Machining of Freeform Optical Surfaces by Slow Slide Servo Method

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Motivation

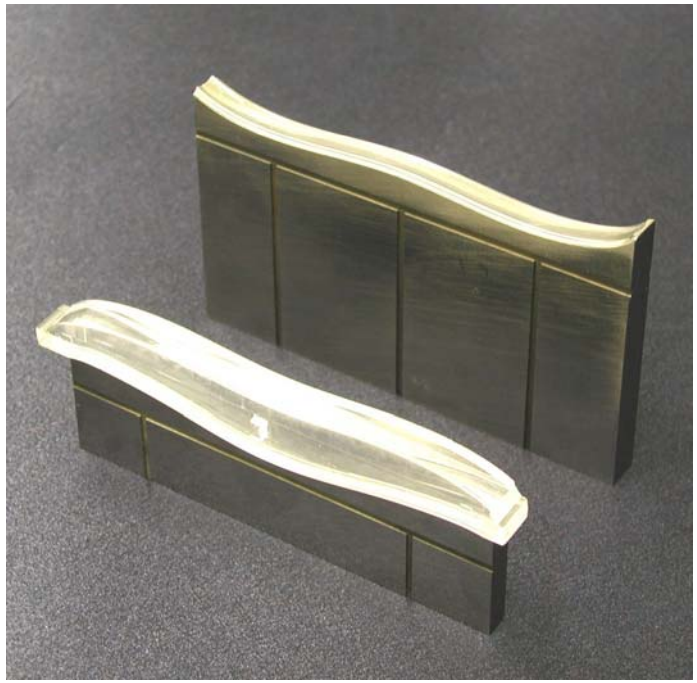
- Provide a simple cost effective method to produce freeform optical surfaces
  - Minimize the amount of axes and equipment
  - Simple tool set-up
  - Simple part set-up
  - Simple CNC programming
  - Improve surface finish
  - Improve form accuracy
  - Reduce machining cycle time

Examples of Freeform Surfaces

Grinding Application

Automotive Heads-Up Displays
Finish Cycle: 50hrs. (Large lens)
Finish Cycle: 30hrs. (Small lens)
Courtesy: B-con Engineering

Fly Cutting Application
F-Theta Lenses
Finish Cycle: 20hrs



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Manufacturing of Freeform Optics

- Grinding
  - Slow machining cycle
  - Un-deterministic process (Wheel Wear)
- Fly Cutting or Raster Cutting
  - Slow machining cycle
  - Difficult to set-up
  - Limited by tool swing diameter
- Fast Tool Servo
  - Fast machining cycle
  - Limited travel

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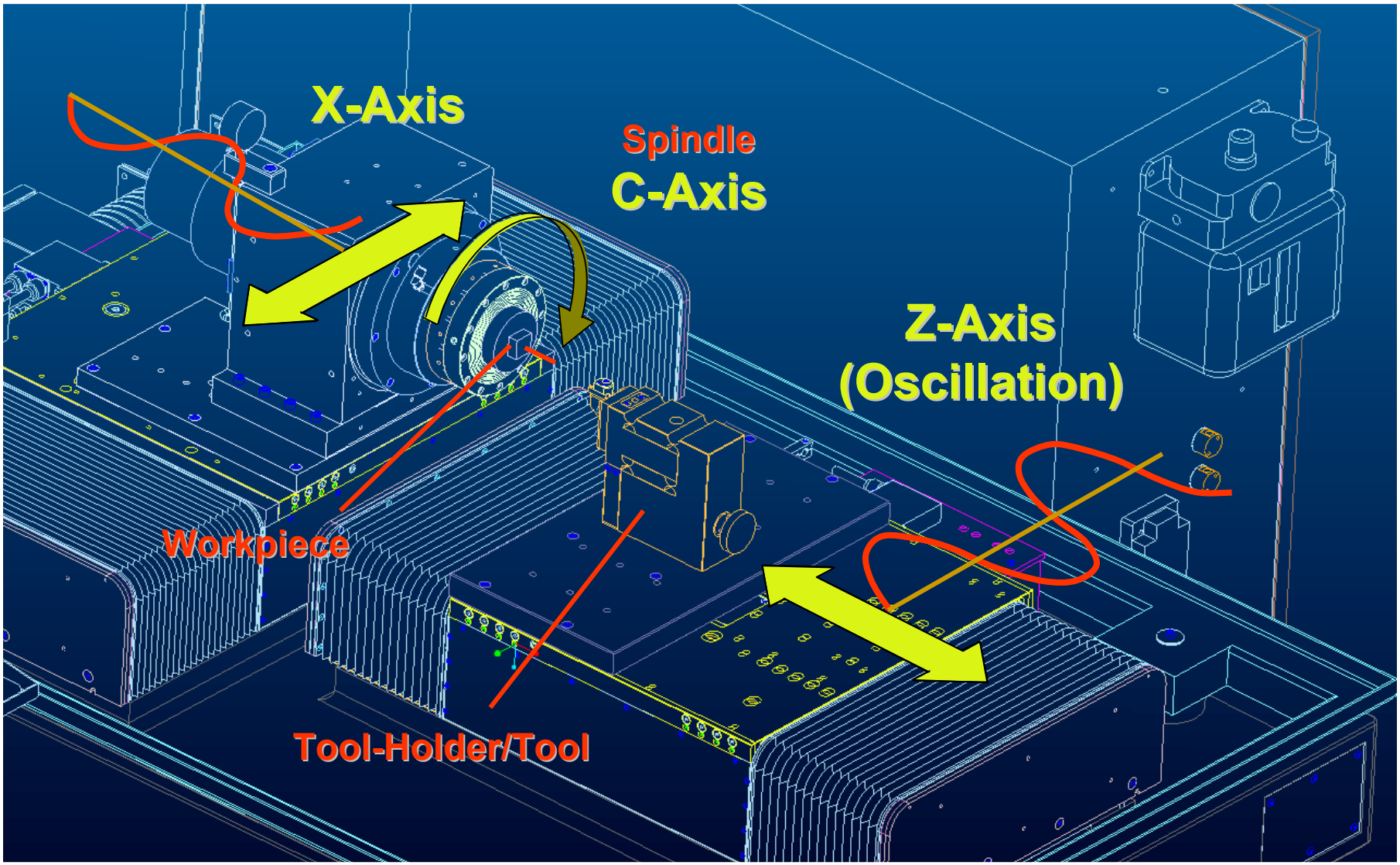
Slow Slide Servo



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Key Requirements for Slow Slide

- Two linear axes X and Z
- Position controlled spindle or C-axis
- Direct drive motors on all axes
- Friction free bearings on all axes
- Low heat generation from motors and bearings (Air or liquid cooling)
- High resolution feedback systems
- High bandwidth closed position loops

- CNC requirements
  - High speed data processing
  - Look ahead capabilities
  - High order trajectory generation

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Diamond Turning Lathe

- Two Linear axes
  - Hydrostatic bearings
  - Air cooled linear motors
  - 8.6nm feedback resolution
  - 100 Hz position loop bandwidth
- Open Architecture CNC
  - Look ahead capabilities
  - High order trajectory generation
  - High speed servo loop
  - Unlimited file size

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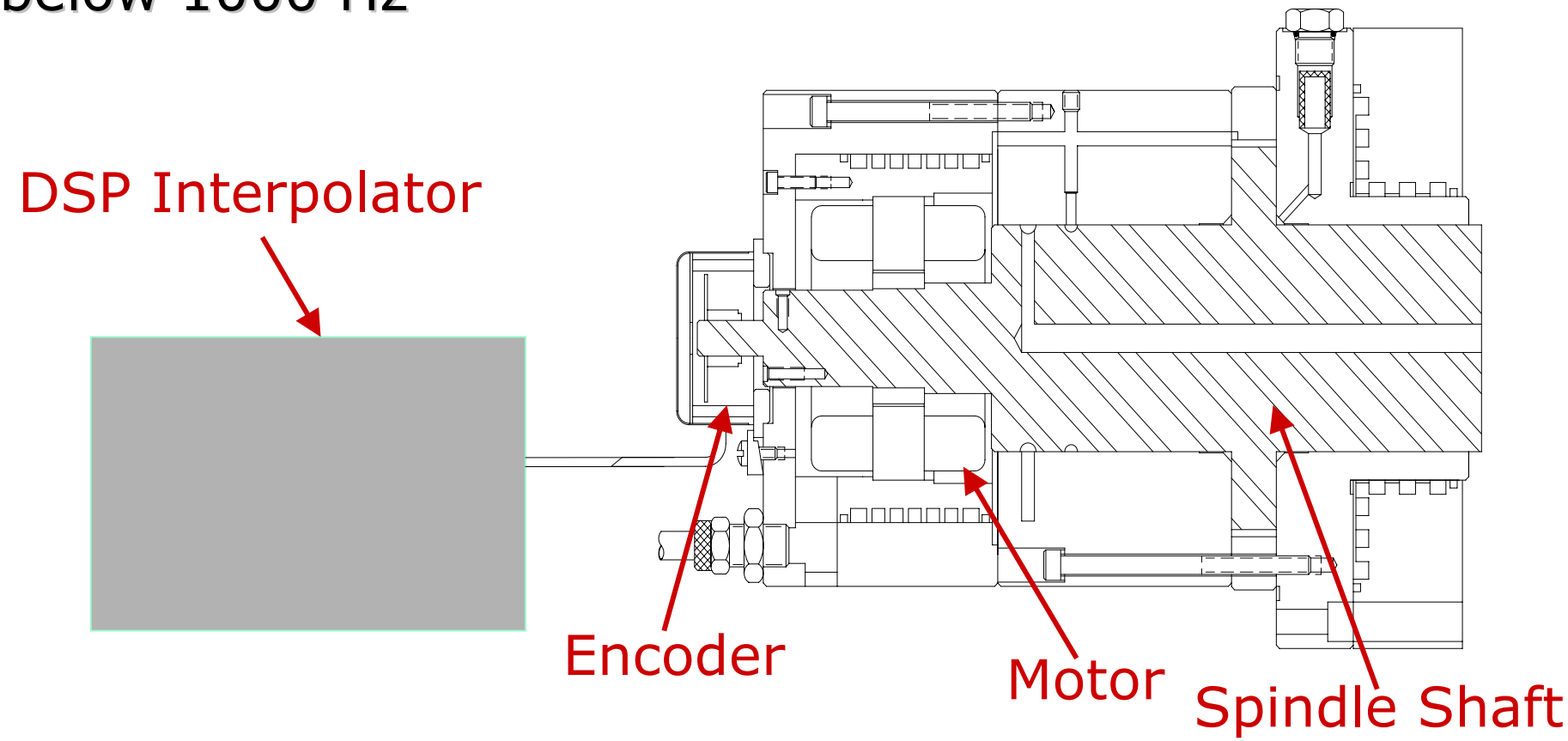
Spindle / C-axis

- Groove compensated air bearing (Liquid cooled)
- Integrated motor (Liquid cooled)
- Integrated encoder: 20,480,000 counts/rev (0.06 arc-sec)
- Max. speed in position mode 2000 RPM
- No structural dynamics between command and response below 1000 Hz



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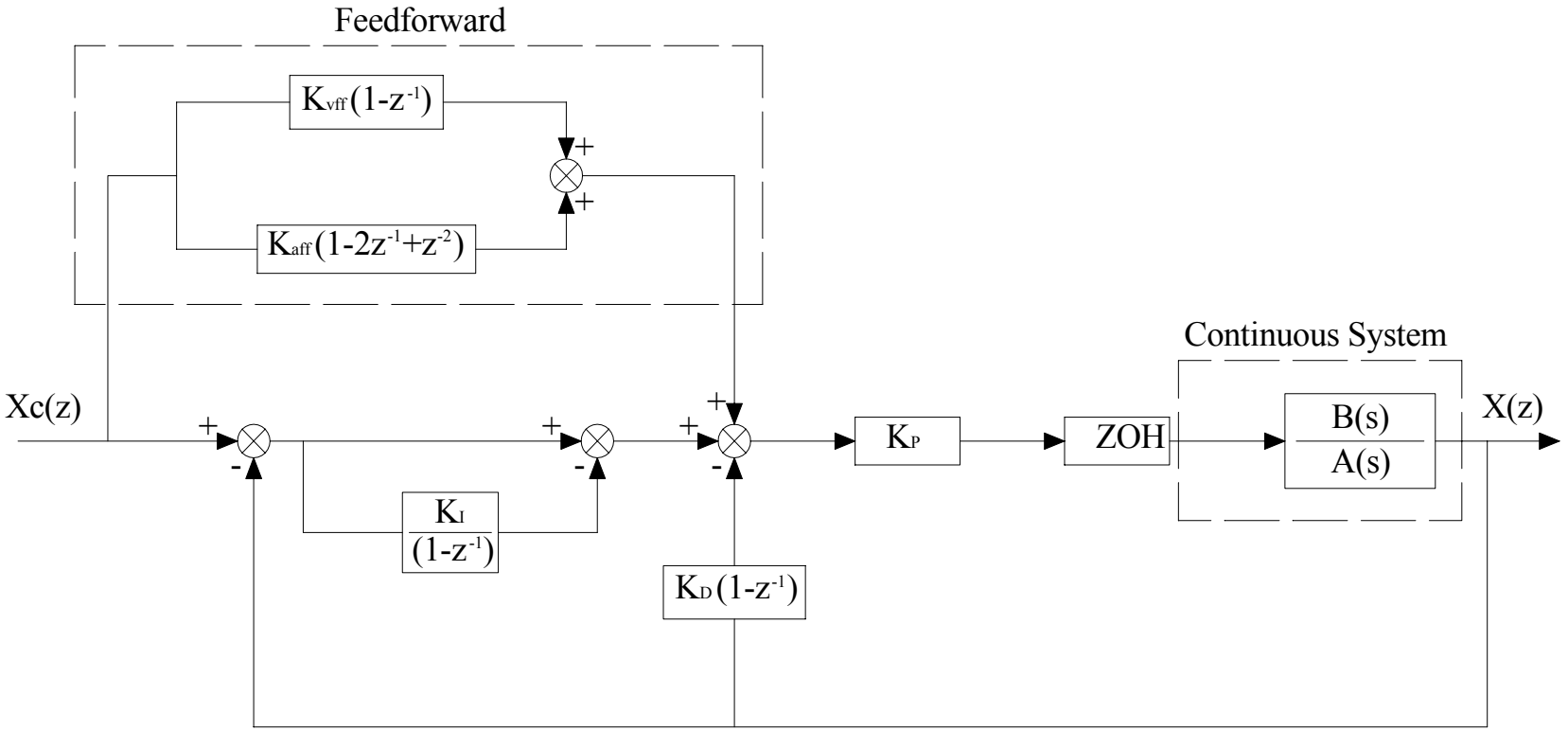
C-axis Block Diagram



Where -- K_P : Proportional Gain K_{vff} : Velocity Feedforward Gain
K_I : Integral Gain K_{aff} : Acceleration Feedforward Gain
K_D : Derivative Gain ZOH: Zero-Order-Hold
B(s)/A(s) : Open Loop Transfer Function

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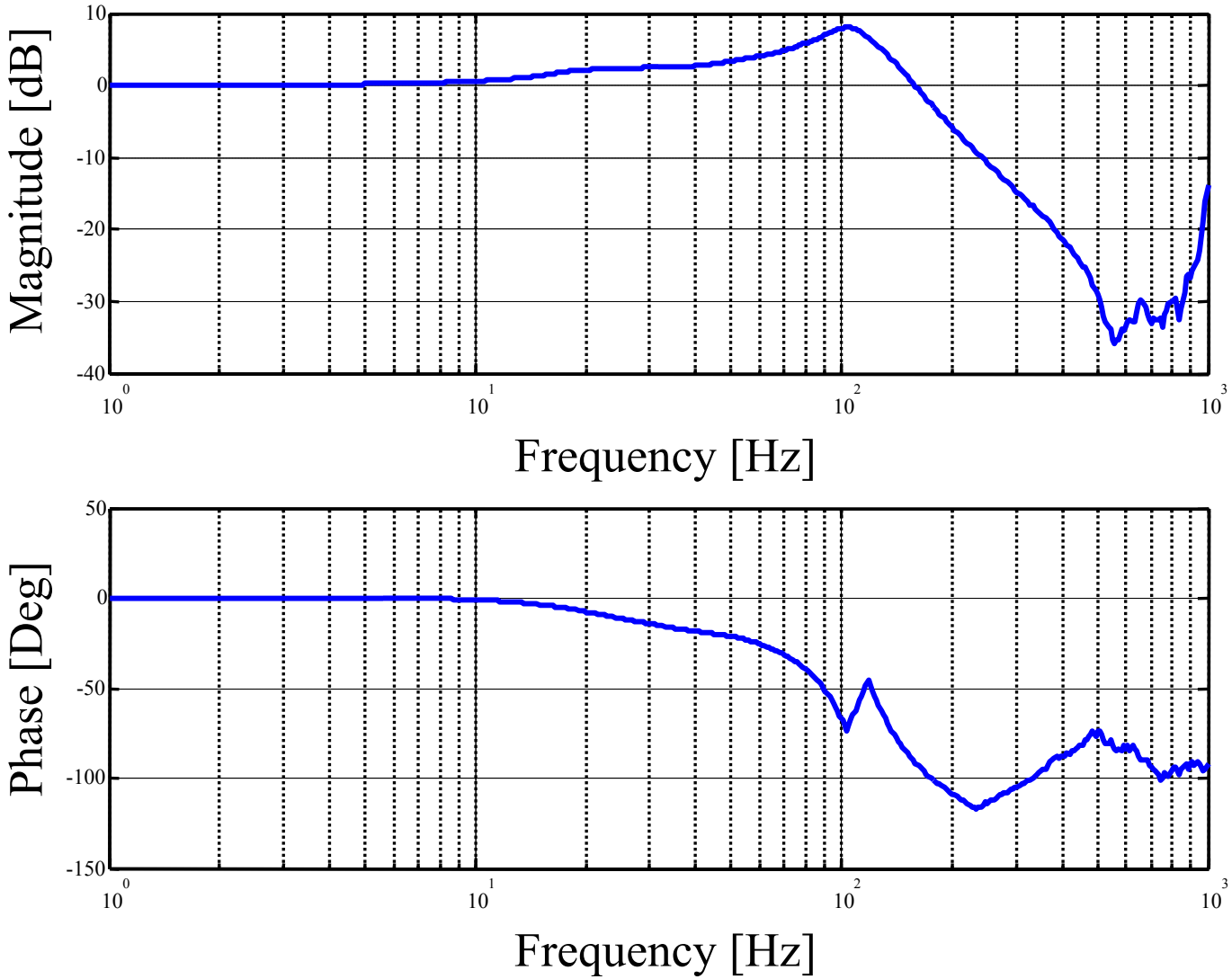
Closed Loop Transfer Function



- 170 Hz Closed position loop bandwidth
- No phase shift up to 10Hz

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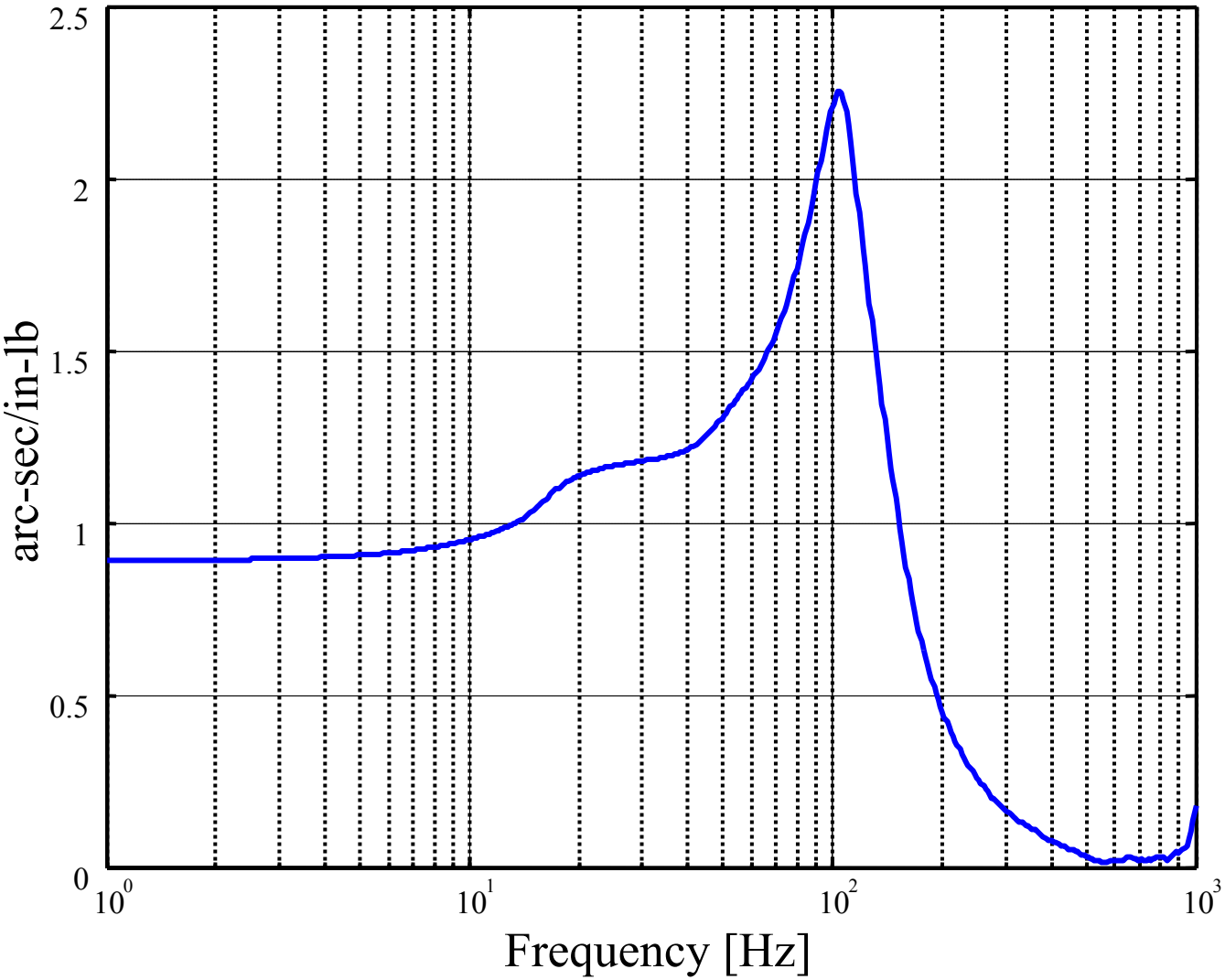
C-axis Compliance



- 1 arc-sec/in-lb from 0 to 10 Hz
- 2.25 arc-sec/in-lb

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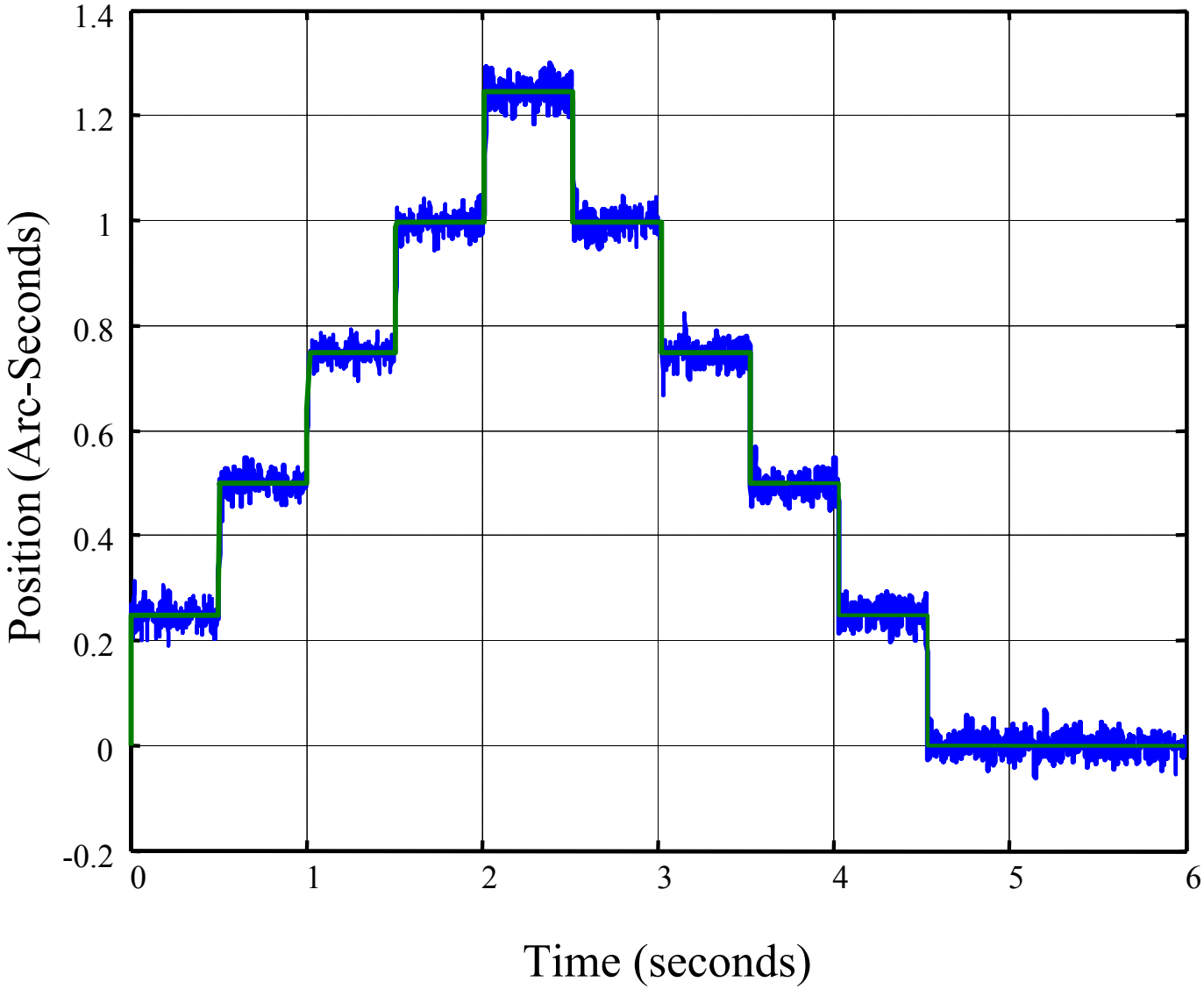
1/4 Arc-Second Step Moves



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Cutting Tests

- De-Centered Concave Sphere (6061 Al)
  - Diameter: 75mm, Concave Radius: 75mm
  - Off-axis Distance: 19.4mm, Sag:10mm PV
  - Finish Machining Cycle: 30 minutes
- On-axis Tilted Flat (6061 Al)
  - Diameter 50mm, Tilt Angle 2.25 Degrees
  - Sag: 2mm PV
  - Finish Machining Cycle: 30 minutes
- Cubic Phase Plate (ZnS)
  - Size: 20mm X 20mm
  - Sag: ~100 μm PV
  - Finish Machining Cycle: 21 minutes

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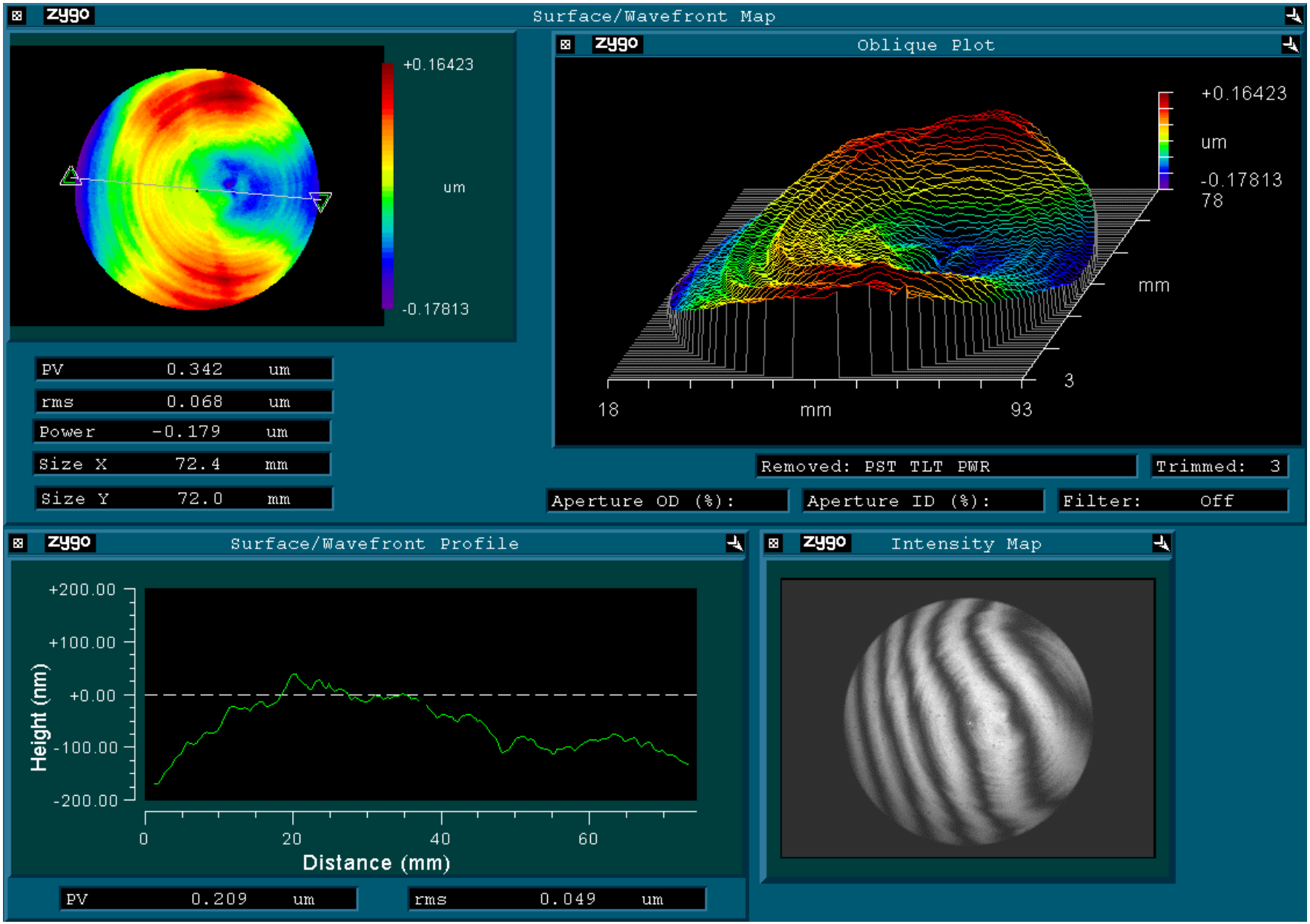
De-Centered Sphere -Form Results



PV-error 0.342 μm

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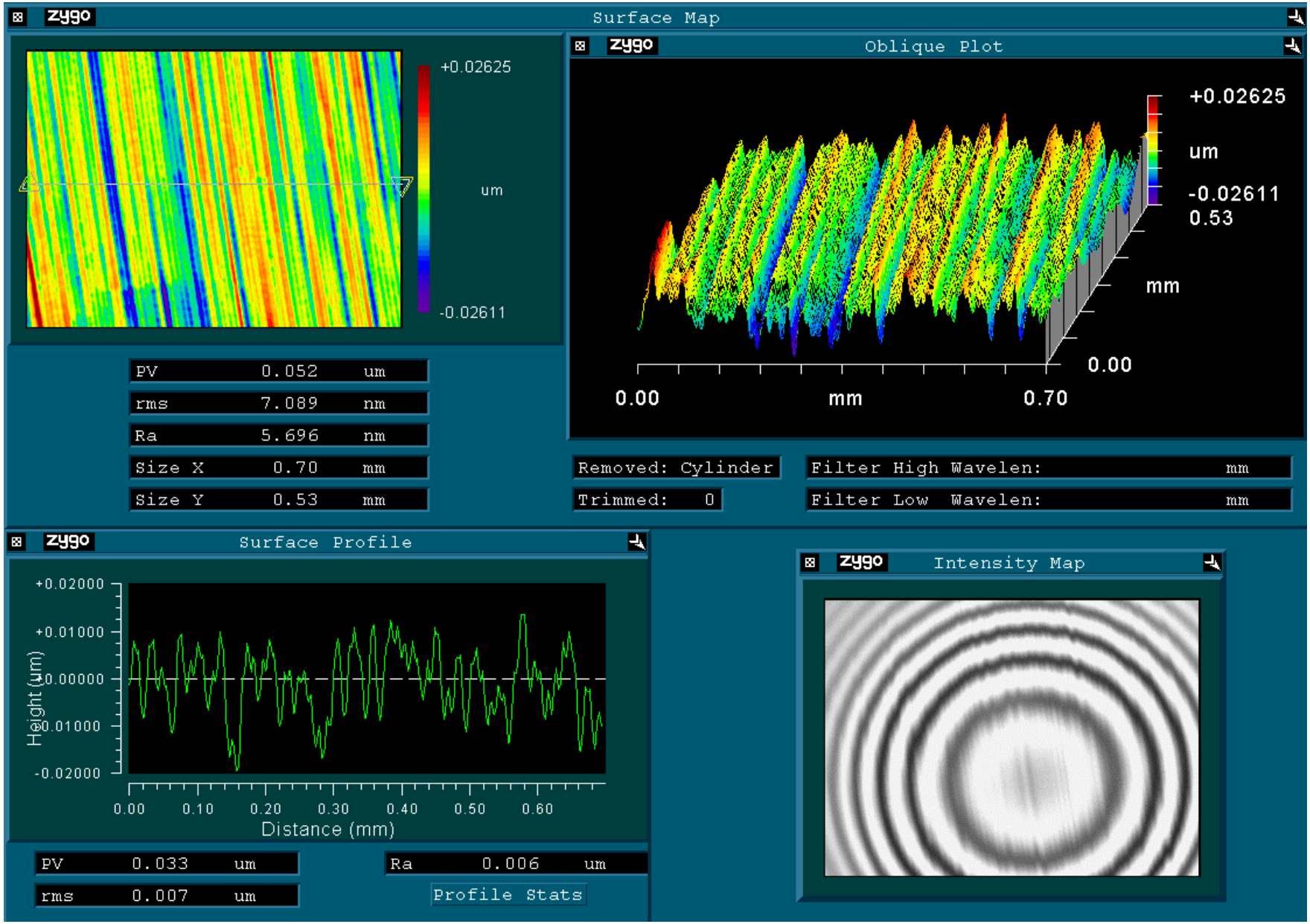
De-Centered Sphere -Finish Results



Actual Ra: 5.696nm, Theoretical Ra: 4.6nm

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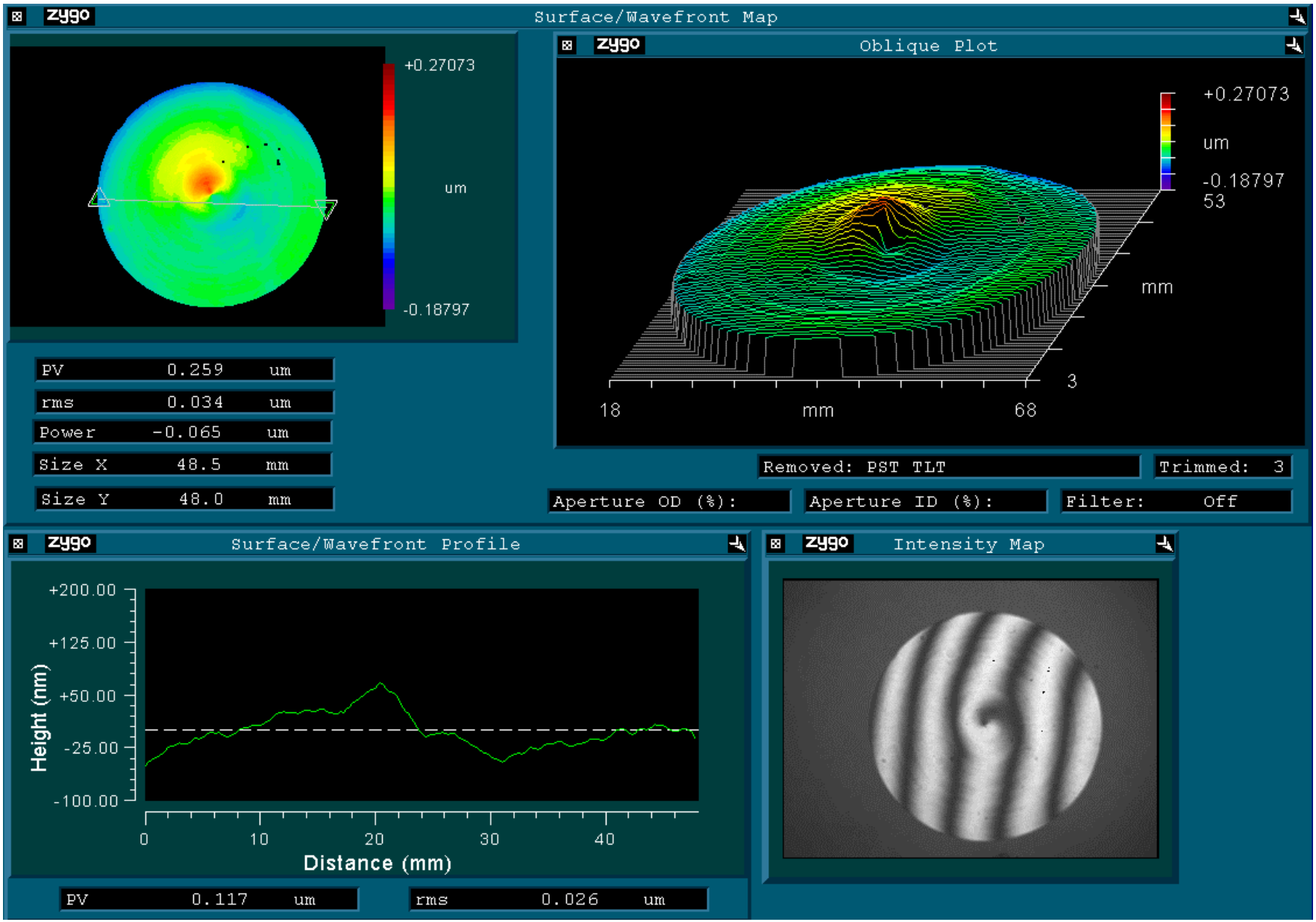
Tilted Flat -Form Results



PV-error 0.259 μm

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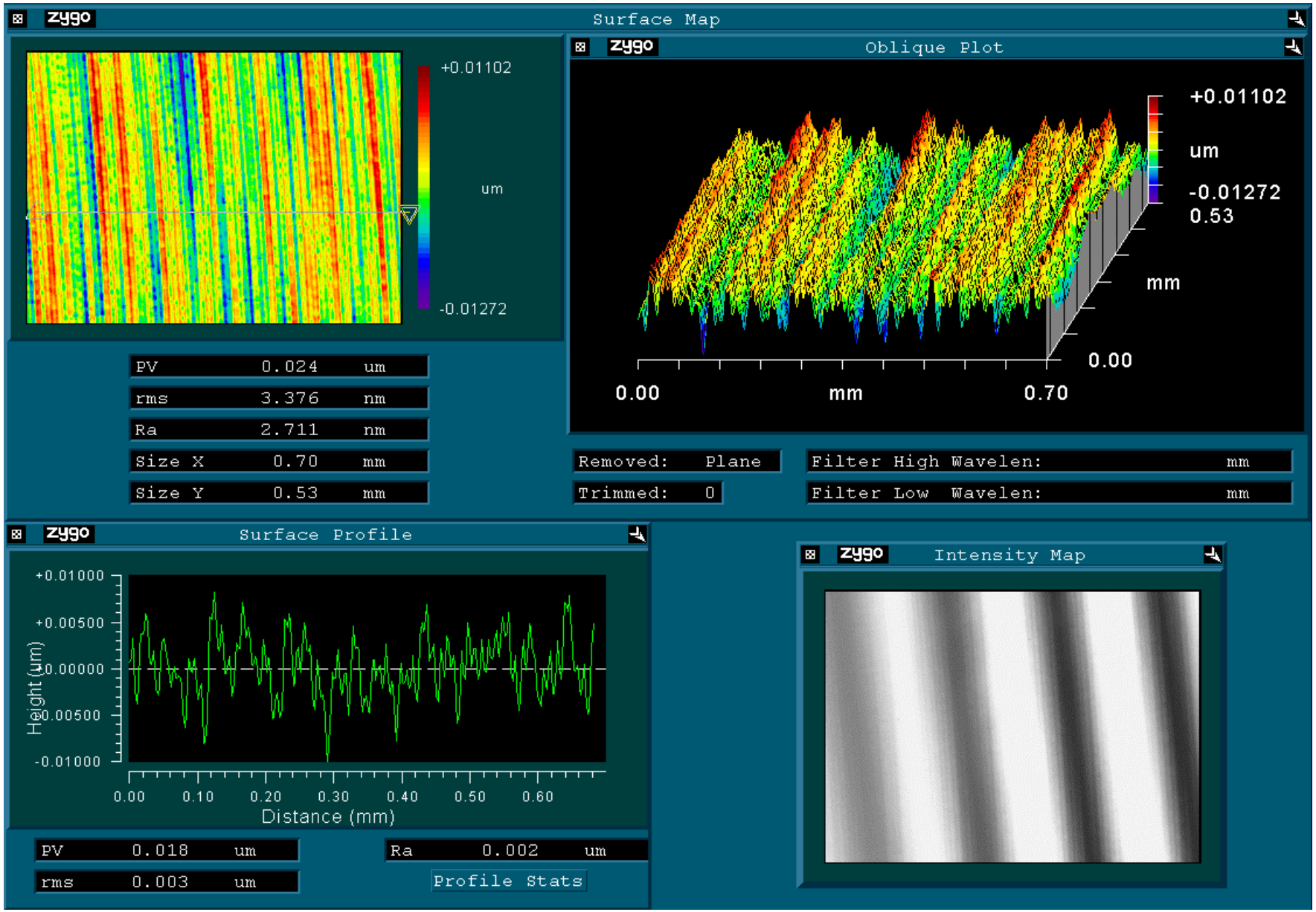
Tilted Flat -Finish Results



Actual Ra: 2.711nm, Theoretical Ra: 2.0nm

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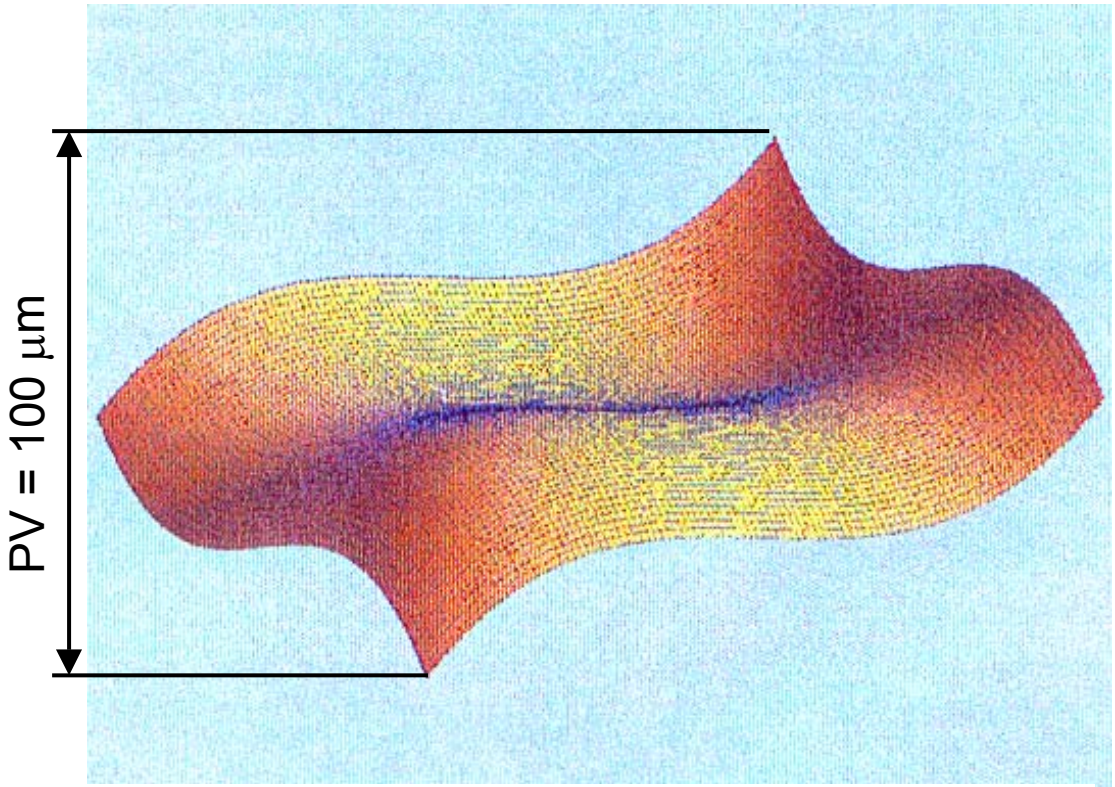
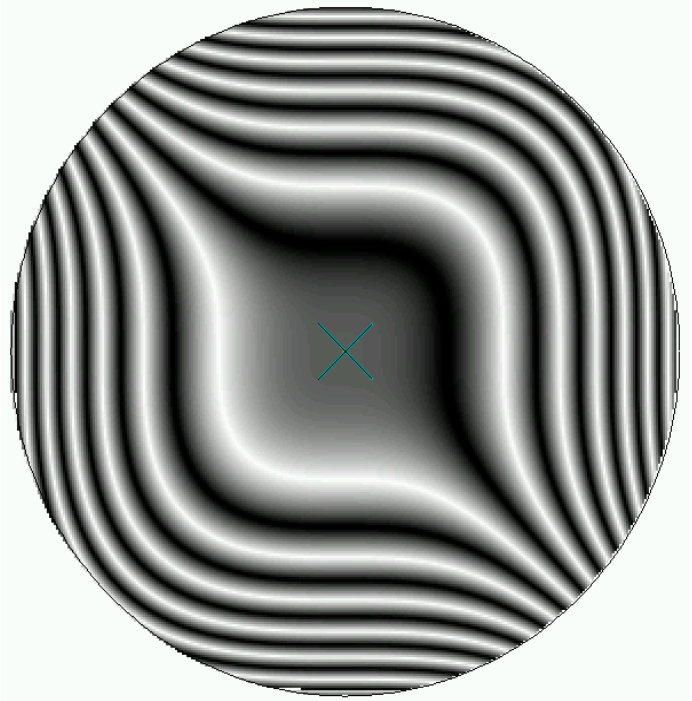
Cubic Phase Plate

Surface Equation: $Z=0.025\ ((X/10)^3 + (Y/10)^3)$



Mathematical Representation of the Cubic Phase Plate Surface

Material: ZnS (Zinc Sulfide)
Tool: . Material: Diamond
. Rake Angle: -25º
. Tool Radius: 0.6 mm
Feedrate: 7 μm/rev



Interferometric Representation of the Cubic Phase Plate Surface

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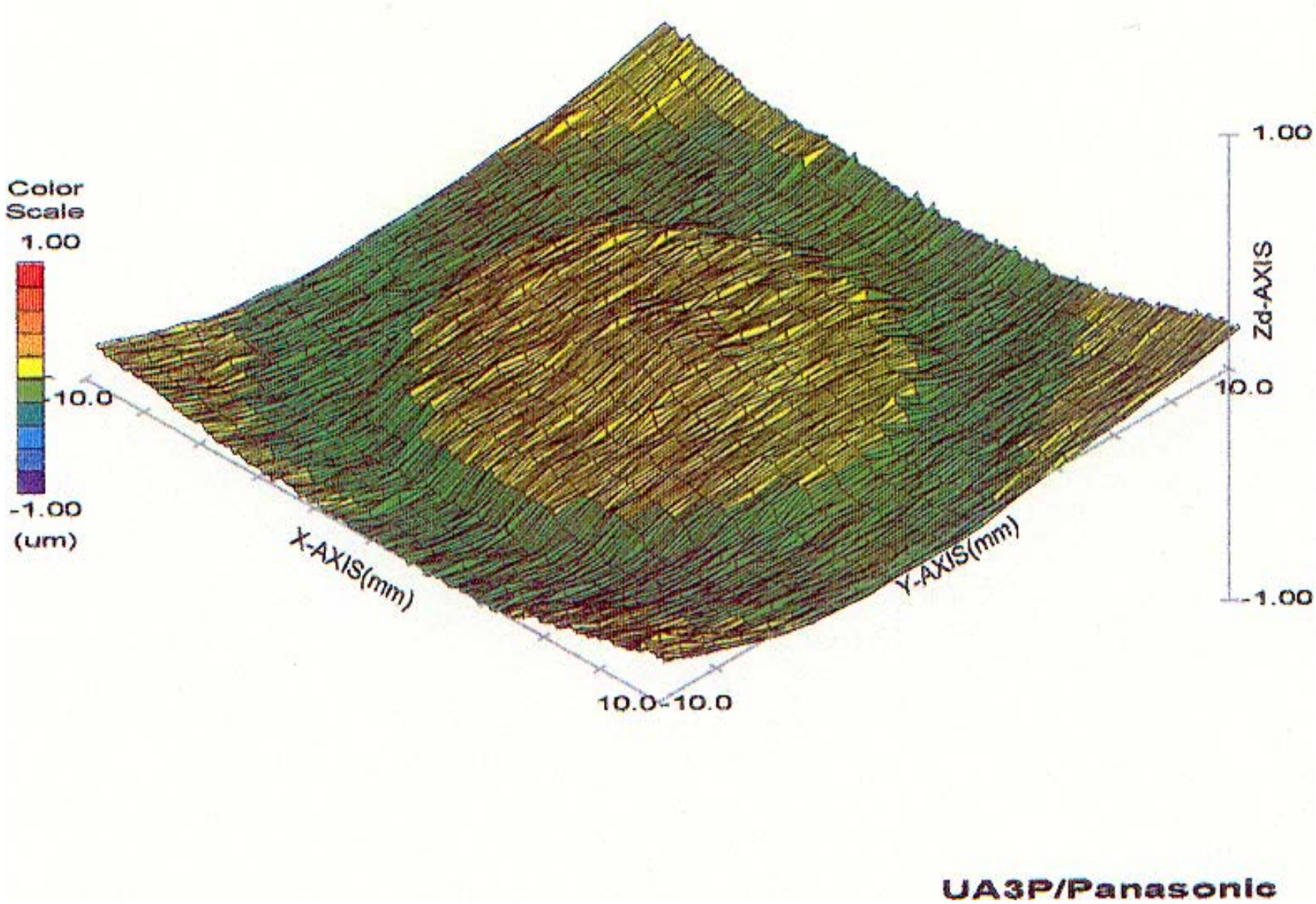
Cubic Phase Plate -Form Results



Form Error: 0.263 μm

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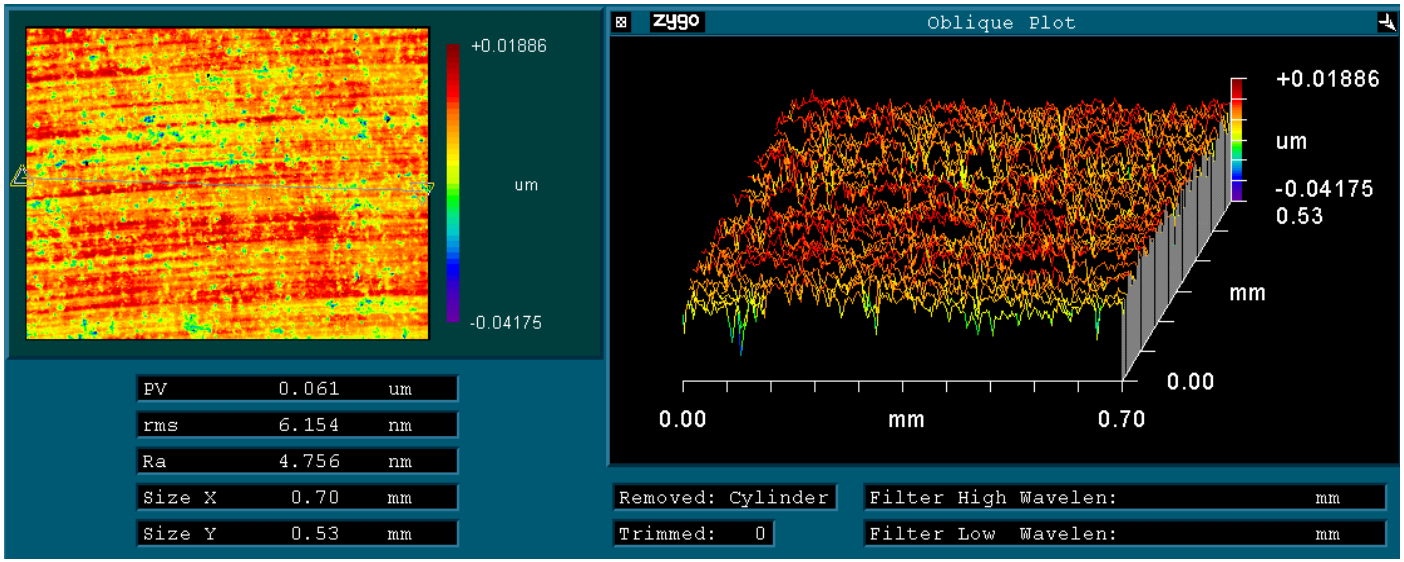
Cubic Phase Plate -Finish Results

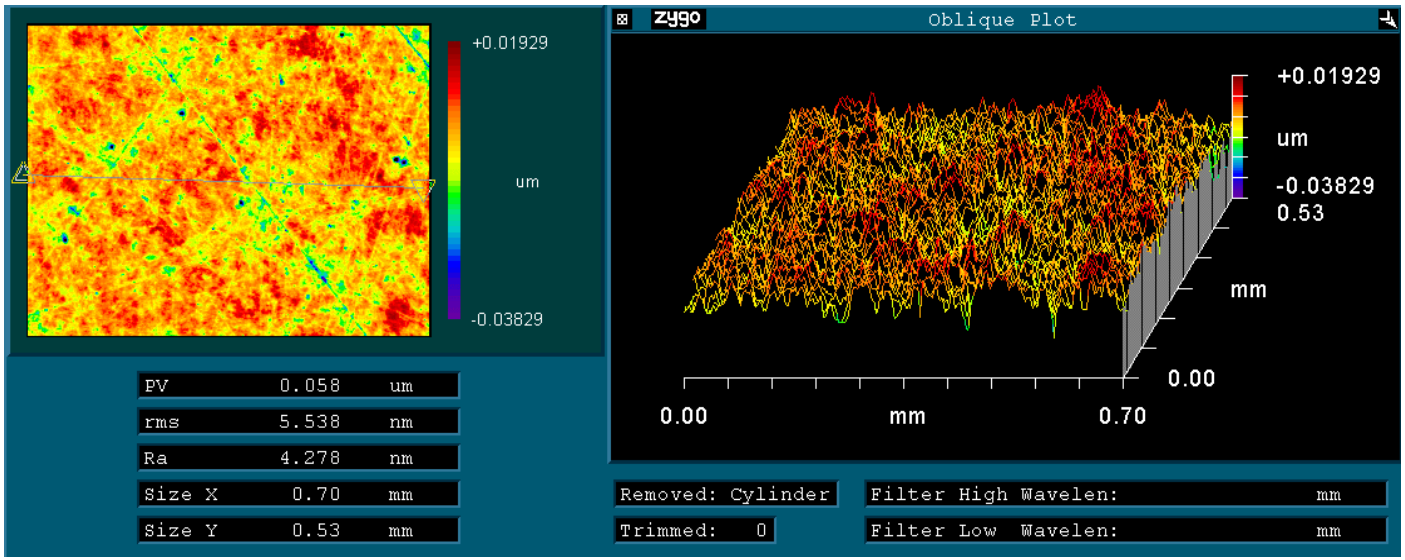
Slow Slide Servo Results

Ra: 4.756nm



Typical Polishing Results

Ra: 4.278nm



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Future Work/Questions

- Improve form accuracy to less then 0.2 μm
- Machine different surfaces
- Understand cutting mechanics

- Questions?

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