

**COP Gage Design Review**

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**ERROR BUDGET**

**D. THOMPSON**

**The COP Gage Error Budget is Based in Part On:**

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- **LODTM Error Budget (Donaldson, 1979)**
- **Dual Transducer Error Budget (Thompson, 1985)**
- **Suggestions From Others (e.g., Hocken)**

## **PFMS Working Group 2 Specified Overall Accuracy Requirements**

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- **Inner Contour: 30 Microinches P-V  
(Size & Contour)**
- **Outer Contour: 30 Microinches P-V  
(Size & Contour)**
- **Wall Thickness: 70 Microinches P-V  
(Size & Contour)**

## **In Interpreting The PFMS Requirements We Assumed:**

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### **All Identifiable Sources of Measurement Error**

- Machine Errors (Probe Path Accuracy)
- Probe Errors (Linearity, Tip Sphericity, etc.)
- Process Errors (Mastering, Centering, etc.)

### **Thick-Walled Parts (~0.5 inch)**

### **Full Range of Part Sizes**

- 16 Inch Maximum O.D.
- 4 Inch Minimum I.D.

## Assumptions (Continued)

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**Part Data Grid Spacing:  $1^\circ \times 1^\circ$**

### **Correction For Set-up Errors**

- Post-Processing Correction for Centering Error
- Real-Time Correction for Part Angular Misalignment

### **Error Mapping To Reduce Systematic Machine Errors.**

- Non-Repeatable Errors will Dominate After Compensation
- Systematic Components Determined by Calibration Accuracy

## Assumptions (Continued)

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### Combinatorial Rules

- Separate Budgets for Inner and Outer Contour Measurements
- Arithmetic Sums Determine Upper Bound Y and Z-Direction Errors

$$\text{EXAMPLE: } E_{TY} = \sum_{i=1}^N E_{Y_i}$$

- RMS Sums Determine Lower Bound  
Y and Z-Direction Errors

$$\text{EXAMPLE: } \text{RMS}_Y = \frac{1}{2\sqrt{3}} \left[ \sum_{i=1}^N (E_{Y_i})^2 \right]^{1/2}$$

## Assumptions (Continued)

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- Means of RMS and Arithmetic Sums Used for Error Budget.
  
- Total Radial Figure Error Calculated as the Vector Sum of the X and Z Components.

## COP Gage Error Budget

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**MACHINE ERRORS**

**(PROBE PATH ACCURACY)**

## Machine Errors

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### Laser Interferometers

- Standard Zygo System
- 0.1 Microinch Resolution
- Evacuated Beam Paths, 50 Millitorr

<b>Index of Refraction</b>	<b><math>1.8 \times 10^{-8}</math></b>
<b>Central Frequency Stability</b>	<b><math>2.0 \times 10^{-8}</math></b>
<b>Resolution</b>	<b>0.1 Microinch</b>
<b>Optical, Electronic Factors</b>	<b>0.2 Microinch</b>

## Machine Errors (Continued)

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### Rotary Table

- Error Motion Values are Assumed Comparable to Similar A.G. Davis Unit
- Professional Instruments Suggests they Could Improve on These Values

**Total Axial Motion      4.0 Microinches**

**Total Radial Motion    4.0 Microinches**

**Total Tilt Motion        0.1 Arc-Second**

## Machine Errors (Continued)

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### Axis Geometry - - Uncompensated

- Assumes Reasonable Manufacturing Tolerances
- 2 Inch Fixed Abbé Offset on Z-Axis
- 0.5 Inch Variable Abbé Offset on Upper Z-Axis
- Finite Element Modeling Used to Establish Gravity Loading Effects
- 200 Pound Maximum Part Mass
- Values Apply to Measuring Travel

## Machine Errors (Continued)

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<b>Y-Slide Straightness - Manufacturing</b>	<b>20 Microinches</b>
<b>Upper, Lower Z-Slide Straightness</b>	<b>20 Microinches</b>
<b>Upper, Lower Z-Slide Positioning (Pitch)</b>	<b>10 Microinches (1 Arc-Second)</b>
<b>Squareness-Upper Z-Slide to Y-Slide</b>	<b>.4 Arc-Second</b>
<b>Squareness-Lower Z-Slide to Y-Slide</b>	<b>.4 Arc-Second</b>
<b>Squareness-Rotary Table to Y-Slide</b>	<b>.4 Arc-Second</b>

## Machine Errors (Continued)

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### Axis Geometry - - Uncompensated (Continued)

- Loading Effects - Repeatable

**Y-Slide Straightness  
(Base & Moving Slide)**

**4 Microinches**

**Squareness - Upper Z-Slide  
to Y-Slide**

**0 Microinches**

**Squareness - Lower Z-Slide  
to Y-Slide**

**0 Microinches**

## Machine Errors (Continued)

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### Axis Geometry - - Uncompensated (Continued)

- Loading Effects - Non-Repeatable

**Y-Slide Straightness  
(Part Mass)**

**0 Microinches**

- Upper Z-Slide Pitch - - Varying Offset

**Straightness**

**2.5 Microinches  
(1 Arc-Second)**

**Positioning**

**2.5 Microinches  
(1 Arc-Second)**

## Machine Errors (Continued)

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### Axis Geometry - Compensated

- Assumes Instrumentation and Procedures Similiar to Those Used by NBS to Calibrate LODTM
- Assumes Multiple Measurements to Identify Systematic Error Components
- Assumes Calibration Accuracy Approaching (X2) that Achieved on LODTM

## Machine Errors (Continued)

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### Axis Geometry - Compensated (Continued)

- Y-Slide Straightness - Total	4 Microinches
- Upper, Lower Z-Slide Straightness	4 Microinches
- Upper, Lower Z-Slide Positioning	1 Microinch
- Squareness, Upper Z-Slide to Y-Slide	.12 Arc-Second
- Squareness, Lower Z-Slide to Y-Slide	.12 Arc-Second
- Squareness, Rotary Table to Y-Slide	.1 Arc-Second

## Machine Errors (Continued)

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### Thermal Effects

- A Finite Element Model of the Entire Machine Structure Was used to predict Impact of Thermal Distortions on Gaging Accuracy
  - 0.1 °F Gradient - - X Direction
  - 0.1 °F Gradient - - Y Direction
  - 0.1 °F Gradient - - Z Direction
  - 0.1 °F Overall Change
- Values Used in Error Budget Were Largest Calculated for Each Probe and Direction
- Effect of Motor Heat on the Rotary Table was Calculated for a Typical Duty Cycle
- Capstan Drive Motor Heat was Determined to be Negligible and Controllable.

## Machine Errors (Continued)

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### Thermal Effects (Continued)

Upper Probe -- Y-Direction	12.0 Microinches
Upper Probe -- Z-Direction	9.6 Microinches
Lower Probe -- Y-Direction	16.8 Microinches
Lower Probe-- Z-Direction	7.6 Microinches
Rotary Table Drive Motor-- Z-Direction	3.0 Microinches

## **COP Gage Error Budget**

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## **PROBE ERRORS**

## Probe Errors

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### LVDT Probe

- Standard LLNL Air Bearing LVDT
- Standard LLNL LVDT Amplifier
- 30 HZ Bandwidth
- 0.001 Inch Gaging Range
- Zerodur Stylus

**Electronic Noise**

**1 Microinch**

**Linearity**

**1 Microinch**

**Thermal Stability**

**0**

## Probe Errors (Continued)

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### Laser Probe

- 0.75 Inch Gaging Range
- 0.1 Microinch Resolution
- Super Invar Reference Cavity
- Zerodur Stylus

<b>Resolution</b>	<b>0.1 Microinch</b>
<b>Environmental Compensation</b>	<b>0.1 Microinch</b>
<b>Thermal Stability</b>	<b>0.1 Microinch</b>

## Probe Errors (Continued)

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### Probe Tip Errors

- Sapphire
- .156 Inch Diameter
- 3 Microinch Sphericity
- Diameter Established Within 1 Microinch

**Size**

**.4 Microinches**

**Contour**

**2.0 Microinches**

## Probe Errors (Continued)

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### Gaging Force Errors

- 25 IPM Gaging Velocity
- 0.1 G Max Acceleration (Conservative)
- LVDT Probe: 0.5 Gram Stylus Force
- Laser Probe: 1.0 Gram Stylus Force
- Error measured at 45° Probe Angle

**LVDT Probe**

**1.0 Microinches**

**Laser Probe**

**3.0 Microinches**

**COP Gage Error Budget**



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**PROCESS ERRORS**

## Process Errors

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### Mastering

- Two-Ball Master
- Average Ball Diameters Established Within 2 Microinches
- Pole Separation Established Within 2 Microinches
- 360° Sweeps to Establish Best-Fit Centers

**Y-Direction Mastering**

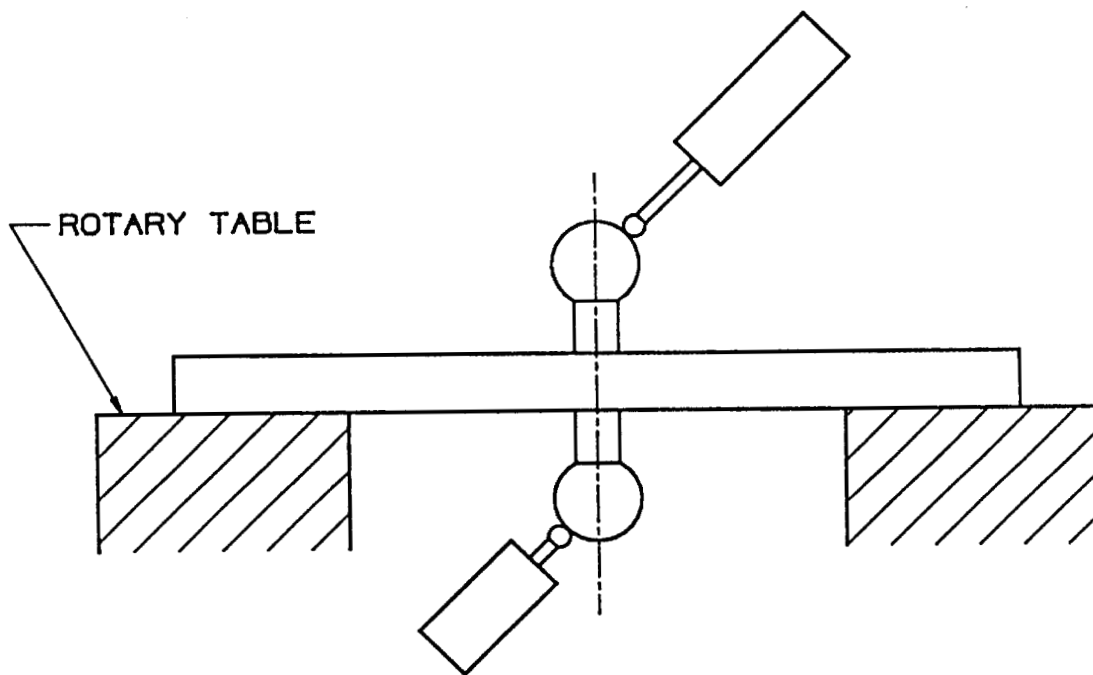
**1 Microinch**

**Z-Direction Mastering**

**1 Microinch**

# TWO BALL MASTER

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## Process Errors (Continued)



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### Part Datum Location Methods of Interpretation Include

- Direct Measurement--Best Fit Plane
- Direct Measurement--3 High Points
- Inferred From Mounting Surface

**Current Practice is to Infer the Datum from the Part Mounting Surface**

**The COP Gage Will Allow Implementation of any Datum Definition. We will Work with the NWC Contractors to Establish a Mutually Agreeable Solution.**

**Part Datum Location**

**0**

## Process Errors (Continued)

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### Data Acquisition

- Time-Based Data
- Anti-Alias Filtering
- Digital Filtering
- Interpolation to Create Spatially Defined Data
- Spatial Filtering

**Sampling Interpolation**

**1 Microinch**

**COP GAGE ERROR BUDGET SUMMARY  
(WITH GEOMETRY COMPENSATION)**

**1. PROBE PATH ACCURACY**

	P-V MAGNITUDE (microinches)			
	E <sub>YL</sub>	E <sub>YU</sub>	E <sub>ZL</sub>	E <sub>ZU</sub>
<b><u>LASER INTERFEROMETERS</u></b>				
Frequency stability	.6	.6	1.2	.9
Resolution	.1	.1	.1	.1
Index of refraction	.5	.5	1.0	.8
Optical, electronic factors	.2	.2	.2	.2
<b><u>ROTARY TABLE</u></b>				
Total radial motion (including tilt)	5.2	5.2		
Total axial motion (including tilt)			5.2	5.2
<b><u>MACHINE GEOMETRY</u></b>				
Y-slide straightness			4.0	4.0
Upper z-slide straightness		4.0		
Lower z-slide straightness	4.0			
Upper z-slide pitch-fixed				1.0
Lower z-slide pitch-fixed			1.0	
Upper z-slide pitch-variable		2.5		2.5
Squareness				
Upper z-slide to y-slide		3.0		3.0
Lower z-slide to y-slide	3.0		3.0	
Rotary table to Y-slide	2.0	2.0	2.0	2.0
Varying load effects				
Y-slide straightness				
Squareness-upper z-slide to y-slide				
Squareness-lower z-slide to y-slide				
<b><u>THERMAL EFFECTS</u></b>				
0.1 degree F gradient--x-direction				
0.1 degree F gradient--y-direction				
0.1 degree F gradient--z-direction		12.0	7.5	9.6
0.1 degree F overall change	16.8			
Slide drive motors				
Rotary table drive motor			3.0	3.0

**COP GAGE ERROR BUDGET SUMMARY  
(WITH GEOMETRY COMPENSATION)**

	P-V MAGNITUDE (microinches)			
	EYL	EYU	EZL	EZU
<b>2. PROBE ACCURACY</b>				
<u>LVDT PROBE</u>				
Electronic noise	1.0		1.0	
Linearity	1.0		1.0	
Thermal stability				
 <u>LASER PROBE</u>				
Resolution		.1		.1
Environmental compensation				
Thermal stability		.1		.1
 <u>PROBE TIP</u>				
Size	.35	.35	.35	.35
Contour	2.0	2.0	2.0	2.0
 <u>GAGING FORCE</u>				
LVDT probe	1.0		1.0	
Laser probe		3.0		3.0
 <b>3. PROCESS ERRORS</b>				
<u>SETUP ERRORS</u>				
Centering				
Angular misalignment--uncorrected	26.0	26.0	26.0	26.0
Angular misalignment-corrected				
 <u>MASTERING</u>				
Two gage ball master	1.0	1.0	1.0	1.0
In-process				
 <u>DATA ACQUISITION</u>				
Sampling interpolation	1.0	1.0	1.0	1.0
Arithmetic sum--Part Tilt Corrected	39.8	37.7	35.6	39.9
Arithmetic Sum--Part Tilt Uncorrected	68.3	63.7	65.1	66.9
RMS Sum--Part Tilt Corrected	5.4	4.3	3.5	3.9
RMS Sum--Part Tilt Uncorrected	9.3	8.7	8.3	8.5

DCT:gys

# COP Gage Error Budget

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## SUMMARY

## Inner Contour Errors



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	Error (Microinches)	
	Y	Z
Arithmetic Sum	39.8	35.6
RMS Sum	5.4	3.5
Mean Sum	22.6	19.6

$$E_{MAX} = \sqrt{E_y^2 + E_z^2}$$

INNER CONTOUR ERROR BY ARITHMETIC SUM METHOD:  $E_{IA} = 54.1$  MICROINCHES

INNER CONTOUR ERROR BY MEAN SUM METHOD:  $E_{IM} = 30.2$  MICROINCHES

## Outer Contour Errors

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	Error (Microinches)	
	Y	Z
Arithmetic Sum	37.7	39.9
RMS Sum	4.3	3.9
Mean Sum	21.0	21.9

OUTER CONTOUR ERROR BY ARITHMETIC SUM METHOD:  $E_{0A} = 55.6$  MICROINCHES

OUTER CONTOUR ERROR BY MEAN SUM METHOD:  $E_{0M} = 30.7$  MICROINCHES

## Wall Thickness Errors

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**Wall Thickness Error = Inner Contour Error + Outer Contour Error**

**Wall Thickness Error by Arithmetic Sum Method:**

$$E_{WA} = 54.1 + 55.6 = 109.7$$

**Wall Thickness Error by Mean Sum Method:**

$$E_{WM} = 30.2 + 30.7 = 60.9 \text{ MICROINCHES}$$

**Note: These values do not assume cancellation of Y-axis errors common to the inner and outer contour measurements.**

## **COP Gage Error Budget**

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## **CONCLUSIONS**

## Conclusions

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- **The Arithmetic Summing Method Predicts That The COP Gage will Exceed the Contour Accuracy Requirements. This Approach, However, is Unrealistically Conservative.**
- **The More Realistic "Mean" Summing Method Indicates that the COP Gage will Meet the Accuracy Requirements.**
- **The Individual Parametric Error Values That we Have Used are Conservative. Thus we Anticipate That the Identification of Additional Small Error Sources Will Not Impact Project Goals.**

## Cop Gage Error Budget

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### **We Have Identified Several Areas for Further Investigation**

- Local Cooling at Air Bearings Due to Joule-Thomson Effect
- Laser Probe Straightness
- Y-Direction Thermal Sensitivity
- Y-Slide Drive Location
- Part Fixturing, Datum Definition