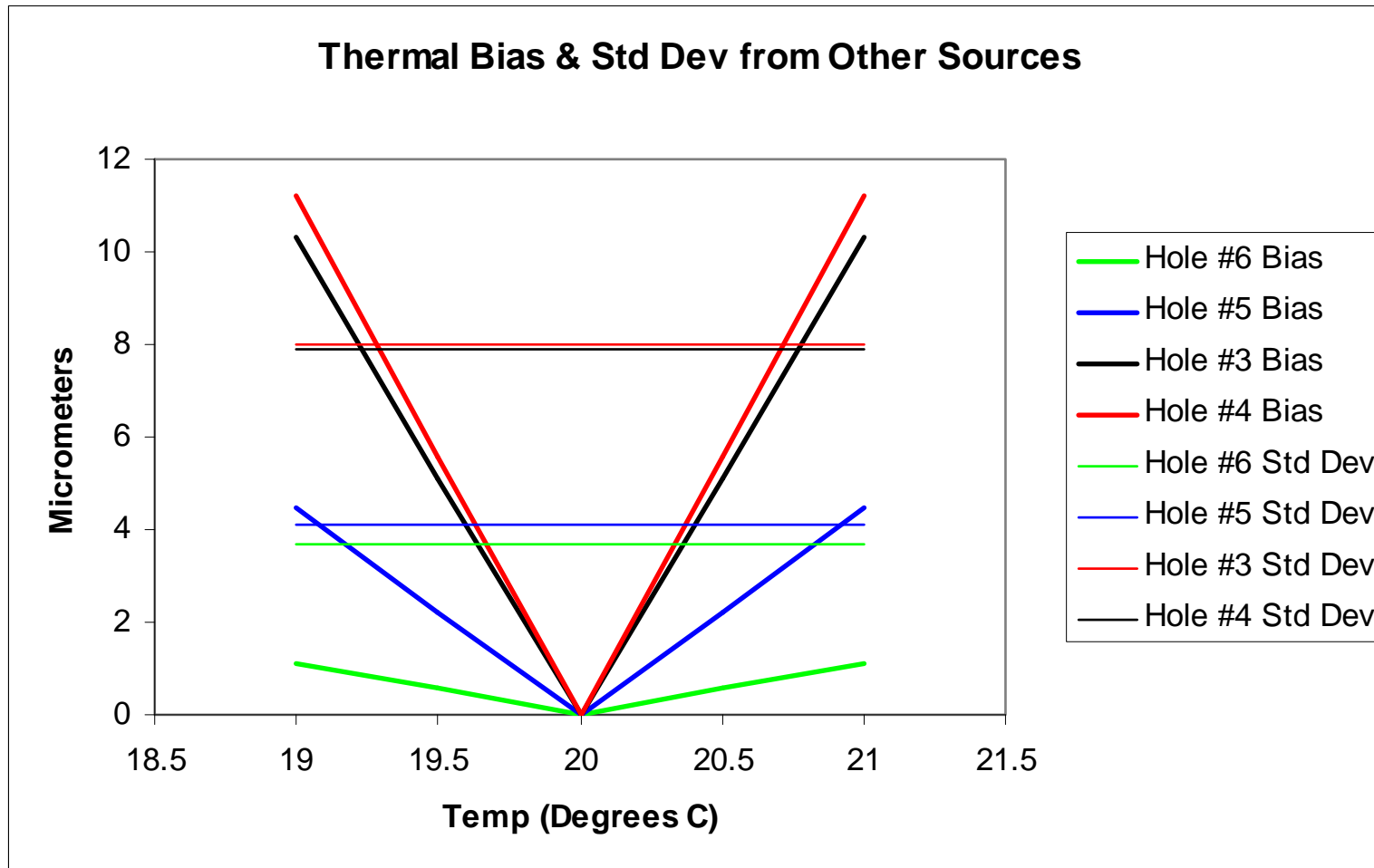
Thermally Induced Bias



Aluminum Part
Glass Scales



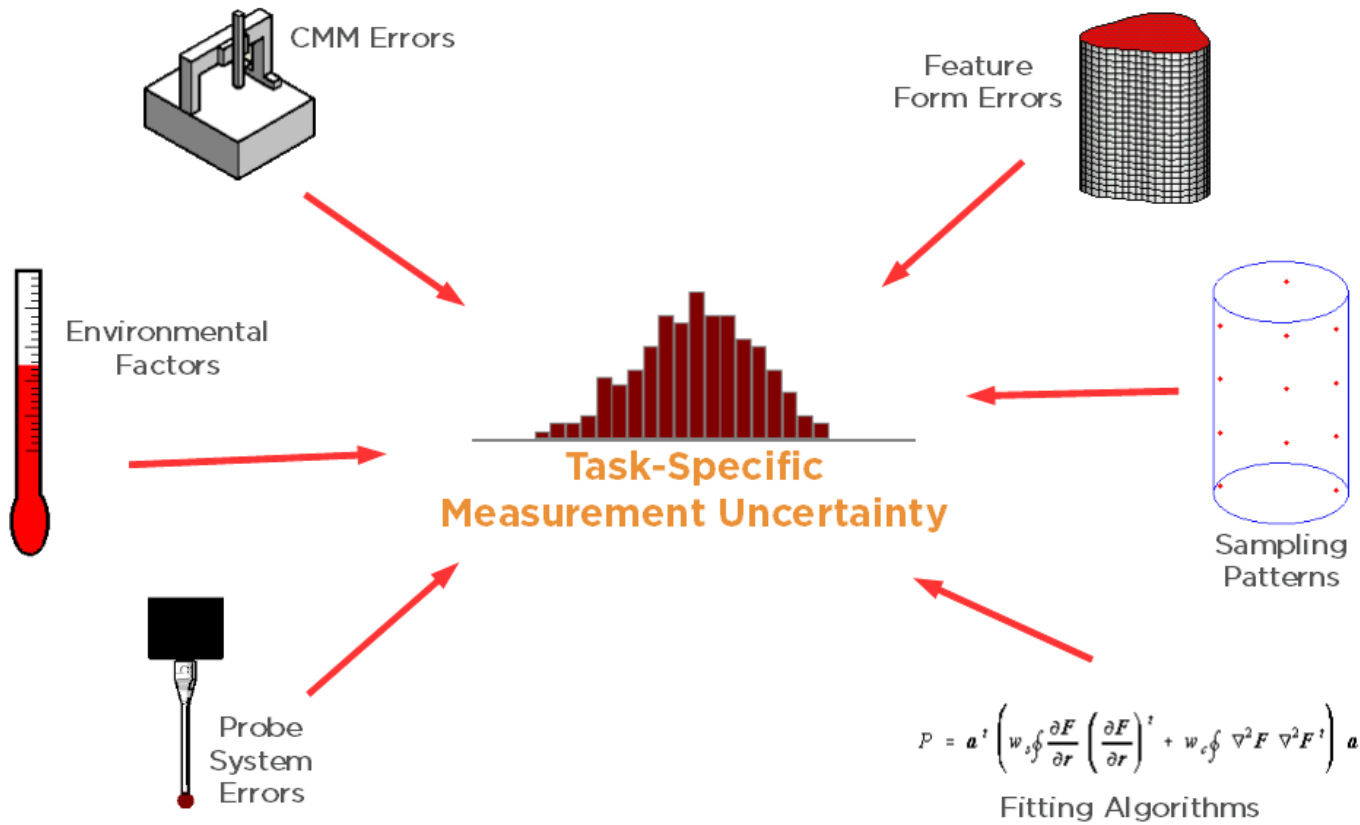
Thermal Bias Compared to Std Dev from Other Sources



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CMM Measurement Influence Quantities



Methods to Estimate Measurement Uncertainty (ISO 15530 draft)

- Sensitivity Analysis - aka “Uncertainty Budgeting”; estimating various contributions
- Expert Judgment - “best-guess” estimate
- Substitution - repeated measurement of calibrated master part
- Simulation - modeling and simulating the measurement process, including the errors
- Measurement History - full range of measurements of part throughput



Uncertainty Method Scorecard for 3-Dimensional Metrology

	<i>Tractable</i>	<i>Comprehensive</i>	<i>Detects Measurement Bias</i>	<i>Detects Measurement Variability</i>	<i>Versatile</i>	<i>Predictive</i>	<i>Economical</i>
Sensitivity Analysis	?	?	✓	✓	X	✓	X
Expert Judgment	✓	?	?	?	X	✓	?
Substitution	✓	✓	✓	✓	X	X	X
Computer Simulation	✓	?	✓	✓	✓	✓	?
Measurement History	✓	✓	X	?	X	X	X

The MetroSage Solution:



 PUNDITCMM

 METROSAGE

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Traceability

“The property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.”

-ISO VIM 6.10



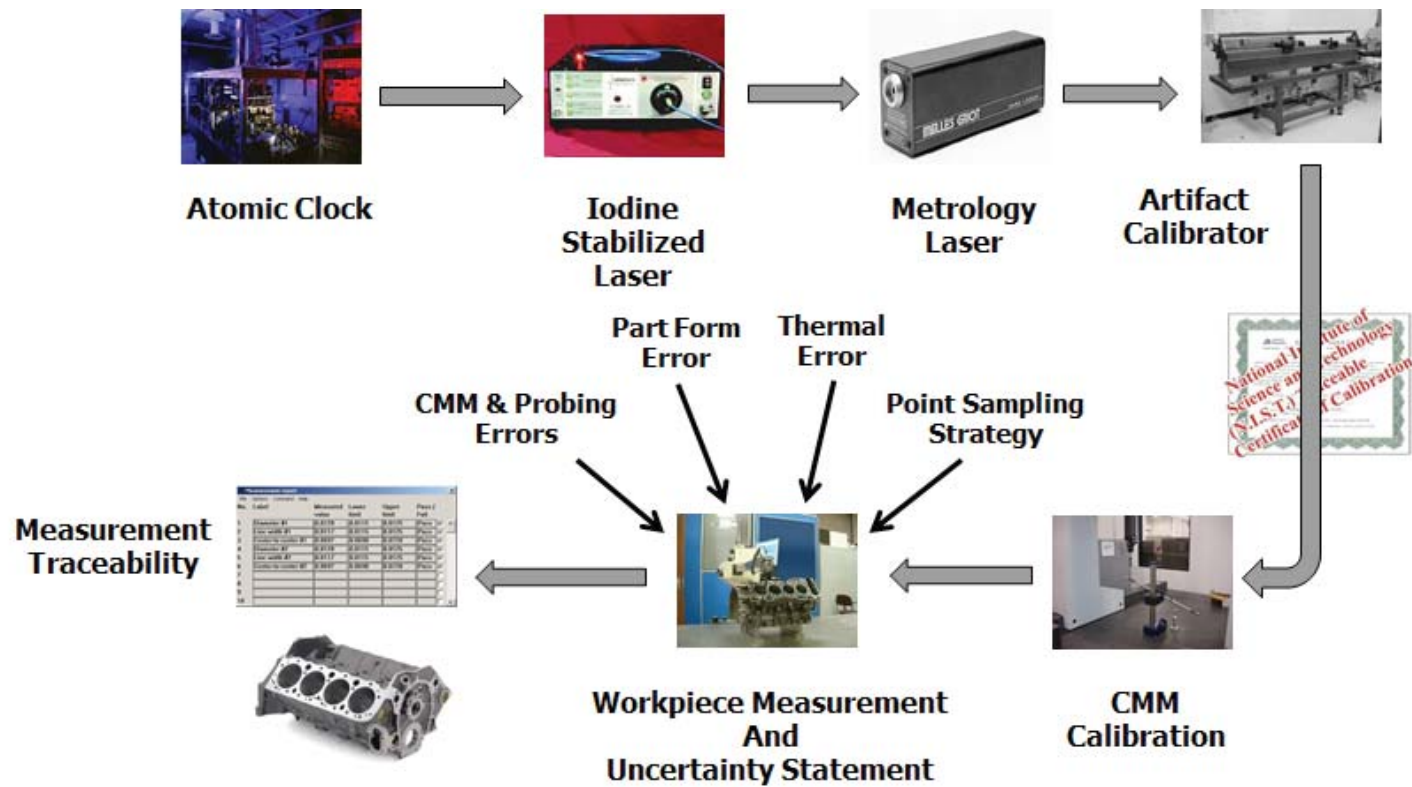
Proof of CMM Measurement Traceability

The Problem:

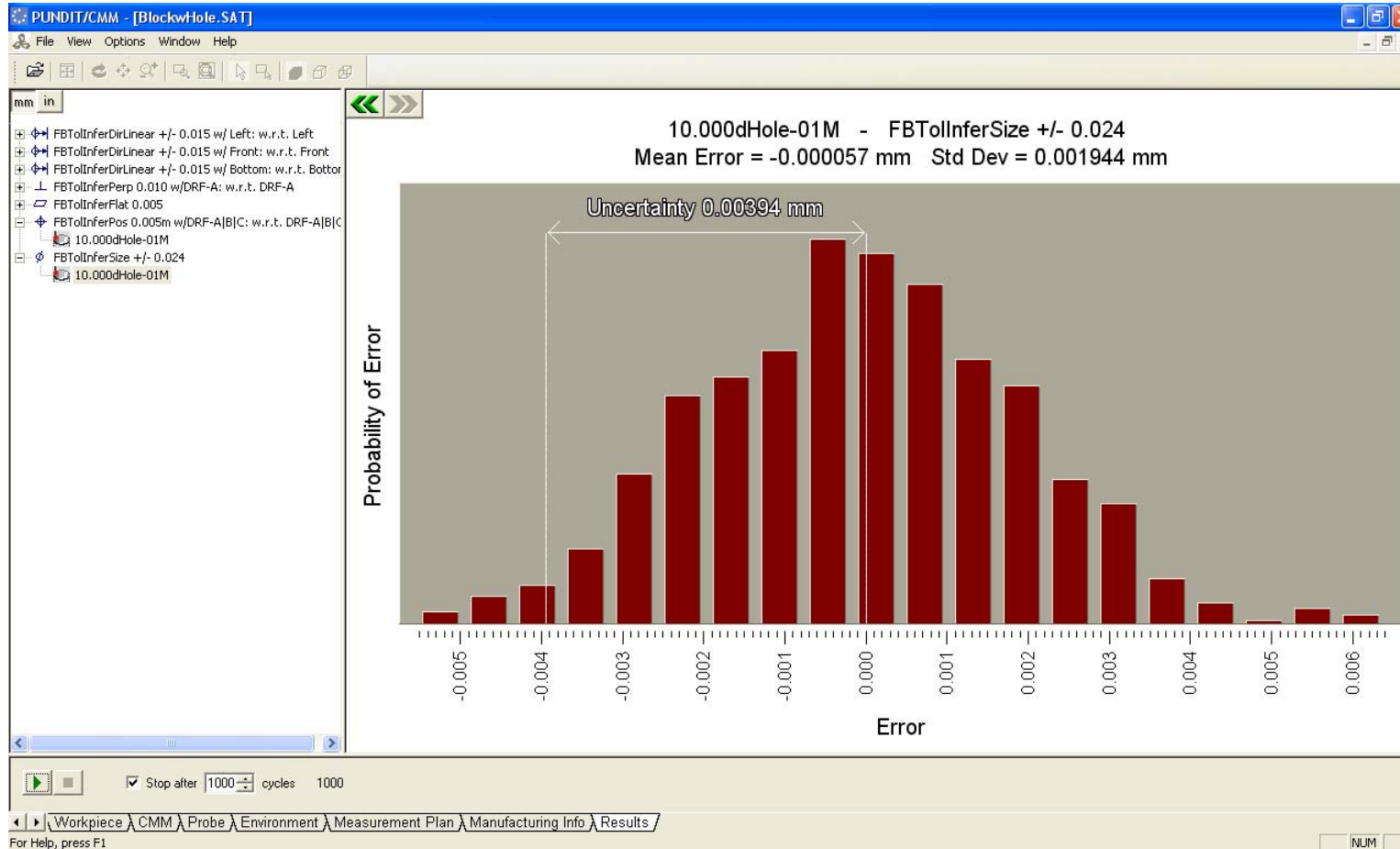
Demonstrating measurement traceability to national or international standards



CMM Traceability Chain



PUNDIT/CMM



Task-Specific Measurement Uncertainty Report

Units:	mm			
		Tolerance	Uncertainty	%Tol Consumed
10.000dHole-10				
	Pos0.125mADsB: w.r.t. DRF-ADsB	0.125	0.0155	12.4% *
	Size +0.05 -0.00	0.05	0.0107	21.4% **
10.000dHole-11				
	Pos0.125mADsB: w.r.t. DRF-ADsB	0.125	0.015	12.0% *
	Size +0.05 -0.00	0.05	0.0108	21.6% **
13.000dHole-03				
	Pos0.10mABC: w.r.t. DRF-ABC	0.1	0.0299	29.9% **
	Size +/- 0.05	0.1	0.0109	10.9% *
13.000dHole-04				
	Pos0.10mABC: w.r.t. DRF-ABC	0.1	0.0318	31.8% ***
	Size +/- 0.05	0.1	0.011	11.0% *
BlockAngledTop				
	Angularity0.07: w.r.t. DRF-A	0.07	0.008	11.5% *
	Prof0.10ADsB: w.r.t. DRF-ADsB	2.54	0.0229	0.90%

⋮



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An Automotive Case Study

A Steering Case: Features, Datums & Tolerances

mm

- Tolerance Definition
 - Tolerance Features
 - 80.950dInnerDiam-01 : A
 - Planar-01 : B
 - Planar-02 : C
 - 9.000dHole-02 : E
 - 9.000dHole-03
 - 46.040dInnerDiam-04
 - 41.277dHole-05 : D
 - 66.700dInnerDiam-06
 - Datum Reference Frames
 - DRF-ABC
 - A : 80.950dInnerDiam-01 : NO_MCM
 - B : Planar-01
 - C : Planar-02
 - DRF-CBA
 - DRF-E
 - DRF-CBE
 - DRF-D
 - DRF-A
 - Tolerances
 - Cylindricity-1
 - Parallelism-1: w.r.t. DRF-A
 - Perpendicularity-1: w.r.t. DRF-A
 - Position-1: w.r.t. DRF-CBE
 - Position-2: w.r.t. DRF-CBA
 - Position-3: w.r.t. DRF-D
 - Position-4: w.r.t. DRF-ABC
 - Size-1
 - Size-2
 - Size-3
 - Total Runout-1: w.r.t. DRF-D
 - General Property Attributes

PUNDIT/CMM - [Steering Case 2a.SAT]

File View Camera Tol Defn Tol Feat DRF Tolerance Gen Prop Attrib Product Info Solids Tools Window Help

mm

- Tolerance Definition
 - Tolerance Features
 - 80.950dInnerDiam-01 : A
 - Planar-01 : B
 - Planar-02 : C
 - 9.000dHole-02 : E
 - 9.000dHole-03
 - 46.040dInnerDiam-04
 - 41.277dHole-05 : D
 - 66.700dInnerDiam-06
 - Datum Reference Frames
 - DRF-ABC
 - A : 80.950dInnerDiam-01 : NO_MCM
 - B : Planar-01
 - C : Planar-02
 - DRF-CBA
 - DRF-E
 - DRF-CBE
 - DRF-D
 - DRF-A
 - Tolerances
 - Cylindricity-1
 - Parallelism-1: w.r.t. DRF-A
 - Perpendicularity-1: w.r.t. DRF-A
 - Position-1: w.r.t. DRF-CBE
 - Position-2: w.r.t. DRF-CBA
 - Position-3: w.r.t. DRF-D
 - Position-4: w.r.t. DRF-ABC
 - Size-1
 - Size-2
 - Size-3
 - Total Runout-1: w.r.t. DRF-D
 - General Property Attributes

Workpiece CMM Probe Environment Measurement Plan Manufacturing Info Results

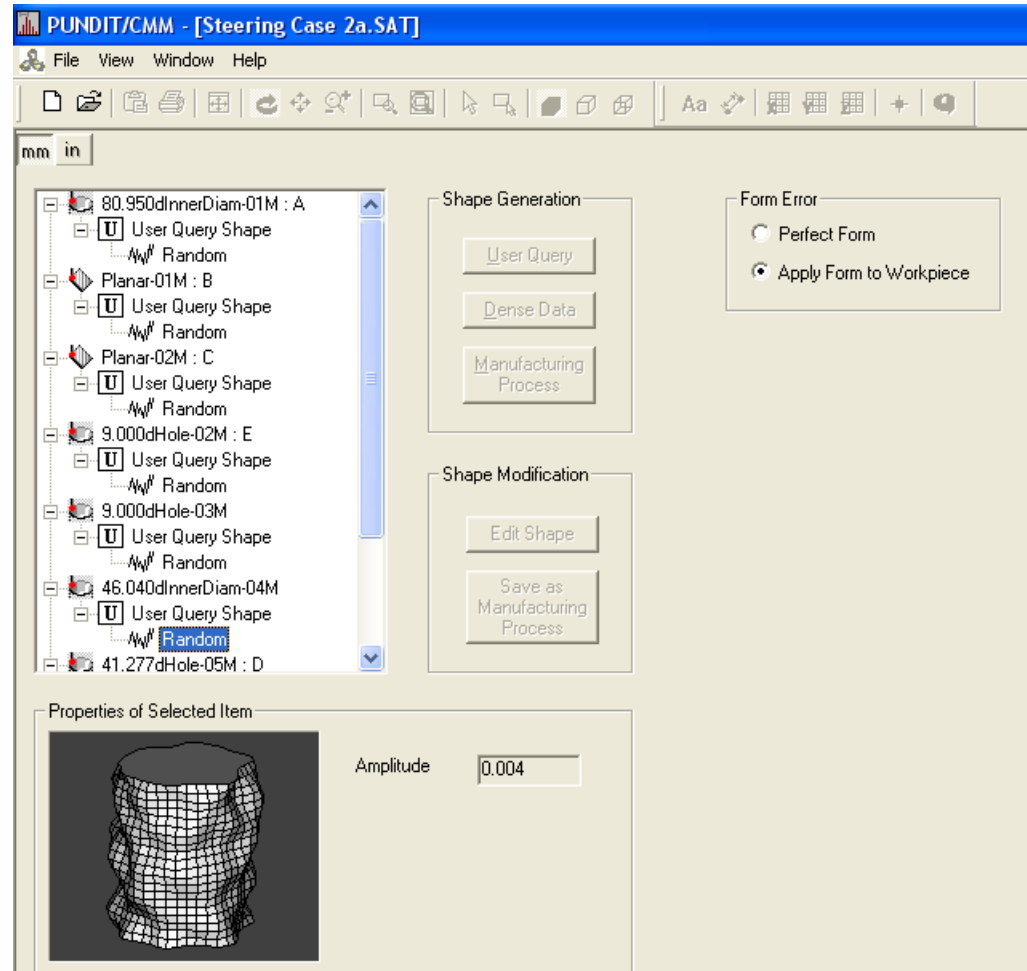
Feature Form Error Definitions

- Style:

Random surface error

- Amplitudes:

Feature-dependent: 4 to 11 μm



CMM Definition

- Style:

Moving Bridge

- Dimensions:

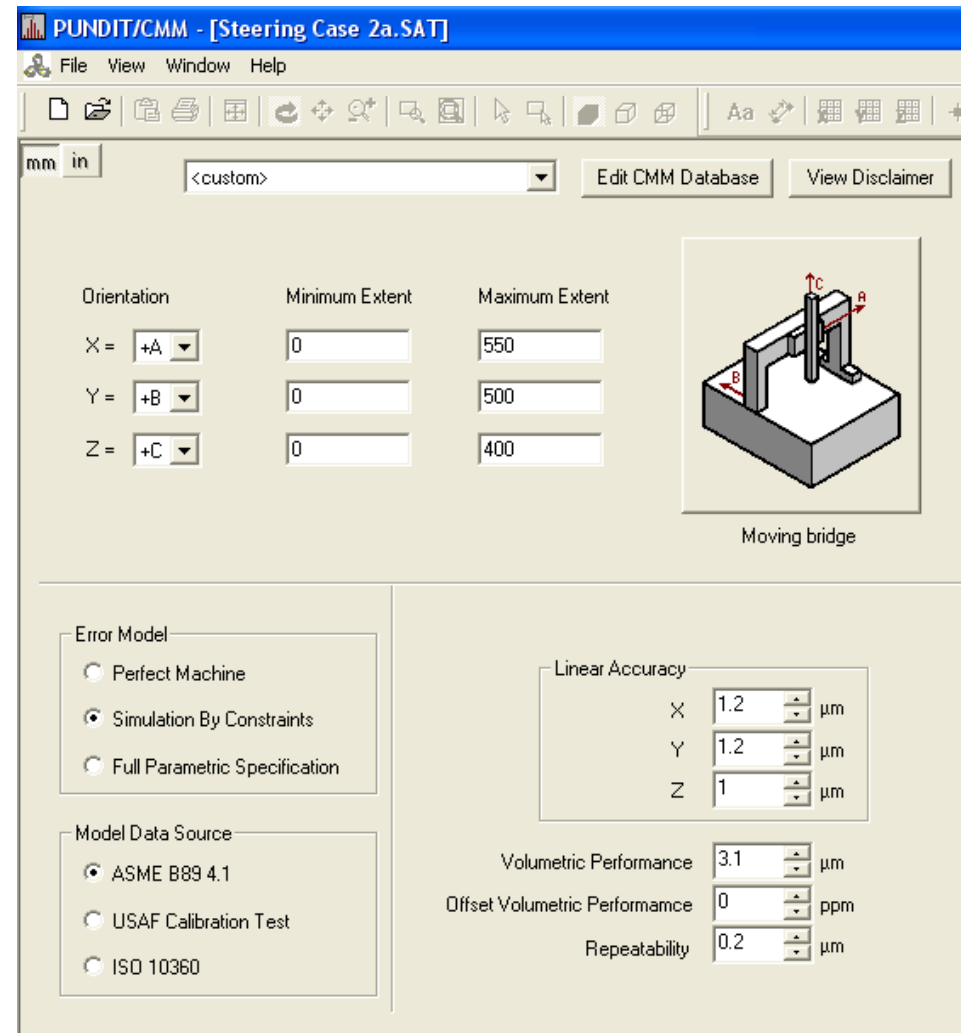
X: 550mm Y: 500mm Z: 400mm

- Error Model:

Simulation by Constraints

- Model Source Data:

ASME B89 4.1



Probe Definition

- Styli:
 - Fixed Orientation, Multi-Tip
- Dimensions:
 - All stylus lengths 80mm
- Error Model:
 - Switching Probe
- Model Source Data:
 - ISO 10360

PUNDIT/CMM - [Steering Case 2a.SAT]

File View Window Help

mm in

Probe Configuration

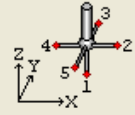
- Fixed Orientation Single Tip
- Fixed Orientation Multi-Tip
- Articulated Single Tip

Probe Error Model

- Perfect Probe
- Piezoelectric Probe
- Switching Probe

Performance Evaluation Test

- ISO 10360
- ASME B89.4.1
- VDI / VDE
- Specified Std Dev
- USAF Calibration Test



Stylus length of tip 1: 80 mm

Stylus length of tips 2 through 5: 80 mm

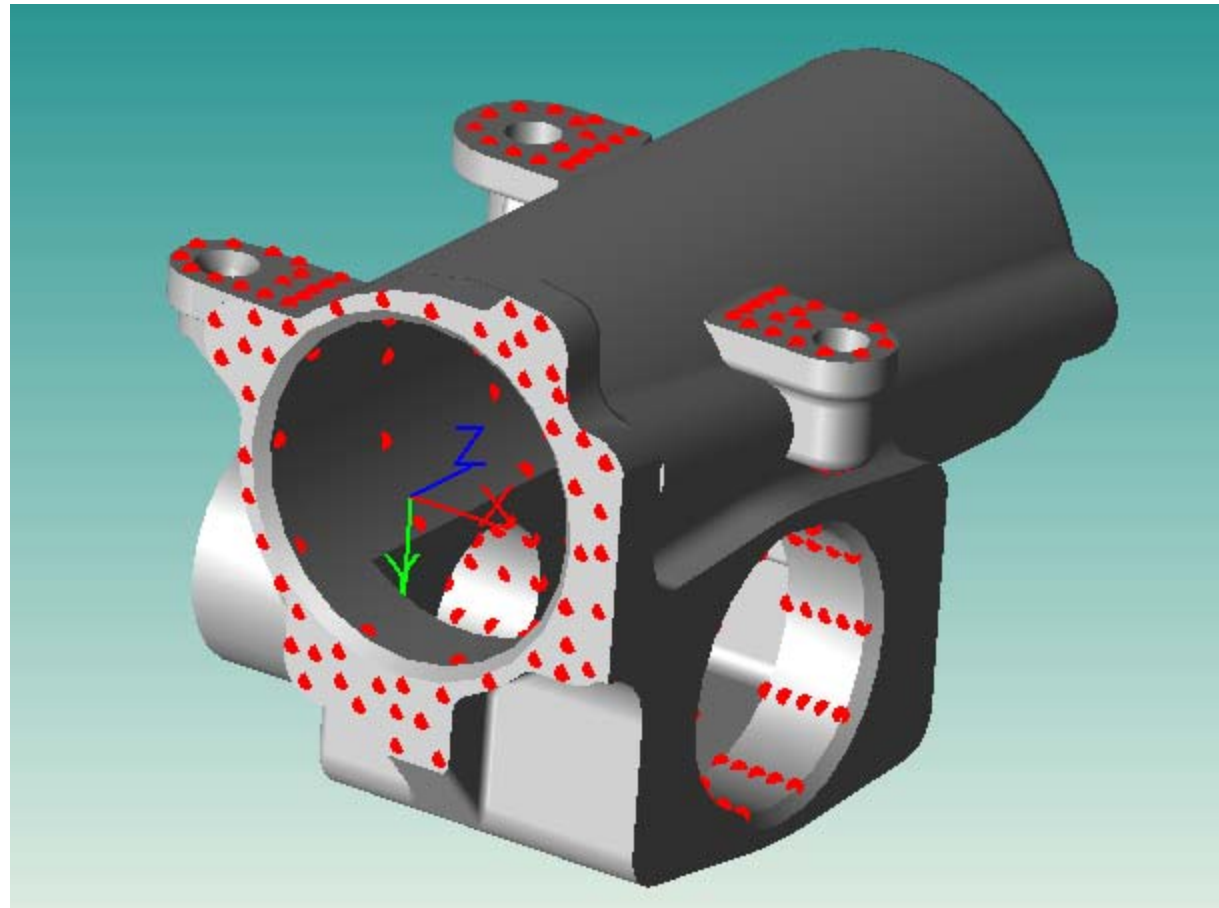
ISO-10360-5 Performance Test for Fixed Orientation Multi-Tip Probe

Stylus Length (mm)	MPE _{ML}	MPE _{MS}	MPE _{MF}	
10	1.7	0.1	0.5	μm
20	0	0	0	μm
30	0	0	0	μm
50	0	0	0	μm
100	0	0	0	μm
200	0	0	0	μm
400	0	0	0	μm

MPE_{ML} = Largest range of center coordinates for the 5 25-point spheres
MPE_{MS} = Deviation of the 125-point sphere fit diameter from calibrated diameter
MPE_{MF} = Range of residuals of the 125-point sphere fit

Sampling Point Specifications

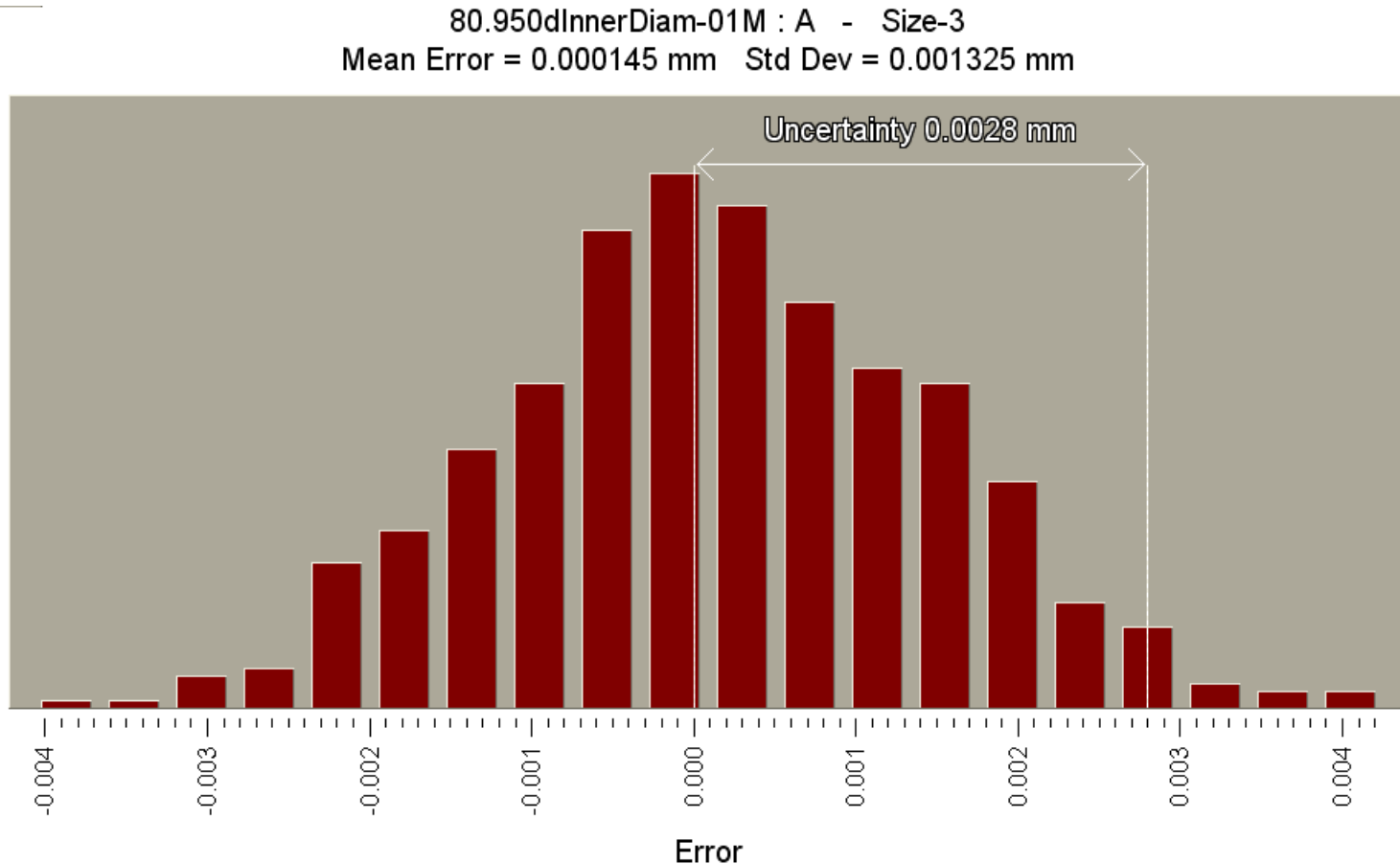
- Apply probing points to features
 - Manual selection
 - Automated regular patterns
- Regular patterns can be uniform or staggered, rows & columns or by point density
- Edge offsets can be specified
- Points falling into voids are discarded automatically



Results & Analysis

For each toleranced feature characteristic, PUNDIT/CMM reports:

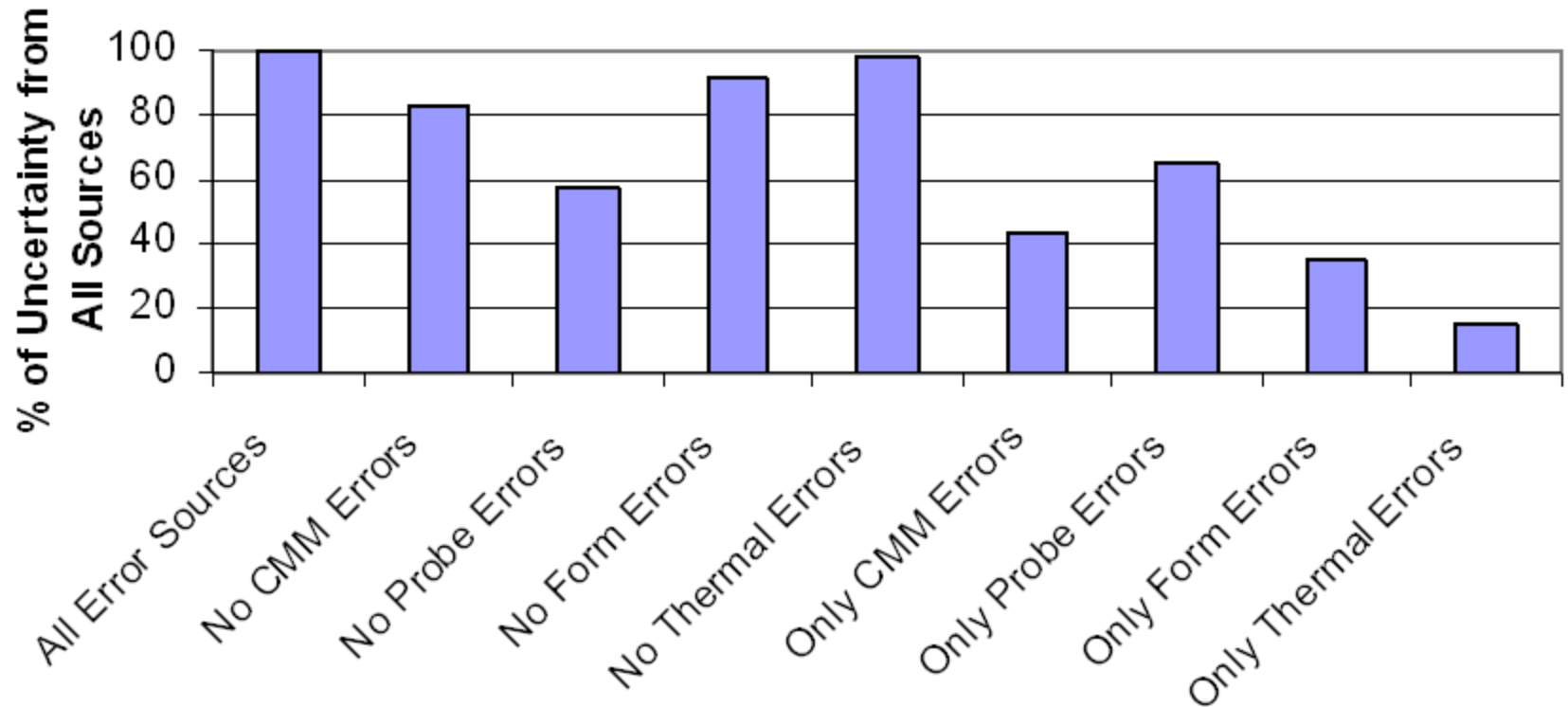
- Mean Error (i.e. bias in measurement)
- Standard Deviation
- Expanded Uncertainty at 95% certainty



Task-Specific

Measurement Uncertainty Analysis

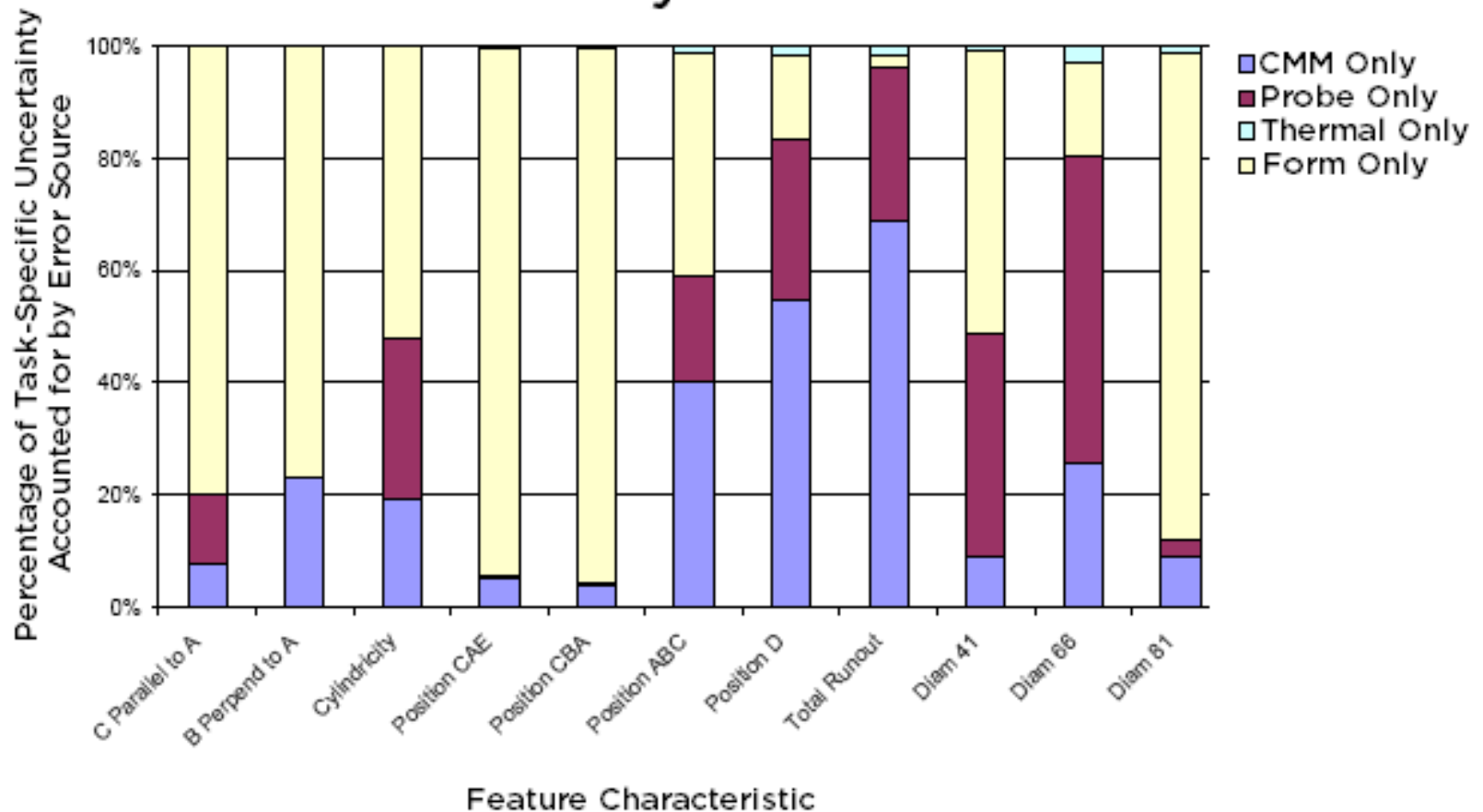
Diameter Uncertainty for Nominal 66.7mm ID Cylindrical Feature



Task-Specific

Measurement Uncertainty Analysis

Steering Case Task-Specific Measurement Uncertainties by Error Source



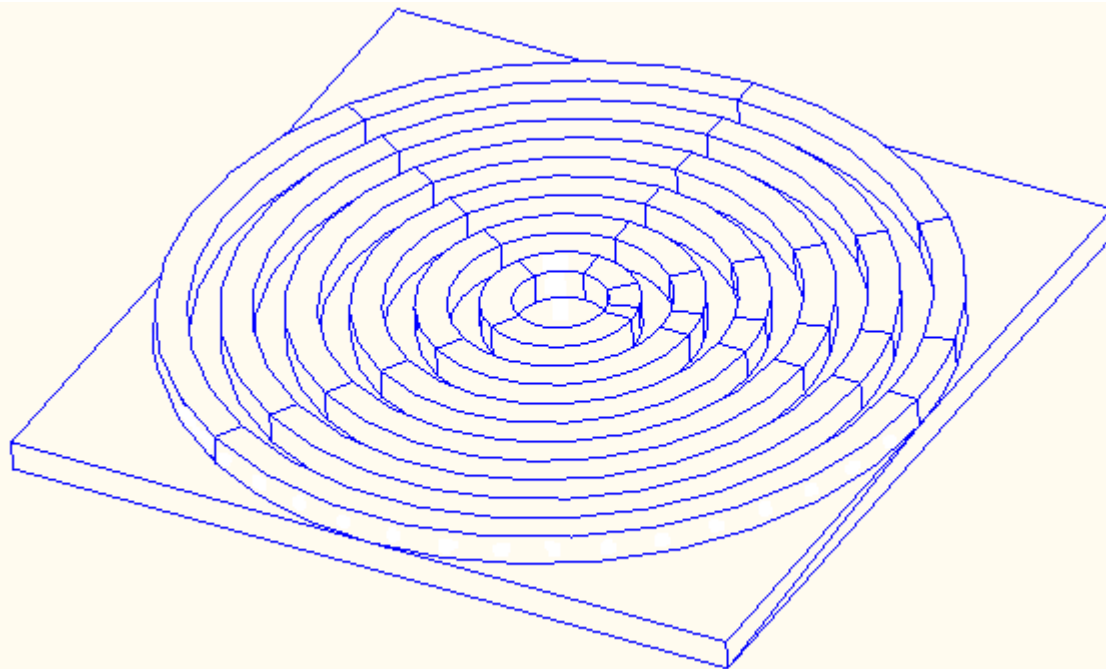
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Arc Feature Measurement

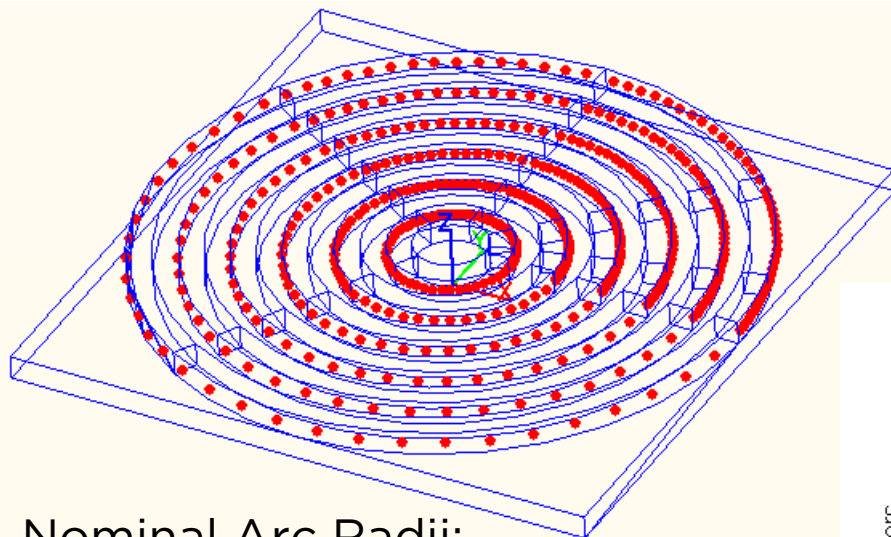
Virtual Part

Concentric Rings of Outside Diameters from 100 mm to 500 mm and Inside Diameters from 60 mm to 460 mm Sliced into Arcs of 15°, 30°, 45°, 60°, 90° and 120°



Size Controlled by Diameter

Location/Orientation by Position



Nominal Arc Radii:

50, 90, 130, 170, 210, 250 mm

Arc Segments:

15°, 30°, 45°, 60°, 90°, 120°

Sampling Points over Arc:

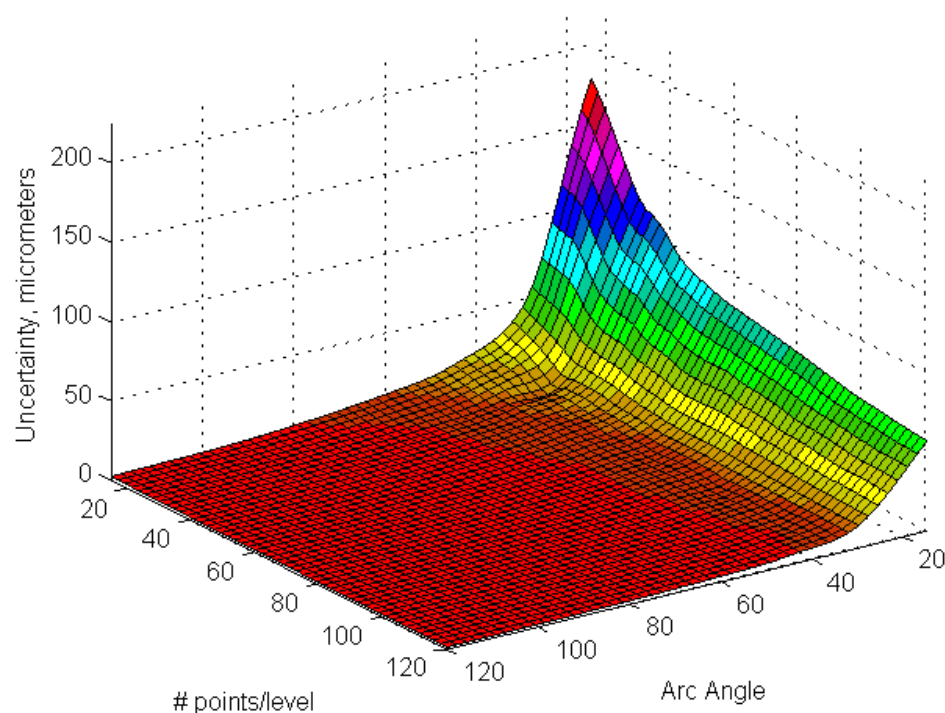
2 x 15, 30, 60, 80, 100, 120

Random Probe Error with $\sigma = 0.65\mu\text{m}$

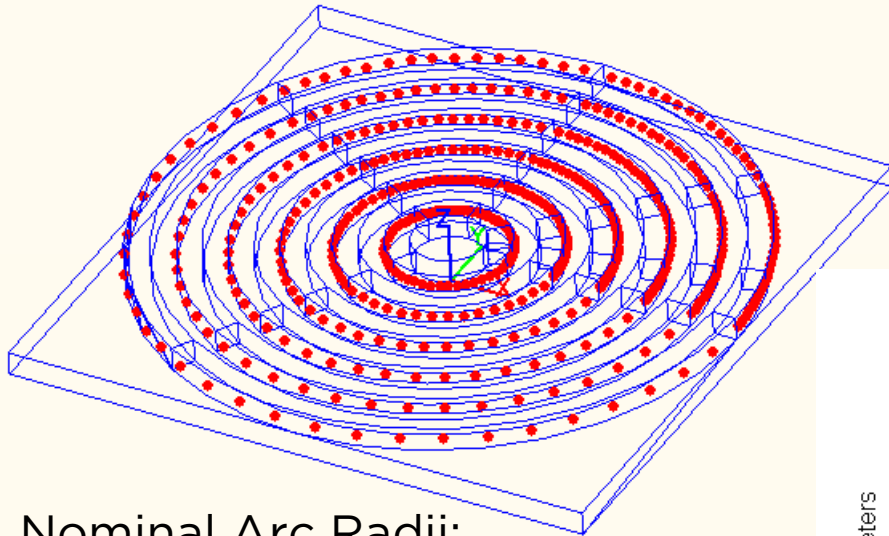
Uncertainties Largely Insensitive to Size of Feature or ID/OD Type

Positional Data Similar to Diameter:

Diameter, 3D



Size, Location & Orientation Controlled by Profile



Nominal Arc Radii:

50, 90, 130, 170, 210, 250 mm

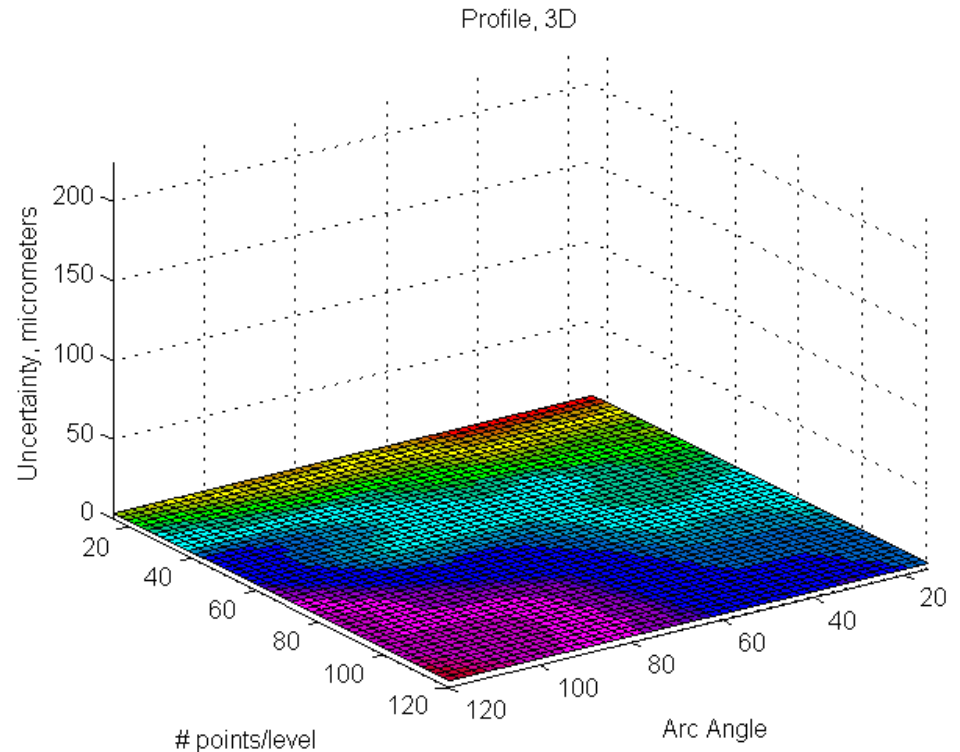
Arc Segments:

15°, 30°, 45°, 60°, 90°, 120°

Sampling Points over Arc:

2 x 15, 30, 60, 80, 100, 120

Random Probe Error with $\sigma = 0.65\mu\text{m}$
 Uncertainties Largely Insensitive
 to Size of Feature or ID/OD Type
 Profile Uncertainties in 3-4 μm range



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Production & Measurement

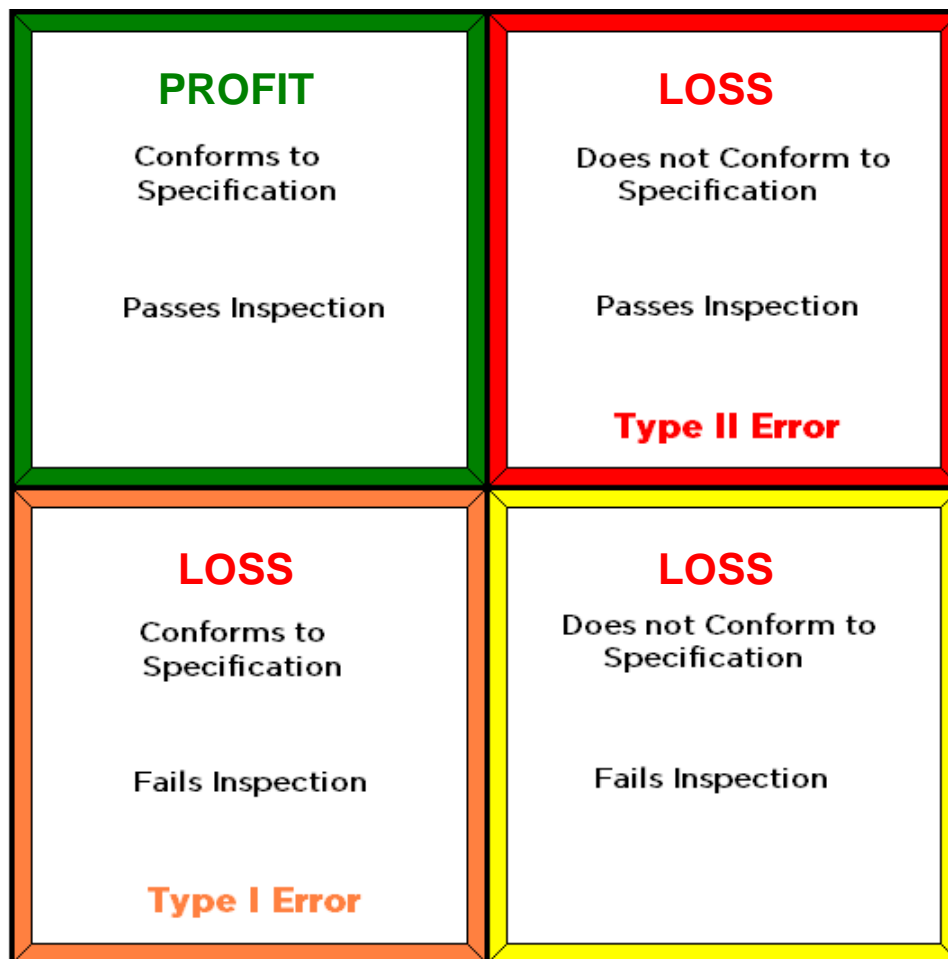
4 Possible
Outcomes:

<p>Conforms to Specification</p> <p>Passes Inspection</p>	<p>Does not Conform to Specification</p> <p>Passes Inspection</p> <p>Type II Error</p>
<p>Conforms to Specification</p> <p>Fails Inspection</p> <p>Type I Error</p>	<p>Does not Conform to Specification</p> <p>Fails Inspection</p>

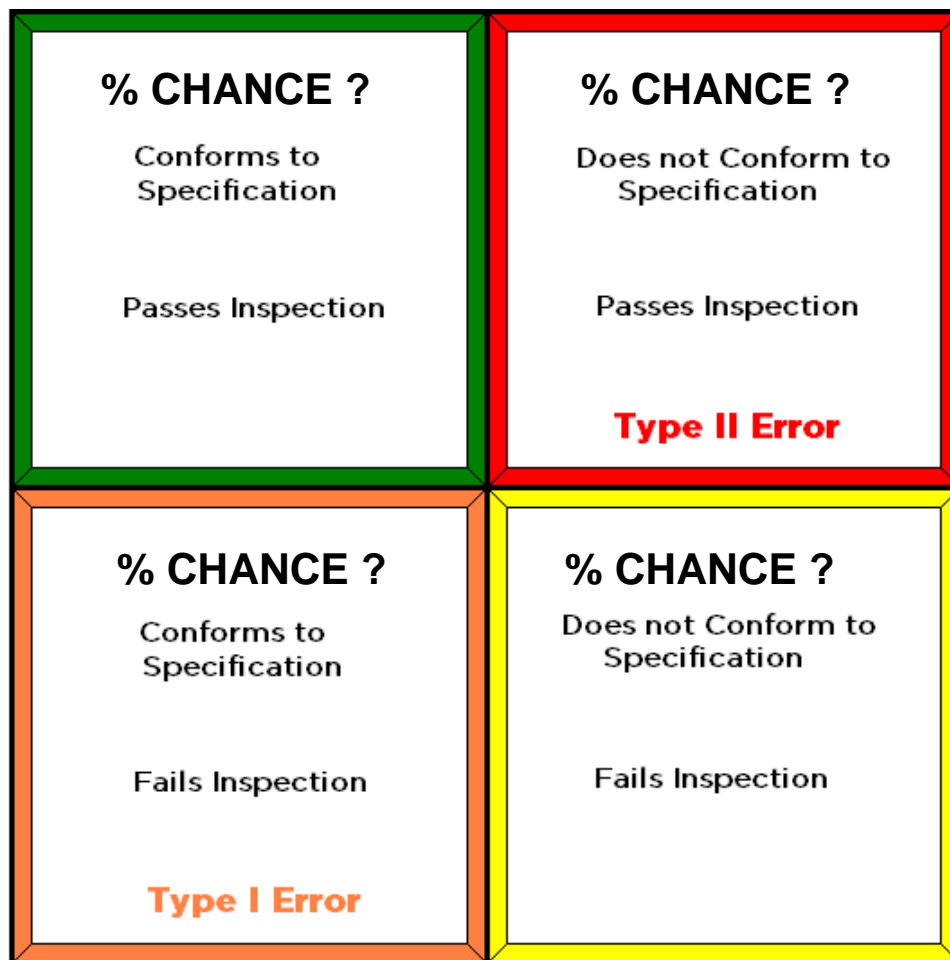


Production & Measurement

3 out of 4
Yield
Losses



Production & Measurement



Economics of Measurement Uncertainty

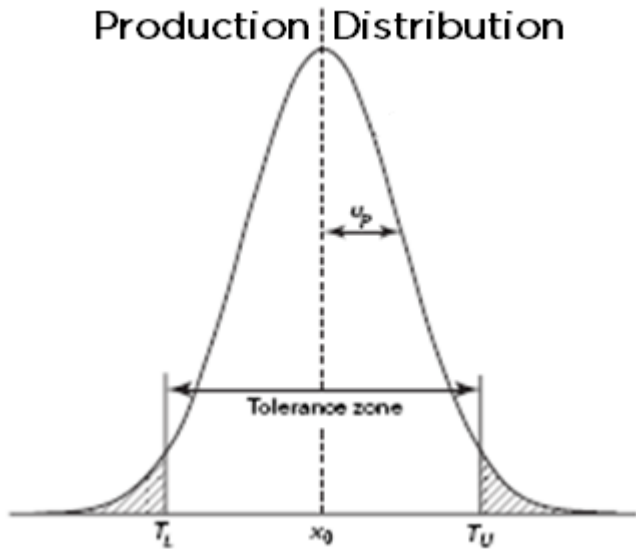
Factors for Consideration:

- ✓ Production Capability
- ✓ Measurement Capability
- ✓ Cost of Rejecting a Good Part (Type I Error)
- ✓ Cost of Accepting a Bad Part (Type II Error)

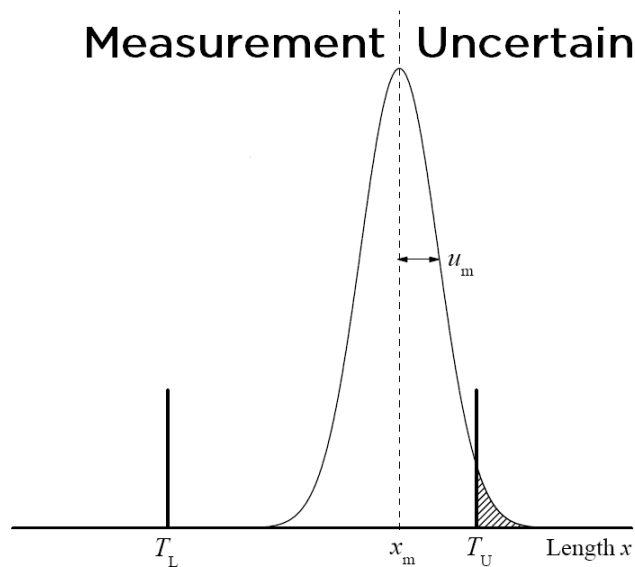


Production & Measurement Capabilities

Production Distribution



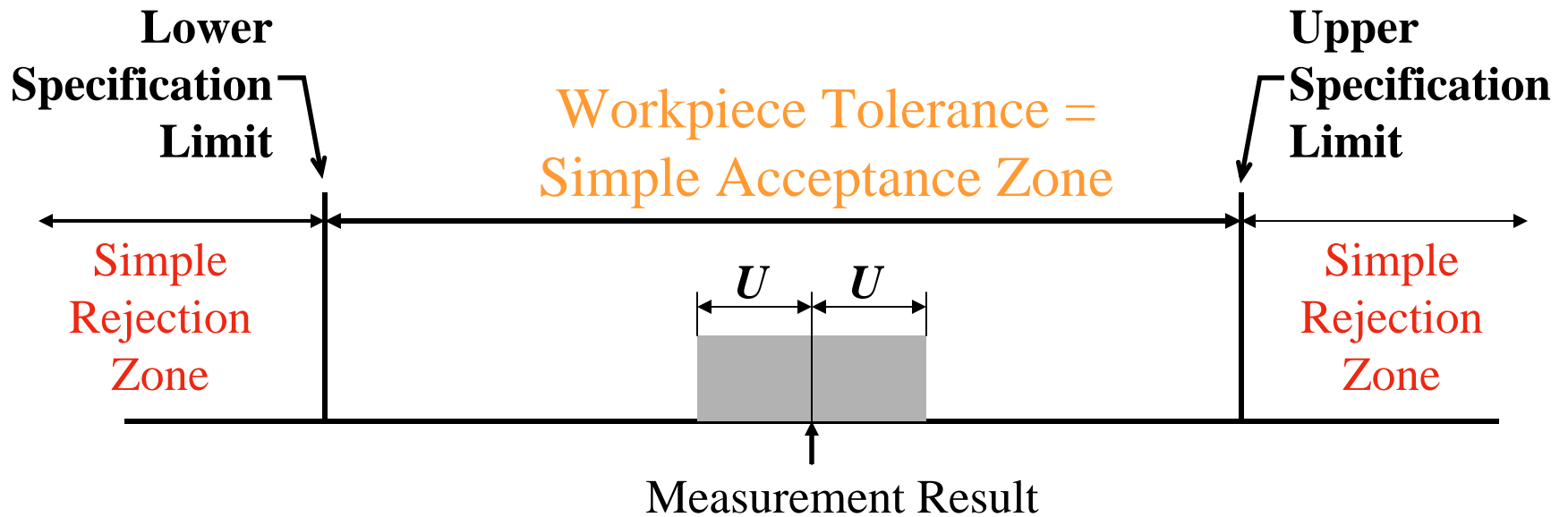
Measurement Uncertainty



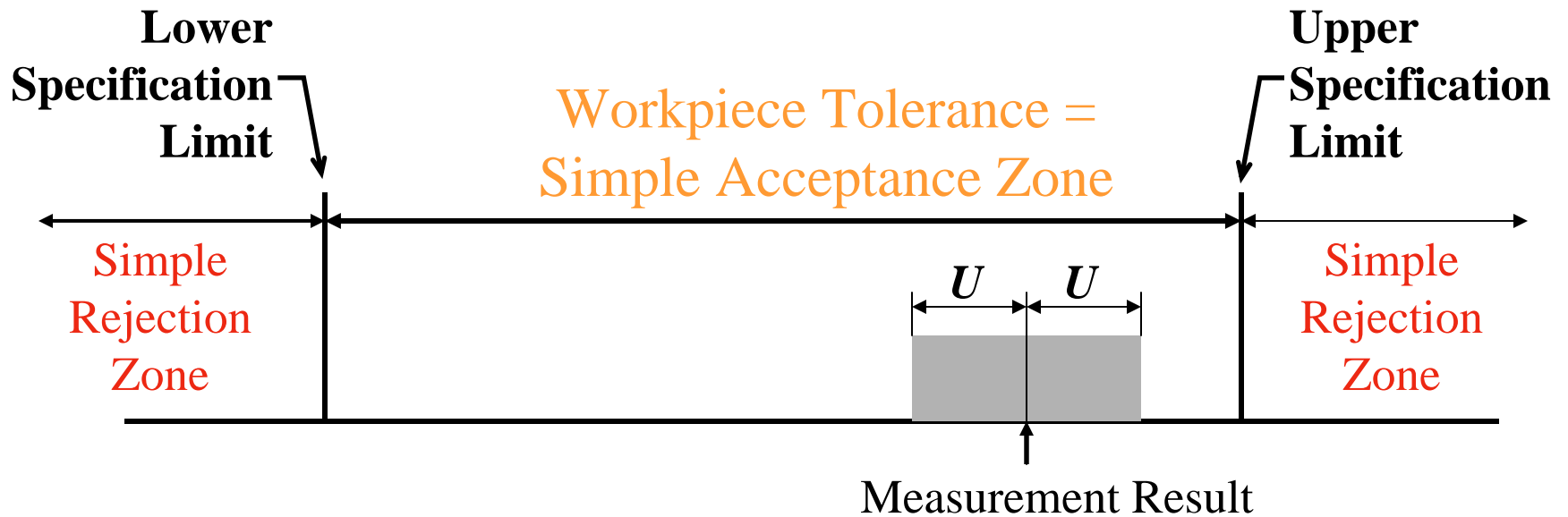
Decision Rule without Regard to Measurement Uncertainty



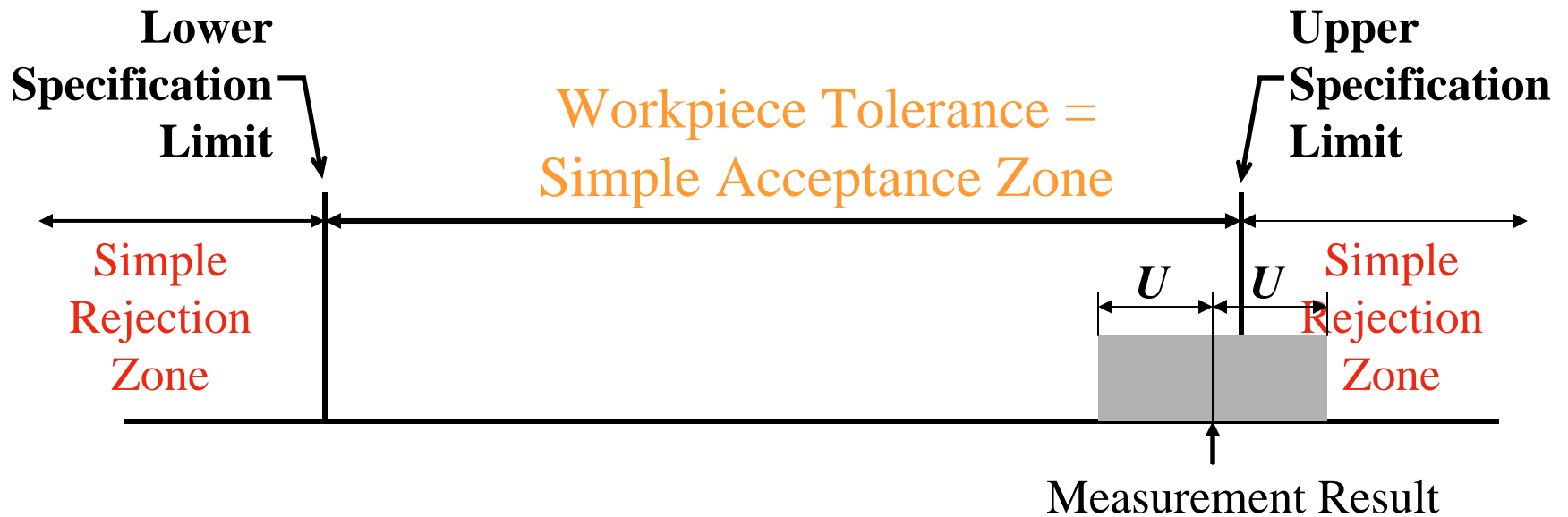
Factoring in Measurement Uncertainty



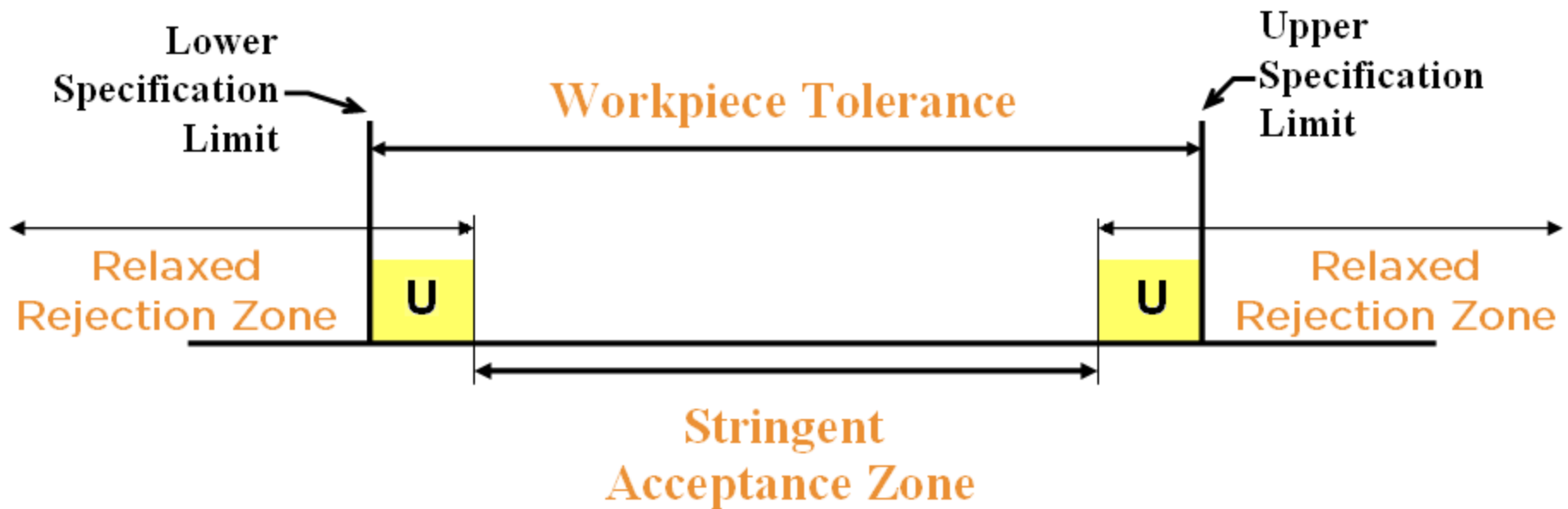
Factoring in Measurement Uncertainty



Factoring in Measurement Uncertainty



Decision Rule: Stringent Acceptance



Less chance of accepting a bad part

Greater chance of rejecting a good part



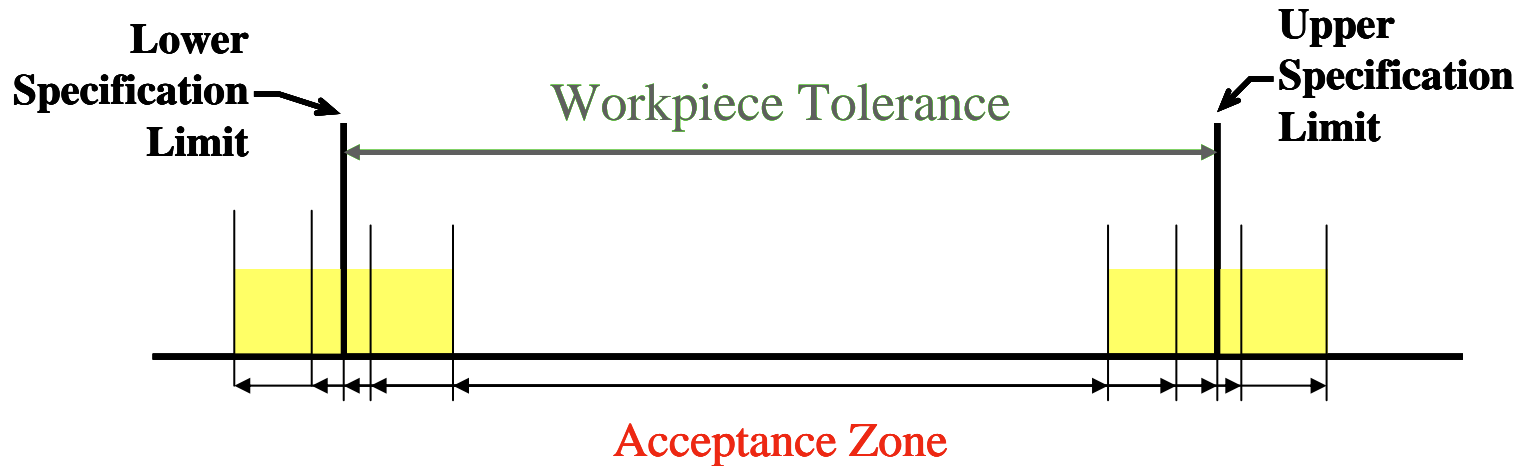
Decision Rule: Stringent Rejection



Greater chance of accepting a bad part
 Less chance of rejecting a good part



Economic Optimization of Decision Rules Guardband Selection

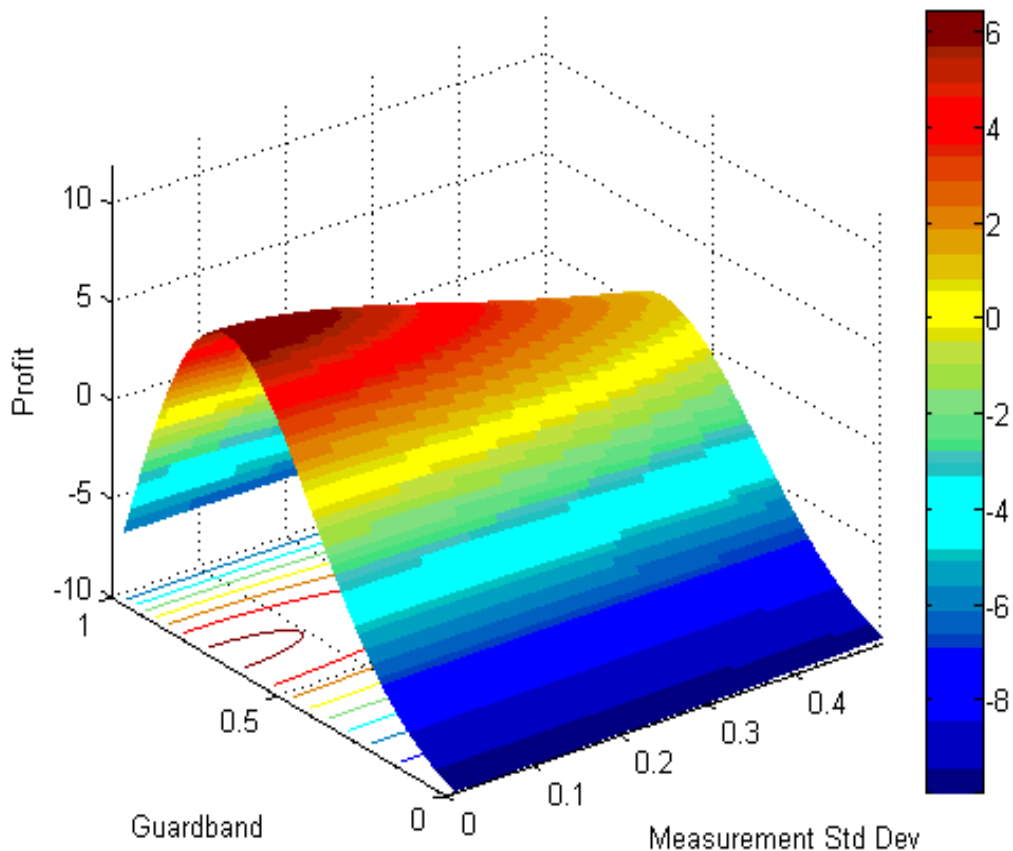


Which Decision Rule Maximizes Profits?



Measurement Uncertainty & Profitability

Per Unit Profit vs. Measurement Uncertainty & Guardband



- 100 mm diameter shaft**
- Tolerance ± 1 mm**
- Production Process Centered**
- Production Std Dev. 0.33 mm**
- Measurement Unbiased**
- Cost of unit production: \$7.50**
- Sales Price: \$30**
- Expense of release of bad part (Type II Error): \$300**

Profit Maximized when each Guardband = 0.65 mm



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