Developing on-machine 3D profile measurement for deterministic fabrication of aspheric mirrors

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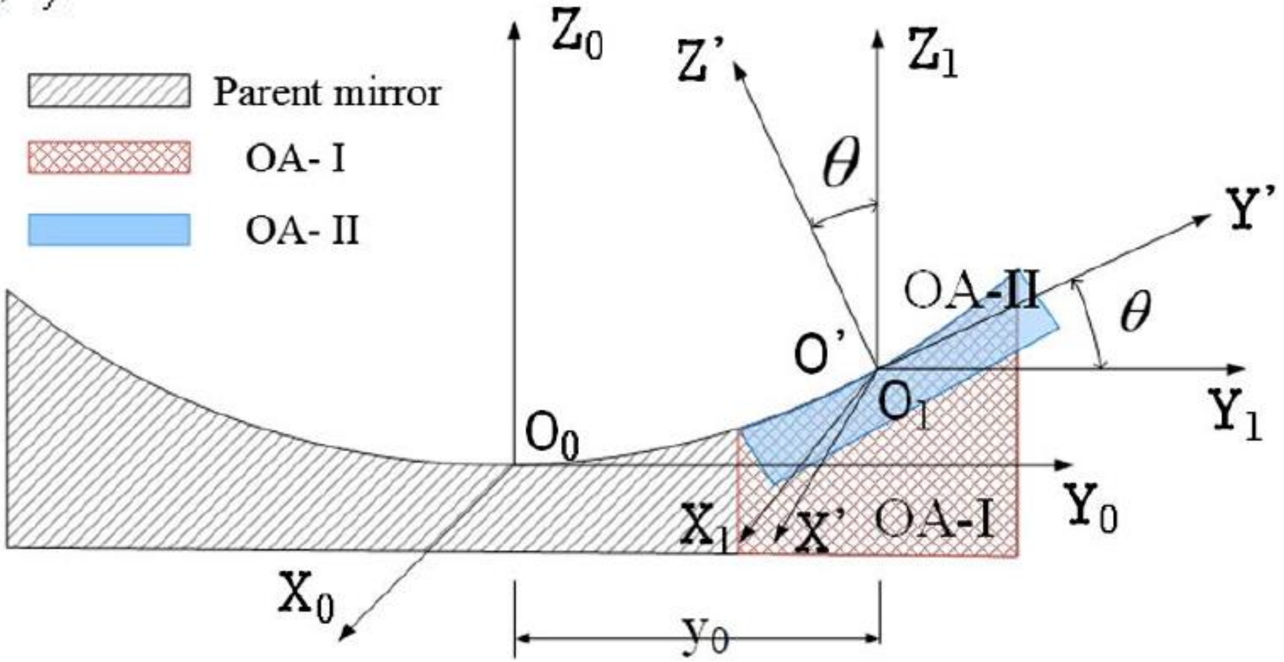
Introduction

- Aspheric components are a valuable resource for optical design
- Compared to spherical optics, aspheres can reduce size and weight while improving image quality
- Manufacture and metrology of aspheric components is difficult
- Machine tool to measure 3D profile of aspheric mirrors is presented to aid in deterministic manufacturing
- Overview of JR-1800 system
- Sources of error
  - Mechanical errors, alignment errors, temperature, etc.
- Validation Experiments

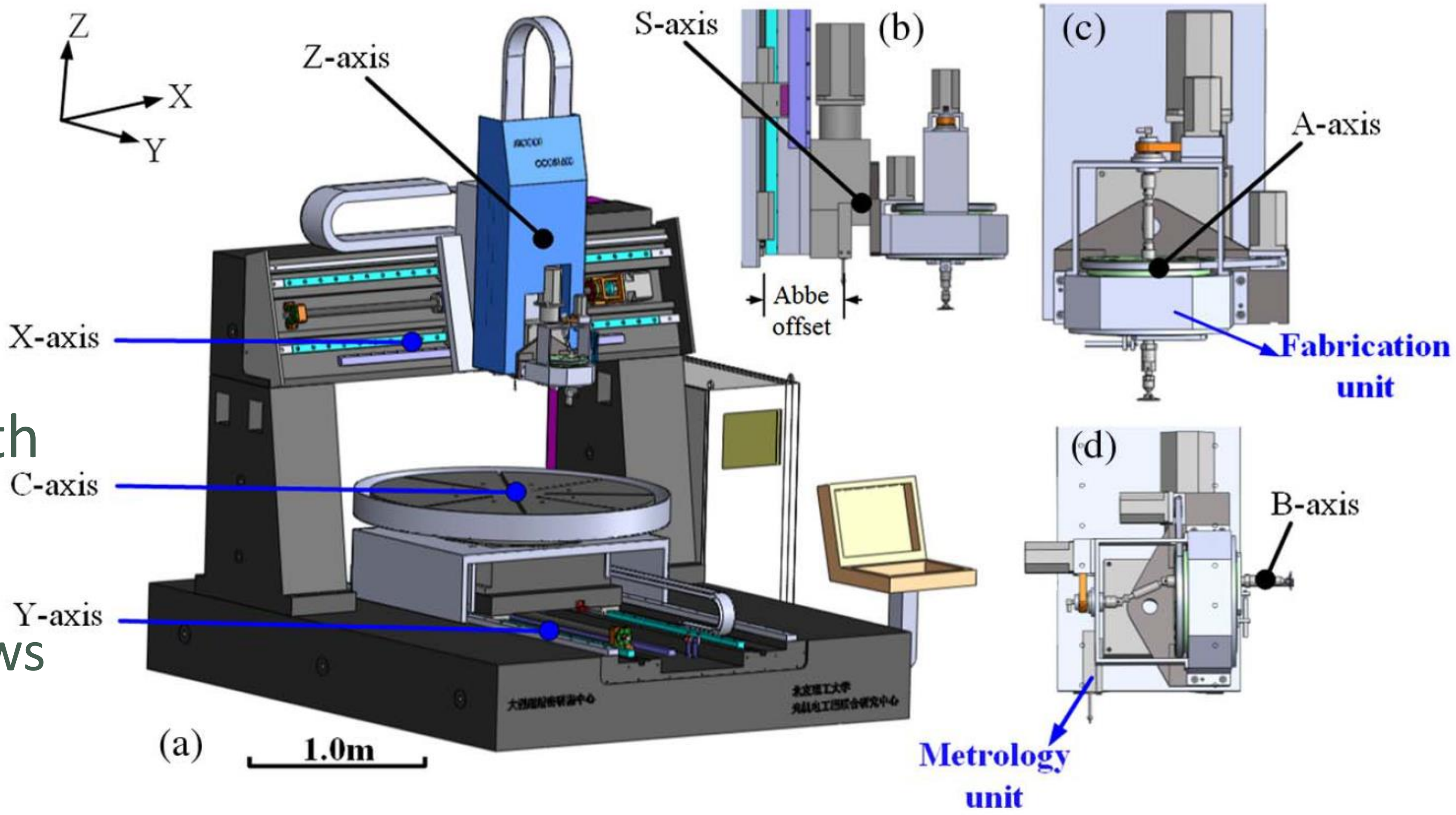
Aspheric Surfaces

- Parent Mirror: $$Z(X,Y) = \frac{c(X^2+Y^2)}{1+\sqrt{1-(K+1)c^2(X^2+Y^2)}} + \sum_{i=1}^{n} A_{2i}(X^2+Y^2)^i$$
- OA-I: $$Z_1(X,Y) = \frac{c(X_1^2+(Y_1-y_0)^2)}{1+\sqrt{1-(K+1)c^2(X_1^2+(Y_1-y_0)^2)}} - z_0$$
- OA-II: $$Z' = \frac{-B+\sqrt{B^2-4AQ}}{2A}$$



JR-1800 Measurement System

- Marble Base
- X Travel: 1840 mm
- Y Travel: 2096 mm
- Z Travel: 603 mm
- C Axis: Ø 1800 mm
- Heidenhain MT60 length gage
  - Max travel: 60.8 mm
  - Large travel range allows for Z axis to remain stationary eliminating abbe offset error
- XY and XC measurement



Comparison to Interferometry

- Any surface shape can be measured with out null correctors or CGHs
- Specular and non-specular surfaces can be measured
- Sag heights are directly measured allowing for analysis of vertex curvature and conic constant
- An accuracy of ~1 µm is expected, which is much lower than that of an interferometer.
- Measurement time is dependent on the number of points collected
    - 1000-2000 points per hour

Mechanical Errors

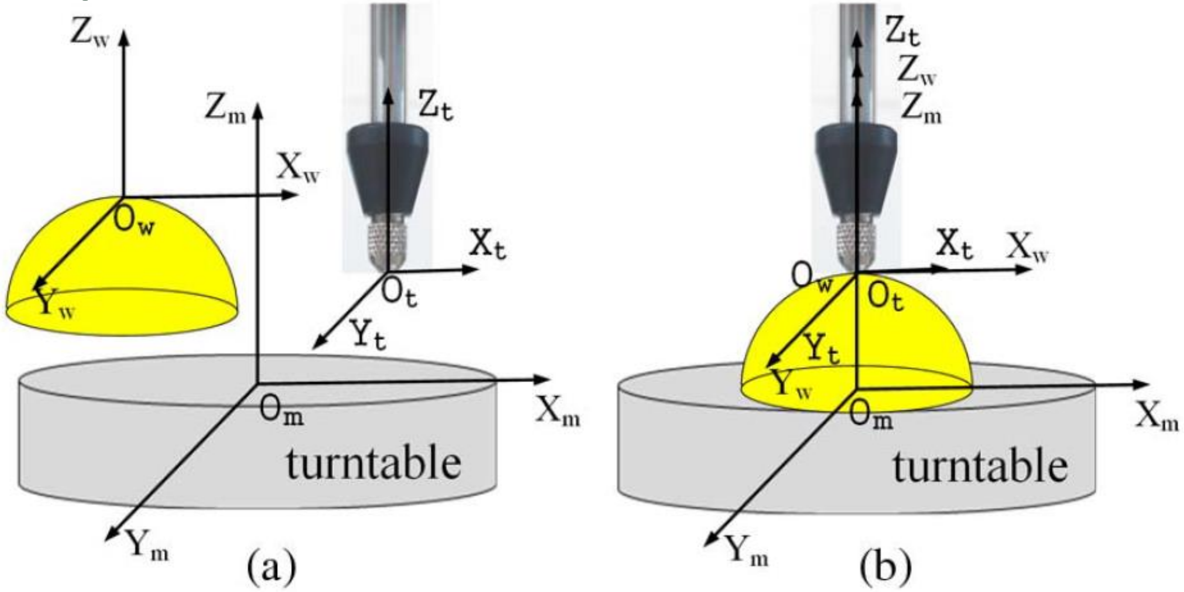
- Linearity of guide rails
  - X axis found to be 1.75 µm
- Positioning error of axes
  - XY positioning errors less than 6.0 µm
  - XY repeatability ~3.3 µm
  - C positioning errors less than 9.2 s
  - C repeatability ~4.3 s
- C axis radial and axial runout, parallelism of X and C axis, perpendicularity of XY, XZ, and YZ
  - Difficult to correlate with measurement results
- 440 mm x 440 mm reference window with PV = .23 µm was used to calibrate system
  - XC mode PV = 2.3 µm and RMS = 0.38µm
  - XY mode PV = 3.0 µm and RMS = 0.53 µm
  - Must be subtracted and results are only valid over this area

Table 1. Mechanical Errors of *XYZC* Axis

Axis	Positioning Accuracy	Repeat Positioning Accuracy	Slider Linearity	Measured Range
X	5.9 µm	3.3 µm	1.75 µm	1600 mm
Y	5.6 µm	3.2 µm	4.30 µm	2000 mm
Z	2.2 µm	1.3 µm	1.66 µm	600 mm
C	9.2 s	4.3 s	—	360°

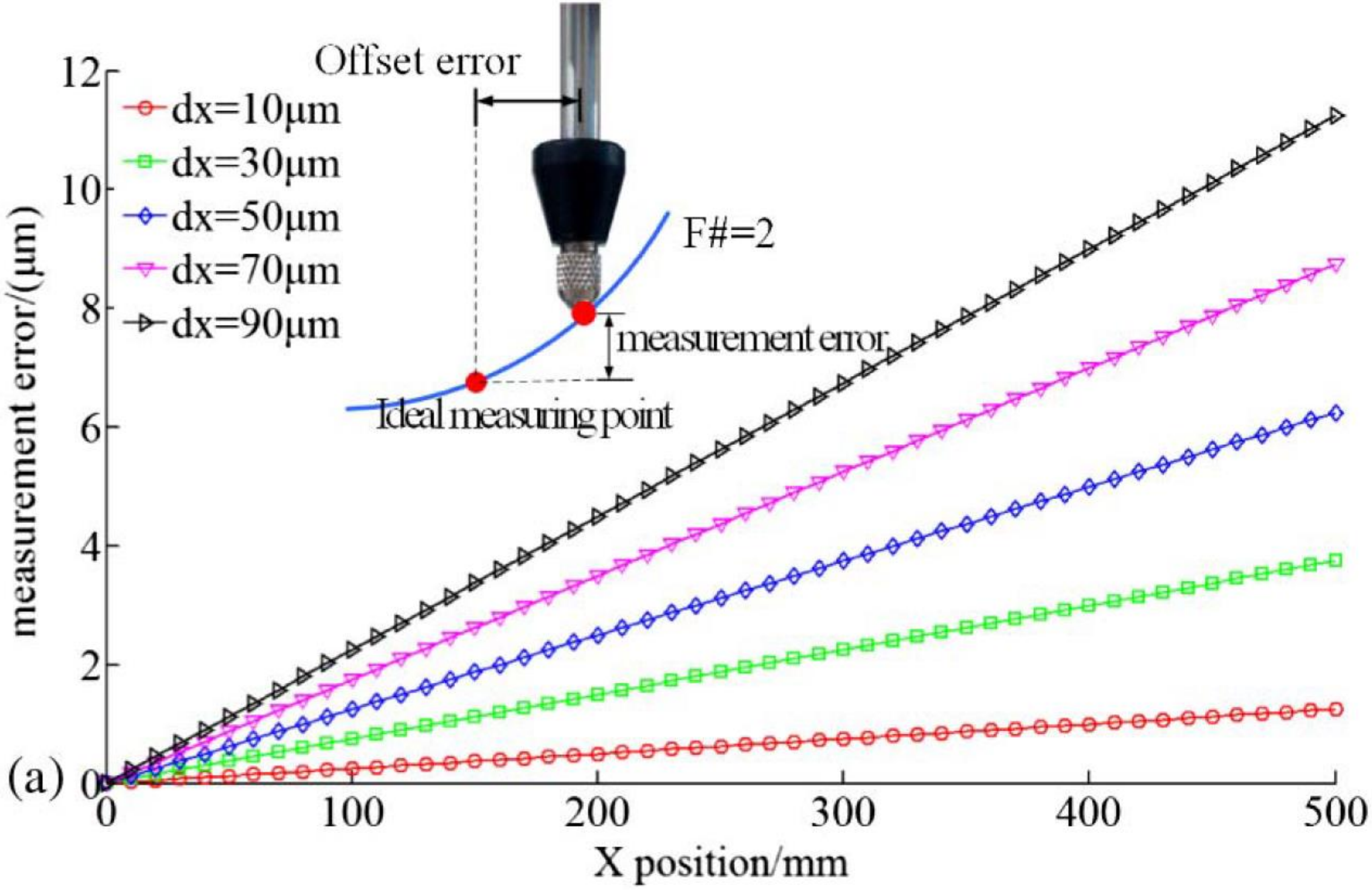
Length Gage Alignment

- Length gage must be aligned to the workpiece
- Three coordinates of interest
  - Center of the turntable
  - Vertex of the workpiece
  - Vertex of the probe tip
- Alignment process:
  - Center calibration sphere to turntable with dial indicator until there is less than 0.001 mm of runout
  - Profile in X and Y direction
  - Using these profiles reposition probe tip
- ±5 µm offset was achievable



Length Gage Alignment

- Misalignment in X produces a linear error proportional to F/#



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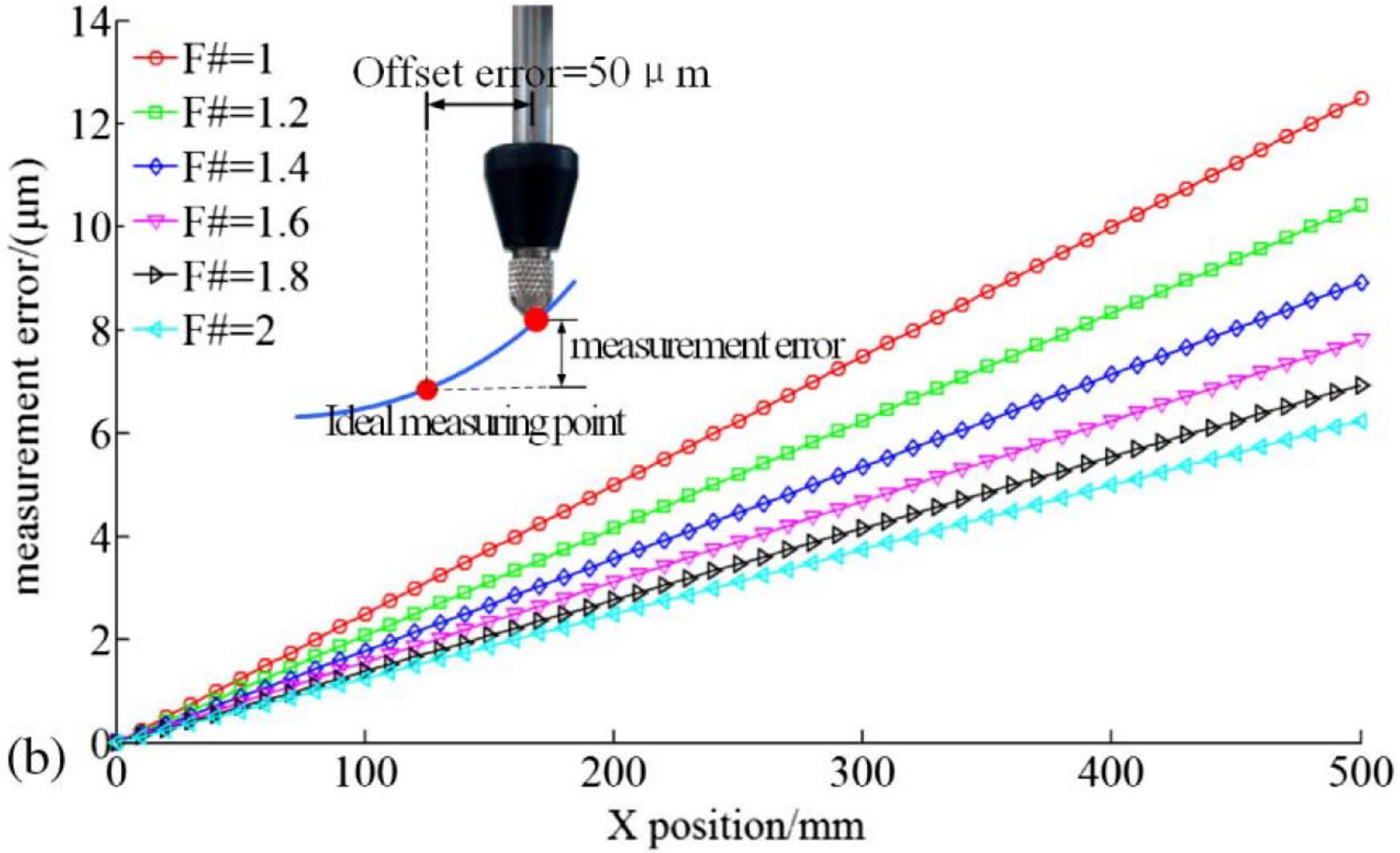
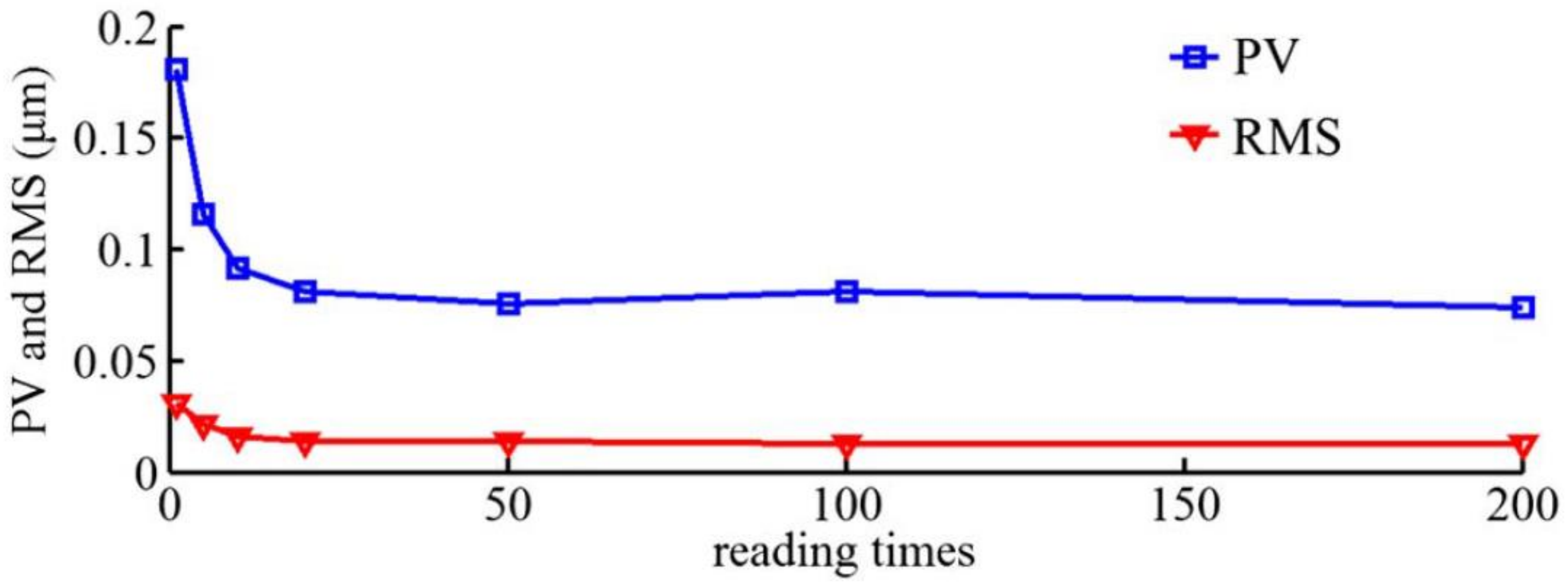


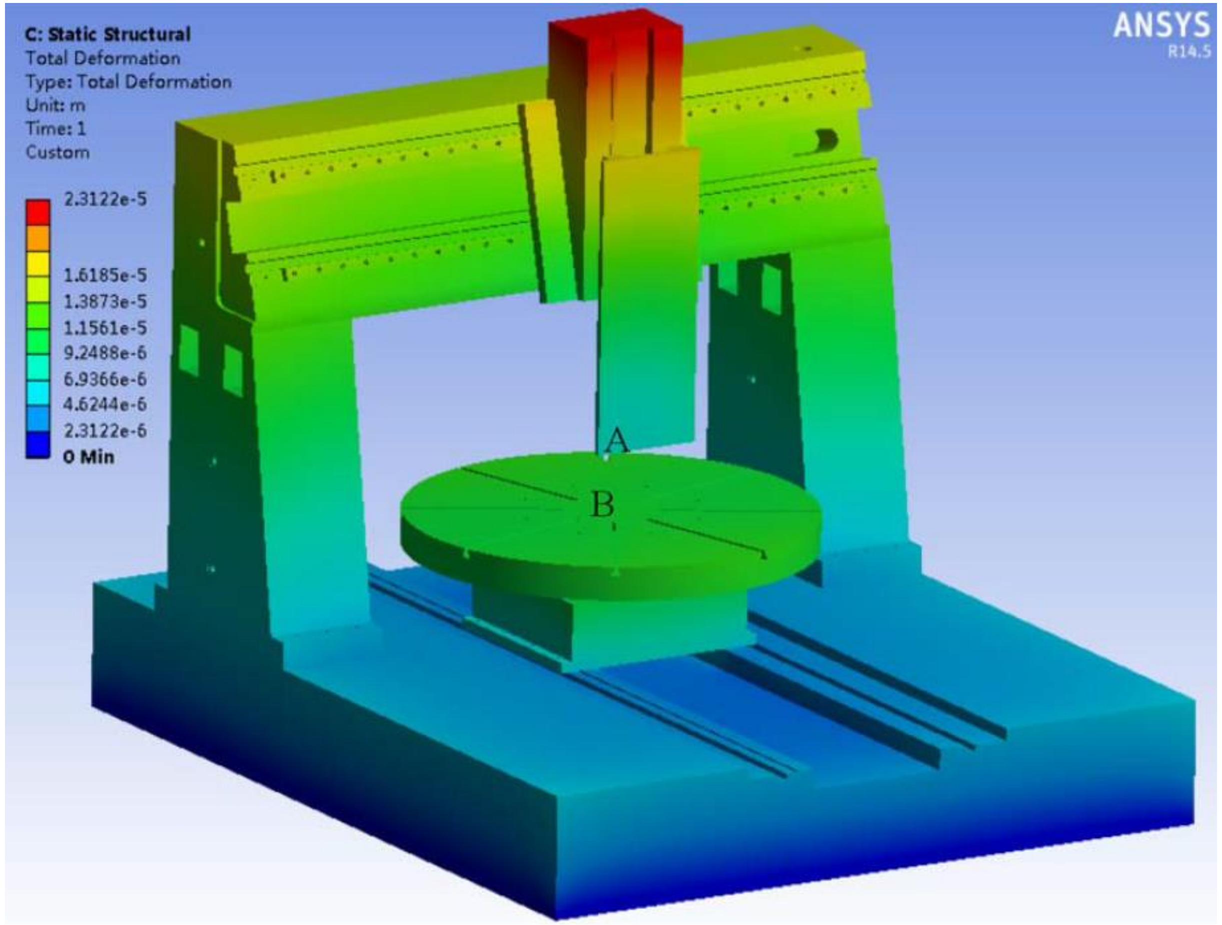
Length Gage Stability

- Measurement can vary 0.02 – 0.05 µm while in contact with the surface



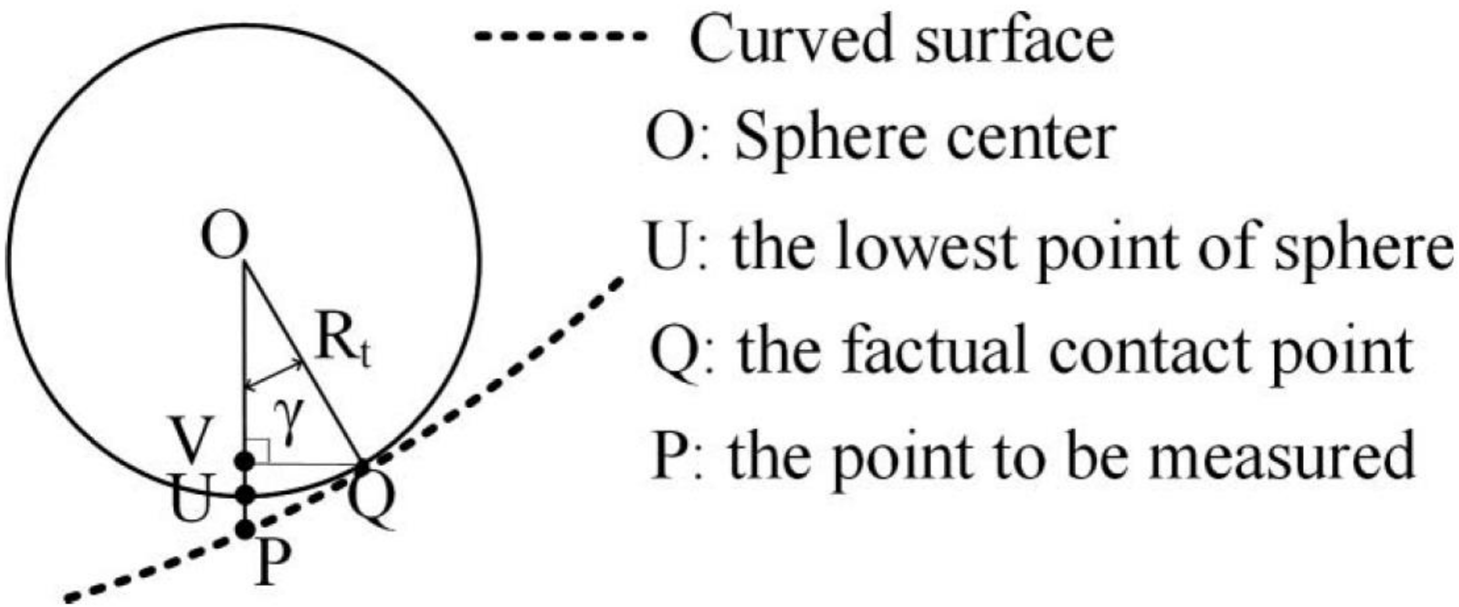
Influence of Temperature

- Maximum deformation of 23 µm with an increase of 1°C
- Only 0.91 µm/°C at points A and B
- System is maintained to 20 ± 0.2°C resulting in ± 0.182 µm
- MT60 deforms 0.16 µm/°C resulting in ± 0.032 µm
- Workpiece also need to be considered



Tool Radius Compensation

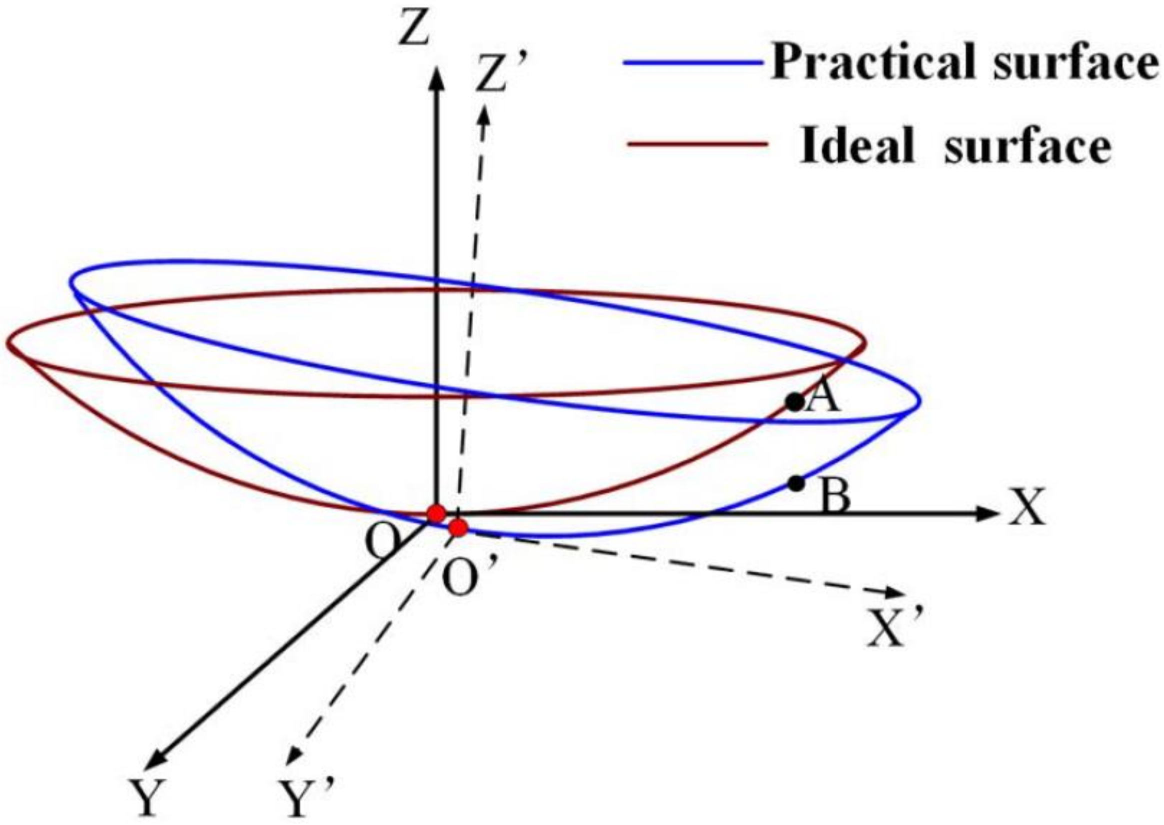
- The spherical probe tip will induce a nonlinear error into the measurement
- The theoretical sagittal deviations of points U and P are added to correct this error



$$Z_{UP} = Z\left(\sqrt{X_P^2 + Y_P^2} + R_t \sin(\gamma), 0\right) - Z\left(\sqrt{X_P^2 + Y_P^2}, 0\right) - R_t(1 - \cos(\gamma))$$

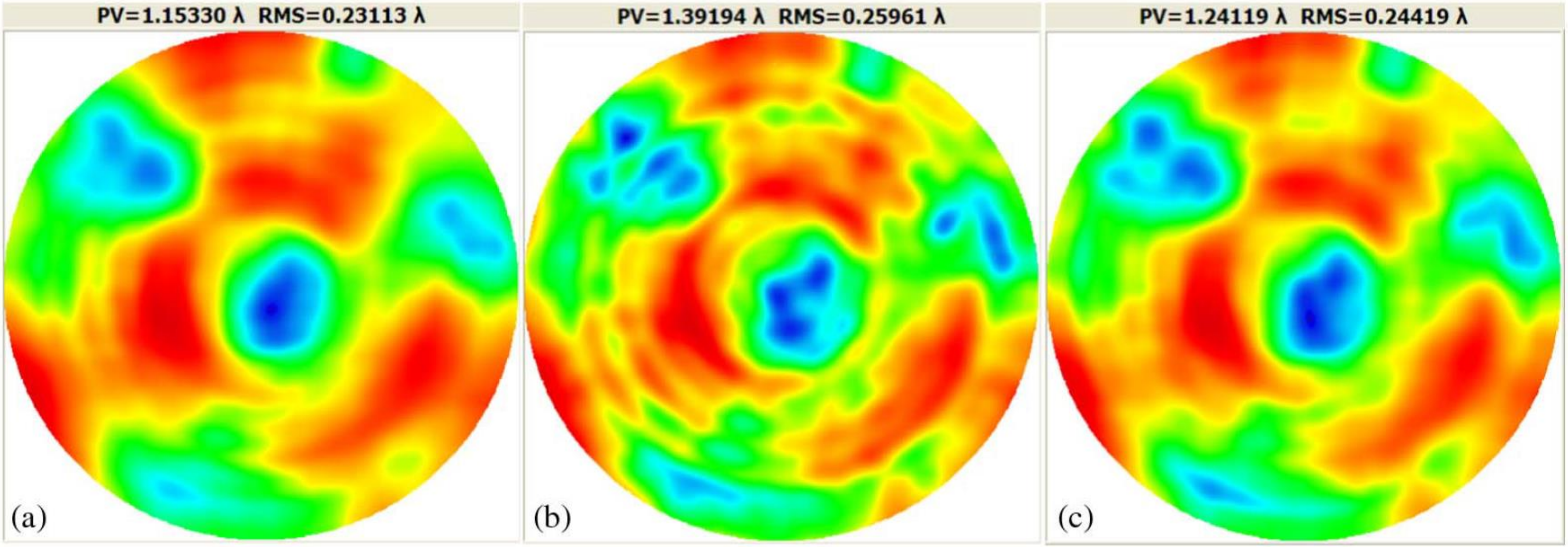
Tilt and Offset Compensation

- Residual error due to misalignment still remains
- Least-squares algorithm is then used to fit the measured points to compute final surface form



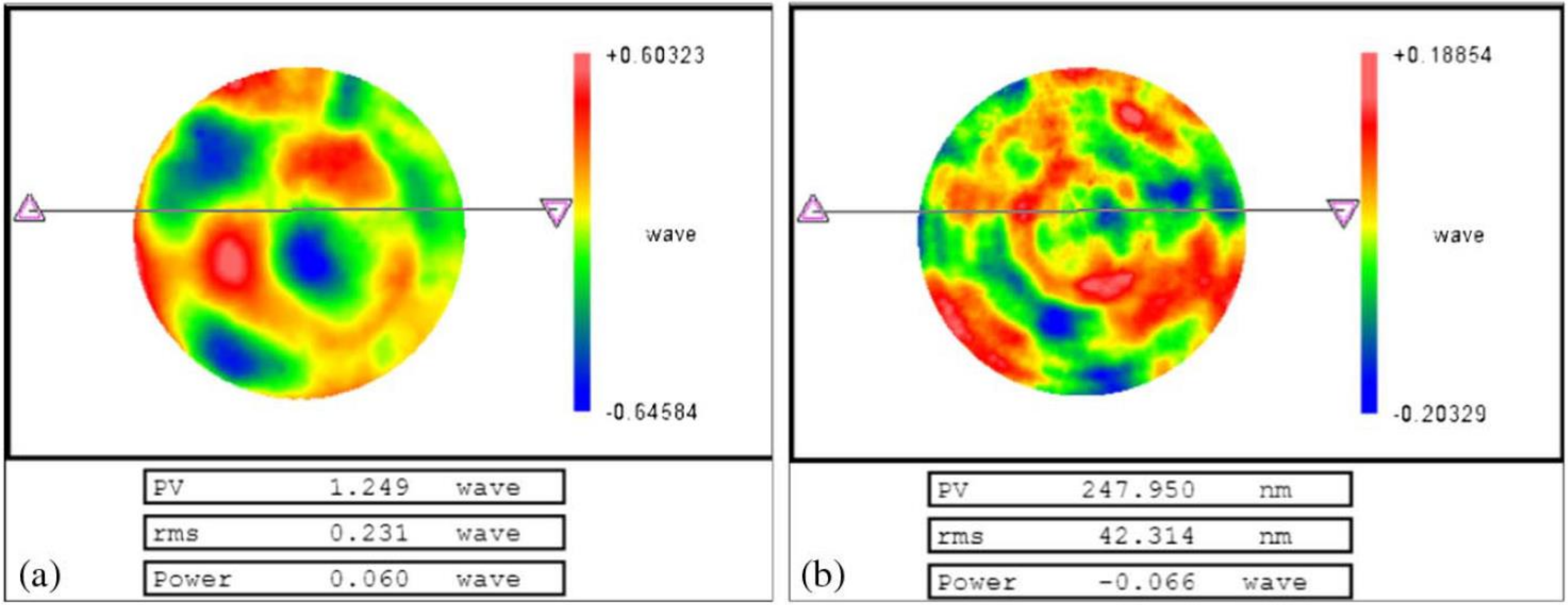
Validation Experiments

- Concentric circle path was chosen with points spaced every 8 mm on Ø400 mm window
- RMS deviation less than 1/30 λ



Validation Experiments

- Direct subtraction of measurement results from Zygo GPI and JR-1800



Validation Results

- Measurement of parabolic surface Ø320 mm, R = 4000 mm
- Measurement error PV = 0.512 μm, RMS = 0.067 μm