Good Practice Guide: Straightness Orthogonality Measurements
REG2 D5.2
JRP D2.3.8
Flatness measurements of machine reference mirrors

Workshop: Metrology for Movement and Positioning in Six Degree of Freedom, 30\textsuperscript{th} May 2016,


* Physikalisches-Technische Bundesanstalt (PTB)

** Institute of Process Measurement and Sensor Technology, Technische Universität Ilmenau
• Optical flatness metrology (interferometry / deflectometry)
• Some aspects to ageing effects and thermal behavior of flats
• Example: Zerodur cube for calibration of 6 DoF systems
• Example: Flatness measurements of a Zerodur test bed for a three-dimensional nanomeasuring and nanopositioning machine (NPM-machine)
• Summary and conclusion
## Absolute flatness measurement

### Interferometry and small angle deflectometry in comparison:

<table>
<thead>
<tr>
<th>Interferometry</th>
<th>Small Angle Deflectometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement uncertainty: few nanometer</td>
<td>Measurement uncertainty: down to sub-nanometer</td>
</tr>
<tr>
<td>Interferometer optic limits the size of the specimens</td>
<td>Scan axis allows for the measurement of large specimens</td>
</tr>
<tr>
<td>high lateral resolution (down to 10 µm for small specimens)</td>
<td>low lateral resolution (typically &gt; 1 mm, independent of the specimen size)</td>
</tr>
<tr>
<td>Determination of the absolute topography by the 3 flat test (vertical specimen with lower MU)</td>
<td>Straightness reference is given by the straight light propagation</td>
</tr>
</tbody>
</table>

Zygo VeriFire MST 12” Interferometer

Deflectometric Flatness Reference (DFR)
Flatness metrology: Interferometry
Interferometry

Zygo Verifire MST, wavelength shifting, aperture 100 mm & 300 mm
Calibration typically by 3 flat test

\[ W_1 = W_{Binv} + W_C \]
\[ W_2 = W_A + W_C \]
\[ W_3 = W_A + W_{Crot} \]
\[ W_4 = W_A + W_B \]

\[ W_A = 0.5*(2W_3^o - W_1^e + W_2^e + W_4^e) \]
\[ W_C = 0.5*(W_2^o - W_3^o + W_1^e + W_2^e - W_4^e) \]

For example:
Flatness Metrology: Small angle deflectometry
Deflectometric Flatness Reference (DFR)

For horizontal specimens

For vertical specimens
Measurement of the topography in autocollimation = small angles

Different deflectometric procedures / gradient methods:

1.) Direct deflectometry
2.) Difference deflectometry (ESAD: Extended Shear Angle Difference)
3.) PTB procedure: Deflectometry with tilting of the specimen (EADS: Exact Autocollimation Deflectometric Scanning)
DFR System for horizontal specimen

- Linear x-stage
- Carriage 1
- Auto-colimator
- Specimen
- Rotation stage
- Tilting table
- Linear y-stage
- Carriage 2
- Alignment unit for DMU
- Double mirror unit (DMU)
Measurement comparison between interferometry and deflectometry
Comparison between deflectometry and interferometry

Measurement at a Zerodur specimen, scanlength: 290 mm

The mean absolute difference is 1.8 nm
Some aspects to ageing effects and thermal behavior of flats with respect to topography changes
Effects over time: EURAMET comparison

Type: EURAMET 672 - Cooperation in research
Specimen: Zerodur
Participants: BE, CH, CZ, DE, ES, FI, GB, IT, LV, NL, PL, TR, (ZA, CN)

Design of the three support points. The black circle represents the maximum measurement area of 150 mm in diameter. To minimize the sag in this area, the support points do not coincide with the Bessel points.
Effects over time: EURAMET comparison

Weighted mean of the group of measurements with 150 mm aperture

(The measurements have been corrected for zero gravity)

PV value of the low frequency contributions of PTB’s control measurements over 4 years
Effects over time: EURAMET comparison

- Between each partner measurement PTB measured the topography of the specimen
- Measurements were carried out at rather large cavity length
- Difference to mean topography is shown
- Uncertainty \((k = 2)\): 10 nm
Effects over time: EURAMET comparison

High frequency residuals

- High frequency residuals are partly property of the surface
- Effects from non perfect cleaning (see topography from 2011_01 to 2011_04)
Calibration of a 150 mm flat of Zerodur

$T = 21.5^\circ C \ (\pm 0.3^\circ C)$

No change of the topography during the last 8 years
Temperature effects of a 12” transmission flat

Transmission flat manufactured by INRAD Optics (US), specified $\lambda/30$
Temperature effects of a 12” transmission flat

TF manufactured by INRAD Optics (US), specified λ/30

T = 21°C

T = 24°C
Example: Glas cube for calibration of 6 DoF systems
Example: Zerdour cube with edge length of 50 mm

Zerdour cube with edge lengths of 50 mm produced/polished by Fa. Horst W. Kaufmann

**Orthogonality better than 1 arcsec**
(measured with the rotation stage of the spectrometer)

cube surface 3-4: orthogonality deviation = 0.06 arcsec
cube surface 4-1: orthogonality deviation = 0.24 arcsec
cube surface 1-2: orthogonality deviation = 0.39 arcsec
cube surface 2-3: orthogonality deviation = 0.22 arcsec

**Flatness of the cube surface better than \( \lambda/20 \)**
measured with the Zygo Verifire MST
Example:
Flatness measurements of a Zerodur test bed for a three-dimensional nanomeasuring and nanopositioning machine (NPM-machine)
Nanopositioning and Nanomeasuring testbed

- Positioning range: 200 x 200 mm
- Resolution: 80 pm
- Velocity: < 30 mm/s

- Moving masses:
  - x-axis: 13.8 kg
  - y-axis: 11.4 kg

Planar structure guiding system (200 x 200 mm)
x-y-Interferometer
2-axes autocollimator
Mirror cube of the NPM-testbed

- Overall Dimensions (L x W x H): 280 x 280 x 60 mm
- Material: Zerodur® (glass ceramic with nearly zero thermal expansion)
- Coating: Al
- Flatness: $\lambda/2$ within the test area 200 x 25 mm (L x H)
- Orthogonality error between the x-y mirror flats: < 10 arcsec
- Weight: 7 Kg

Error-free laser beam mirror system:
- Probe system
- Touch point
- Mirror cube
- X-laser-beam (adjusted perpendicular to the mirror axis)
- Y-laser-beam
Calibrating the reference flat surface of an interferometer by the three-flat test method

In general, the wavefront errors arising from the multi-rotation three-flat test can be calculated using the equation from Küchel:

\[
\begin{pmatrix}
A(x, y) \\
B(x, y) \\
C(x, y)
\end{pmatrix} = \frac{1}{240} \begin{pmatrix}
-6 & 86 & 46 & -6 & -54 & -26 & 14 & -54 & 13 & 77 & -23 & -7 & 77 & -23 & 13 & 60 & -60 & -60 & 60 \\
-54 & -26 & 14 & -54 & -6 & 86 & 46 & -6 & 77 & 13 & -7 & -23 & -23 & 13 & -7 & 77 & 60 & -60 & -60 & 60
\end{pmatrix}
\]
Calibrating the reference flat surface of an interferometer by the extended three-flat test method

Results from the extended three-flat test:

Flat A  
Flat B  
Flat C
Absolute measurement of the deviations from flatness of the side surfaces of the mirror cube using a 6-inch Fizeau interferometer

Stitching interferometry for accurate measurement of large optical surfaces

Measurement regions for subaperture data

Simulated video of the stitching process

6-inch Zygo GPI interferometer

motorized xy stage
Absolute measurement of the deviations from flatness of the side surfaces of the mirror cube using a Fizeau interferometer

Before stitching: 4x $\phi 150$ mm sub-aperture, 50% diameter overlap

After stitching: Stitching algorithm for subaperture stitching interferometry

PV: 351.2 nm

PV: 345.3 nm
Absolute measurement of the deviations from flatness of the side surfaces of the mirror cube using a Fizeau interferometer

Before stitching

4 ø150 mm sub-aperture, 50% diameter overlap

Mask size: 200 X 25 mm

After stitching

Stitching algorithm for subaperture stitching interferometry

PV: 315.4 nm  RMS: 88.6 nm

PV: 270.3 nm  RMS: 74.2 nm
Absolute measurement of the deviations from flatness of the side surfaces of the mirror cube using a Fizeau interferometer

Comparison of the profiles:

Horizontal profiles

Vertical profiles
Summary and conclusion

- Absolute flatness metrology with interferometric 3 flat test and small angle deflectometry is possible
- Within the measurement uncertainty range of flatness metrology no ageing effects for Zerodur (matured) are observed
- Temperature behavior of the specimens have to be checked
- Highly accurate Zerodur cube can be used for axis calibration of 6 DoF movement systems
- Interferometric flatness measurements of a Zerodur test bed for a three-dimensional nanomeasuring and nanopositioning machine (NPM-machine) are shown
- For transferring the accuracy of the 3 flat test to the NPM mirror cube it is proposed to use a specific transfer standard
Straightness measurements at the Nanometer Comparator

Christoph Weichert
Rainer Köning
Axel Wiegmann
Paul Köchert
Jens Flügge
Outline

1. Error separation method – Reversal technique
2. Error separation method – Traceable Multi-Sensor method
3. Implementation at the Nanometer Comparator
4. Calibration of a straightness encoder system
1. Superposition with guiding errors

- Straightness error motion of the slide
- Straightness deviation of the scale
- Measurement result

\[ \text{Measurement result} = \text{Straightness error motion of the slide} + \text{Straightness deviation of the scale} \]
1. Superposition with guiding errors

Straightness error motion of the slide

Straightness deviation of the scale

Measurement result

Error separation methods essential!
1. Classical reversal technique

- Mirror topography as stable reference

\[
m_1(x_i) = t(x_i) + g(x_i)
\]
\[
m_2(x_i) = t(x_i) - g(x_N - x_i)
\]

- Classical reversal technique is NOT applicable for measurements of scales
1. Reversal method

- Measurements with different relative positions of the scale
- Linear equation system → solved by least-squares method
- Mirror topography used as reference
2. Traceable Multi-Sensor method

- Two or more sensors + angle measurement
- Reconstruction of mirror topography, systematic sensor errors and horizontal slide straightness error
- Small angle approximation $\rightarrow$ linear equation system
2. Traceable Multi-Sensor method

- Lagrange interpolation of topography
  - non-equidistant sensor interspaces
  - higher lateral resolution
- Single measurement sufficient
- Angle measurement as reference instead of mirror topography
2. Lateral resolution

Two point sensors: Lateral resolution limited by sensor interspace

Three point sensors: First common zero point

Beams profile: High pass filter
Calibration of line scales, encoder systems and interferometer along a range of up to 550 mm
3. Setup for straightness measurements

- 3 heterodyne Y-interferometers
- Grating scale placed inside the sample carriage with Y-mirror
- Encoder head mounted at the bride as well as all reference mirrors
3. Measurement result – encoder system
3. Measurement results – Y-interferometers
3. Measurement results – Y-interferometers
3. Measurement result – Yaw-interferometer

[Graphs and charts showing measurement data]

30.05.2016
3. TMS method – mirror topography

- Y-interferometers
- Yaw-interferometer
- TMS

- Encoder measurement values / nm
- Position / mm
- Y-interferometers
- Mirror topography / mm
- Yaw-interferometer / nrad
- Mirror topography
3. TMS method – slide straightness error

- Y-interferometers
- Yaw-interferometer

TMS

Slide straightness error / nm

Position / mm

Y-interferometer values / µm

Y-interferometer 1
Y-interferometer 2
Y-interferometer 3

Position / mm

Yaw-interferometer / nrad

Position / mm

Encoder measurement values / nm

Deviation from best-fit line / nm

Position / mm
4. Straightness deviation of the scale

Encoder

Slide straightness

Encoder measurement values / nm

Deviation from best fit line / nm

Slide position / mm

Encoder measurement values / nm

Deviation from best-fit line / nm

Position / mm

Straightness deviation of the scale / nm

Position / mm

Slide straightness error / nm

-300
-200
-100
0
100
200
300
400
-60
-30
0
30
60
90
120

Slide straightness

Position / mm
4. Repeatability with TMS method

Encoder

Slide straightness

Standard deviation < 0.4 nm
4. Shifting and rotating the scale
4. Reproducibility of the TMS result

- Reproducible in the range of ±5 nm
- Limited by length-proportional error of yaw-interferometer
- Standard uncertainty of single measurement: 4.2 nm
- Standard uncertainty of 13 measurements: 1.3 nm
4. Reversal method

Rotating and Shifting

Reversal method
4. Reversal method

- Standard uncertainty: 5.2 nm for solving equation system for eight measurement series
- Limited by variations of mirror topography

![Graph showing straightness deviation reconstructed with reversal method and mirror topography measurements.](image)
4. Comparison of the results

- Peak-to-peak value of scale’s straightness deviation: 144 nm
- Determined with two different error separation methods
- Peak-to-peak value of Difference: 2.5 nm
- Uncertainties limited by violation of requirements of both methods:
  - Stable angle measurement (TMS)
  - Stable mirror topography (reversal)
Summary

- Two error separation methods
  - Reversal method (stable mirror topography)
  - TMS method (stable angle measurement)

- Implement at the Nanometer Comparator

- Similar results of both methods within their uncertainties
  - Prove: TMS usable for straightness measurements
Many thanks to HEIDENHAIN for the precision straightness reference
Thank you for your attention
Data acquisition

Taktsynchronisation
Startsignal

Y1 Mess
Y1 Ref
Y2 Mess
Y2 Ref
Y3 Mess
Y3 Ref

Encoder
Encoder

Differential – SingleEnded

APE

1.5MHz

20MHz

Homodyne

Gier

X Ref
X Mess

APE

APE
Calibration of Yaw-interferometer

Position / mm
Angle variation / µrad

-0.16
-0.14
-0.12
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02

slope: -547 nrad/m
slope: -234 nrad/m

yaw autocollimator
pitch autocollimator
yaw interferometer
pitch interferometer

0 50 100 150 200 250

Position / mm
Deformation of the mirror

Temperature difference of 0.2 K between adjustment and measurement
Multilateration for encoder characterisation on the base of a nanomeasuring testbed

EUSPEN 2016
Nottingham, 30th May 2016

Prof. Dr.-Ing. habil. Eberhard Manske
Institute of Process Measurement and Sensor Technology
Technische Universität Ilmenau
Overview

- Motivation
- 200 mm x 200 mm Nanomeasuring testbed
- Squareness of mirror cube
- Multilateration measurements
High Precision Measurement Technology

Nanopositioning and Nanomeasuring Machine

Mask Measuring Machines (Exposure tools)

2D/3D CMM

2D-encoder (Heidenhain)

Kunz precision

2D-encoder (Heidenhain)
Motivation

Verification of measurement behavior for nano measurement applications is difficult.

Implementation of self calibration methods is important

for 2D/3D applications: straightness, flatness and squareness:
Multilateration approach and reversion method
Grid referencing method for micro measurement technology

Uncertainty influences:
- the laser interferometer (0.2 µm)
- the probing process (0.2-0.3 µm)
- the thermal expansion coefficient of the artefact

\[ U(k = 2) = \sqrt{(0.4 \mu m)^2 + (L \cdot 0.4 \cdot 10^{-6})^2} \]

*K. Wendt, J. Hirsch: Calibration of grid plates by multi-lateration. IMEKO 2005*
Challenges

Self calibration methods have already proved their potential in the range of micro measurement technology for the verification of coordinate measuring machines.

Use of these methods in nano metrology with several obstacles

Extraordinary precision of the calibration of the references is necessary

Nanometre level: probe system must be able to capture the grid points at the same level of precision, whereas the size of the grid plate must cover the whole motion range.

Investigation and application of self calibration methods considering straightness and orthogonality on a precise long range nano measuring machine
Development of a nano measuring testbed

- Positioning range: 200 x 200 mm
- Resolution: 80 pm
- Velocity: < 30 mm/s

- Moving masses:
  - x-axis: 13.8 kg
  - y-axis: 11.4 kg

Planar H-structure guiding system (200 x 200 mm)
- x-y-Interferometer
- 2-axes autocollimator
Mirror cube of the NPM-testbed

Squareness measurements under consideration of topography errors
Measuring orthogonality between x and y mirrors of the mirror cube

1. Adjustment of orthogonality

- Two high-resolution electronic autocollimators (resolution: 0.05 arcsec)
- High precision right-angle prism (uncertainty: < ±0.2 arcsec)
- High precision xy-linear stage (travel range: 300 mm x 300 mm)
Measuring orthogonality between x and y mirrors of the mirror cube

2. Measurement at mirror cube at several xy-positions
Measuring orthogonality between x and y mirrors of the mirror cube

2. Measurement squreeness at several xy-positions

<table>
<thead>
<tr>
<th></th>
<th>X1</th>
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<tr>
<td>Y1</td>
<td>-5.98&quot;</td>
<td>-5.07&quot;</td>
<td>-4.25&quot;</td>
</tr>
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<td>-3.60&quot;</td>
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<tr>
<td>Y3</td>
<td>-4.85&quot;</td>
<td>-3.77&quot;</td>
<td>-3.18&quot;</td>
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Local angular deviations derived from flatness of the side surfaces of the mirror cube

Local surface flatness of the x and y mirrors:

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Measuring orthogonality between x and y mirrors of the mirror cube

Squareness error between the local parts of the x and y mirrors (experimental results):

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Squareness error between the local parts of the x and y mirrors (calculated results from flatness measurements):

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Difference between experimental and calculated results:

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<td>Y1</td>
<td>-4.55&quot;</td>
<td>-4.41&quot;</td>
<td>-4.37&quot;</td>
</tr>
<tr>
<td>Y2</td>
<td>-4.47&quot;</td>
<td>-4.32&quot;</td>
<td>-4.39&quot;</td>
</tr>
</tbody>
</table>
| Y3 | -4.69" | -4.39" | -4.57"

\[
\phi_{xy} \approx -4.46'' \pm 0.12''
\]
Integration of a Heidenhain PP281 two-coordinate encoder into the NPM-testbed for multilateration approach and reversal method.
Mounting Design for the PP281 Two-Coordinate Encoder

Testbed with encoder

Design

- scanning head (PP28R)
- grid plate (PP201)
- rotation table
- mirror cube
Structure of data processing

- dSPACE Workstation
- PC-Data-Processing
- SIOS Dual Beam IF
- SIOS Single Beam IF
- Motion Control
- Trigger
- Heidenhain EIB 741
- Sensor Head
- Grating
- X-Y Motion Stage with Mirrors

IF-Y + IF-Y' (Tilt)
IF-X
IF-Y
IF-Y'
(Tilt)
X-Y Motion Stage with Mirrors
Measurement procedure

First measurement: 0°
First rotation (26.65°)
Second rotation (45°)
Third rotation (63.43°)
Fourth rotation (90°)

... totalling 8 rotations
Status

• First measurements and calculations are realized
• Proof of feasibility successfully
• Improvement of measurement procedure
• Adaption of calculation algorithm

Outlook

• Improvement of measurement algorithm (sequence plan)
• Automatization of data acquisition

Time efficient and low drift measurement procedures
Fast scanning methods for multiple scan measurements

Nanometer uncertainty
Acknowledgement

IND 58 6DoF/ REG 2 (TU-IL):
COMPARISON OF EXTERNAL WITH SELF CALIBRATION METHODS

Thanks to
N. Vorbringer-Doroshovets, H. Xu, U. Gerhardt, M. Domhardt, A. Meister
J.Flügge, Ch. Weichert, J.Hirsch

Thank you for your attention!
Orthogonalitätsmessung der Raumspiegelecke

Konzepte zur Vermessung der 90°-Winkelabweichungen zwischen den Spiegeln (xy-, xz- und yz-Spiegel) der Raumspiegelecke mittels eines Autokollimationsfernrohrs (AKF)

Standardabweichung bei 10 Messungen: 0,01°
What is the accuracy and uncertainty of flats or grids?

Precision flat-, L-shape-, cube-mirrors (2D/(3D)-Laser interferometer) vs Linear, grid scales, lithography masks (2D-Encoder)

Flatness, straightness, squareness: sub-µm to nm
Topography
Straightness deviation of the 2D-Encoder
To perform **time efficient and low drift measurement** procedures for self calibration, the **scanning methods** using these measuring systems will have to be accelerated and the **combination and sequence plan of the multiple scan measurements** will have to be worked out.
Encoder under test

Manufacturer specification:

• two-coordinate TITANID-phasegrid-encoder on glass (70 x 70 mm²)
• pitch= 8 µm, signal period= 4 µm
• resolution: 1 nm
• interpolation deviation < 12 nm
• $\alpha_{\text{therm}} = 8 \cdot 10^{-6} \text{ K}^{-1}$

Goals:
Uncertainty < 10 nm

Requirements:
thermal stability < 0.01 K
resolution calibration interferometer: 0.1 nm
Integration of the Heidenhain PP281 two-coordinate encoder into the NPM-testbed

scanning head (PP28R)
grid plate (PP201)
removable mounting adapter with manual adjustment mechanisms (adjustment of rotation and tip/tilt)
mirror cube
y-interferometer
Thanks for your attention!

Haifeng Xu
Uwe Gerhardt

Prof. Dr.-Ing. habil. Eberhard Manske
Institute of Process Measurement and Sensor Technology
Technische Universität Ilmenau
Design of the Nanopositioning and Nanomeasuring testbed

Planar H-structure guiding system (200 x 200 mm)
x-y-Interferometer
2-axes autocollimator
Method for measuring orthogonality between x and y mirrors of the mirror cube

Accurately align the optical axes of both electronic autocollimators orthogonal to each other using a precision high-tolerance right-angle prism

Precision high-tolerance right-angle prism:
- Material: N-BK7
- Angle Tolerance (arcseconds): < ±2
- Coating: Aluminum Coated Hypotenuse
- Surface Flatness @ 633 nm: \( \lambda/10 \)
- Length of Hypotenuse (mm): 75
Method for measuring orthogonality between x and y mirrors of the mirror cube

Accurately align the optical axes of both electronic autocollimators orthogonal to each other using a precision high-tolerance right-angle prism.
High-precision angle measurement of right angle prisma using a Fizeau interferometer

Setting of the prism for right angle and pyramidal error determination

Right angle error:

$$\alpha_R = -0.97 \text{ arcsec}$$

Pyramidal error:

$$\alpha_P = -0.81 \text{ arcsec}$$

$$U^* = 3.6 \times 10^{-4} \text{ arcsec (10 repeated measurements)}$$

* Expanded uncertainty ($k=2$)
Mounting design for the mirror corner

• Installation on a three-point baseplate with finite stiffness
• Insert and remove components with high repeatability
• Ball and V-Groove design for precise alignment
• Increase the ability of reducing mechanical and thermal stresses in the mirror corner
Mounting design for the optical microscope

Integration of the Heidenhain PP281 two-coordinate encoder) into the NPM-testbed

Three base adapters (with a V-groove, a cone and a flat) are connected to three high-precision adjustment screws (adjustment of the tip, tilt and translation along the vertical axis).
Absolute measurement of the deviations from flatness of the side surfaces of the mirror cube using a Fizeau interferometer

Horizontal profil of the y Mirror:
Absolute measurement of the deviations from flatness of the side surfaces of the mirror cube using a Fizeau interferometer

Horizontal profil of the y Mirror:
Absolute measurement of the deviations from flatness of side surfaces of the mirror cube using a Fizeau interferometer

Local surface flatness of the x and y mirrors:

Squareness error between the local parts of the x and y mirrors:

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Influence of the pyramidal error

The pyramidal error does not have much effect on angle block measurements. Measurement error is introduced when the autocollimator is not properly aligned to the axis formed by the side of the angle block.

<table>
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<tr>
<th>squareness error</th>
<th>pyramidality of faces</th>
<th>effects of the pyramidal error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&quot;</td>
<td>15°</td>
<td>&quot;</td>
</tr>
<tr>
<td>5&quot;</td>
<td>7°</td>
<td>&quot;</td>
</tr>
<tr>
<td>10&quot;</td>
<td>5°</td>
<td>&quot;</td>
</tr>
</tbody>
</table>
Question: What is the accuracy and uncertainty of flats or grids?
Mirror cube of the NPM-testbed

- Overall Dimensions (L x W x H): 280 x 280 x 60 mm
- Material: Zerodur® (glass ceramic with thermal expansion of nearly zero)
- Coating: Al/SO
- Flatness: λ/2 within the test area 200 x 25 mm (L x H)
- Orthogonality error between the x-y mirror flats: < 10 arcsec
- Weight: 7 Kg
Thermal, dynamic and gravity influence?

- Neue Kalibrierstrategien
- Hochpräzise Messung und Korrektur: $< \lambda/120$
- Untersuchungen zur Messdynamik

thermal and dynamic:
Absolute measurement of the deviations from flatness of the side surfaces of the mirror cube using a Fizeau interferometer

Before stitching

4x ø150 mm sub-aperture, 50% diameter overlap

After stitching

Stitching algorithm for subaperture stitching interferometry

PV: 351.2 nm

PV: 345.3 nm
Mounting design for the PP two-coordinate encoder

Metrological frame: Possibility of installing a surface-sensing probe into the NPM-testbed
Absolute measurement of the deviations from flatness of the side surfaces of the mirror cube using a 6-inch Fizeau interferometer

Stitching interferometry for accurate measurement of large optical surfaces

Measurement regions for subaperture data

Simulated video of the stitching process

6-inch Zygo GPI interferometer

Motorized xy stage
Absolute measurement of the deviations from flatness of the side surfaces of the mirror cube using a Fizeau interferometer

Before stitching

4 $\varnothing$150 mm sub-aperture, 50% diameter overlap

Mask size: 200 X 25 mm

After stitching

Stitching algorithm for subaperture stitching interferometry

PV: 315.4 nm  RMS: 88.6 nm

PV: 270.3 nm  RMS: 74.2 nm

x Mirror:

y Mirror:
Absolute measurement of the deviations from flatness of side surfaces of the mirror cube using a Fizeau interferometer

Comparison of the profiles:

Horizontal profiles

Vertical profiles

- x Mirror  - y Mirror