Angle Metrology for Highly Accurate Topography Measurement: New Developments & Applications

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Physikalischn-Technische Bundesanstalt PTB
5.23 Angle Metrology
Outline

Deflectometry: Basic Properties & Advantages

Current Applications of Deflectometric Profilers
> Flatness Standard at NMI
  - ESAD, PTB, Germany
> Synchrotron Mirror Metrology
  - NOM, BESSY, Germany
  - DLTP, ALS, US

Angle Metrology in Support of Deflectometry
> Angle Metrology at PTB
> Precision Autocollimator Calibration
> Angle Deviations of Autocollimators
  - Location of Aperture
  - Distance-Dependency
  - 2D Calibration
Why Access Topography by Angle Measurement?

Increase in sensitivity for topography:

\[
\frac{\Delta s}{\Delta z} = 2 \times \frac{300}{3} = \text{factor } 200
\]
Deflectometric Scanning: Basic Principle

Pentaprism

Auto-collimator

Surface under test
Why Use a Pentaprism for Beam Deflection?

Straightness errors of mechanical stages

> Conv. linear stage: $\approx 10$ arcsec / $50 \, \mu$rad $3 \, \mu$m @ 500 mm
> Air-bearing stage: $\approx 1$ arcsec / $5 \, \mu$rad $300$ nm @ 500 mm
> Wanted: $\approx 0.001$ arcsec / $5 \, n$rad $0.3$ nm @ 500 mm

Straightness error of stage: 1st order error influence
Why Use a Pentaprism for Beam Deflection?

Ultra-stable beam deflection by pentaprism
> Highly robust with respect to angular rotations of prism
> Suppression of stage errors: factor 1000 – 10000
Traceability of Deflectometric Topography Measurement

Topography derived from measurands angle & length

Measurand traceability: angle

Autocollimator calibration:
Std. uncertainty
$u = 5$ milliarcsec
(24 nrad)

PTB 5.23 Angle Metrology

Natural straightness standard:
propagation of light

Ultra-stable beam deflection by pentaprism

Measurand traceability: length
(for positioning only, not for topography)

Calibration of length encoder or length interferometer
Summary: Advantages of Deflectometric Topography Measurement

- High sensitivity of angle measurement to topography changes
- Robustness with respect to environmental influences
- Based on natural straightness standard: propagation of light
- Excellent measurand (angle & length) traceability
- Fully independent of material straightness artifact
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**Flatness Standard: Liquid Hg Surface**

- **Hg layer**: Thickness $200 \pm 50 \ \mu m$
- **Holder**: - Silver (amalgamation) & non-magnetic steel  
  - Structured floor (vibration-dampening)

- **Avoid**: temperature gradients, vibrations, static charges,  
  magnetic fields, liquid flow by movement, contaminations, oxide layer ...

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**Problem: Spherical shape**  
(1nm @ 250 mm)

**Problem: Vibrations**

**Problem: Edge effects**
Shearing Deflectometry: Basic Principle

Angle difference = *intrinsic* surface property
(independent of whole-body tilting)
Definition of Flatness Using Angle Differences

Non-flat Surface

Flat Surface

Angle differences = 0
(independent of shear values, position ...)

Shear
ESAD: Sequential Implementation

Shearing
(sequential implementation by use of movable pentaprism)

STEP 1
- Pentaprism at position 1
- Measure slope

STEP 2
- Pentaprism at position 2 (shifted by shear length s)
- Measure slope

Scanning

STEP 3
- Shift surface under test

Repeat sequence
(to obtain slope differences at different positions on surface under test)
ESAD Facility

Scan area up to 500 x 500 mm²
ESAD Mechanical Implementation

- Autocollimator
- Actuator
- Prism tilting unit
- Pentaprism
- Linear stage
- Shielding tube
- Aperture holder
- Surface under test
ESAD Facility

Note:
> Built up by speaker in 2000-2007
> located at Optics Division of PTB
Angular Adjustment of Optical Components

Adjust:
- Roll SUT ($\alpha_{st}$)
- Roll PP ($\alpha_{pp}$)
- Yaw PP ($\gamma_{pp}$)
Ultra-stable beam deflection by pentaprism

> Error in V angle $\pm 0.21$ milliarcsec @ 95% conf. level
  (angular error in pentaprism orientation: $\pm 5$ arcsec)

> Error reduction by a factor $10,000$
Zerodur Transfer Standards
ESAD Measurement: Zerodur Substrate

> Shear numbers 4 & 35 (140); scan length 200 mm; phys. shears 5.7 & 50 mm
> Shear numbers 4 & 35 (140); scan length 80 mm; phys. shears 2.3 & 20 mm

ESAD Measurement: Zerodur Substrate

> Shear numbers 4 & 35 (140); scan length 200 mm; phys. shears 5.7 & 50 mm
> Shear numbers 4 & 35 (140); scan length 80 mm; phys. shears 2.3 & 20 mm

Topo. 7.6 nm pv @ 200 mm
Difference 0.10 nm rms @ 80 mm
Topo. 0.8 nm pv @ 80 mm

Repeatability topo.
0.37 nm rms @ 200 mm
Repeatability topo.
0.10 nm rms @ 80 mm

Measurement Comparison
ESAD - Fizeau Interf. (Hg)

Fizeau: Using liquid Hg mirror as flatness standard

Difference: 0.55 nm rms @ 120 mm

**Summary: ESAD (Extended Shear Angle Difference)**

- **Principle:** Shearing deflectometry (slope differences)

- **Basis:** straight light propagation

- **Metrological advantages**
  - Near-constant measurement conditions - independent of scan length
  - Optimized measurand traceability to SI units (angle & length)
  - No material straightness artifact (absolute measurement)

- **Std. meas. uncertainty topography** $u_{\text{topo}} < 1 \text{ nm}$
  (near-plane surfaces, up to 500 mm scan length)
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NOM: Nano-Optics Measuring Machine (BESSY)

Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung m.b.H., Berlin, Germany

Measurement uncertainty
> Plane surfaces: 0.05 \( \mu \text{rad rms} \)
> Curved surfaces: 0.2 \( \mu \text{rad rms} \)

F. Siewert, BESSY
NOM: Effective Metrology Tool for Post-Processing

Elliptical cylinder for MAX-Lab (Lund, Sweden):
NOM measurement before and after final ion beam treatment

Height:
66 nm pv / 8.5 nm rms
Residual slope:
1 μrad rms

Height:
25 nm pv / 3.6 nm rms
Residual slope:
0.5 μrad rms
DLTP: Developmental Long Trace Profiler (ALS)
Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, USA
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Angle Metrology at PTB

- Autocollimator Manufacturers: Möller-Wedel Optical
- Synchrotron Metrology: BESSY, ALS / LBNL, USA
- NMIs: AIST / NMJ, Japan, BIPM (G-Exp.), France
- Manufacturers Rotary Tables & Encoders: Johannes Heidenhain

R&D / Calibration Autocollimators

u = 0.005 arcsec (CMC)

Primary Angle Standard
u = 0.001 arcsec

Angle Comparator WMT 220

R&D / Calibration Angle Encoders

u = 0.005 arcsec (CMC)

Calibration Algorithms
Self & cross calibration
Primary Angle Standard: Comparator WMT 220

PTB, 5.23 Angle Metrology, located in clean room facility

Calibration uncertainties

WMT 220
\[ u_{WMT} = 1 \text{ milliarcsec} \]
\[ (5 \text{ nrad}) \]

Calibrations
AC & encoders (CMC)
\[ u = 5 \text{ milliarcsec} \]
\[ (24 \text{ nrad}) \]
\[ U = 10 \text{ milliarcsec (k=2)} \]
Primary Angle Standard: Comparator WMT 220

Grating / signal period: $2^{17} / 2^{18}$ in $2\pi$ rad: 10 arcsec / 5 arcsec
Interpolation factor: $2^{12} = 4096$
Resolution per reading head: $2^{30}$ in $2\pi$ rad: 0.0012 arcsec
WMT 220: Optimized Reading Head Arrangement

Main reading heads
> 2x4 (diametrically opposed)
> Relative angular orientation: 45 deg

Auxiliary reading heads
> 2x4 (diametrically opposed)
> For self-calibration
> Relative angular orientation:
  22.5 / 11.25 / 5.63 / 2.81 deg

Calibration
> Cross-calibration
> Self-calibration
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Electronic Autocollimator (AC): Principle

Autocollimator

- CCD line
- Illumination & reticle
- Beam splitter
- Collimator objective

Surface under test
Electronic Autocollimator (AC): Principle

\[ d = f \tan(2\alpha) \]

Reticle image
SUT angle \( \alpha \)

Reticle image
\( \alpha = 0 \)

Autocollimator

CCD line

Illumination & reticle

Beam splitter

Collimator objective

Surface under test

\( \alpha \)
AC Calibration: Stability

Difference AC angle deviation 2004 / 2005:
> 1.3 milliarcsec (6 nrad) rms
> Slope difference $4 \cdot 10^{-7}$

### Recent AC Calibrations: Synchrotron Metrology Support

<table>
<thead>
<tr>
<th>Institute</th>
<th>Application</th>
<th>AC type</th>
<th>AC aperture</th>
<th>SUT distance</th>
<th>SUT refl.</th>
<th>AC axis</th>
<th>Angle range [arcsec]</th>
<th>Angle sampl. [arcsec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BESSY</td>
<td>Calib. device</td>
<td>Elcomat HR (mod.)</td>
<td>15 mm</td>
<td>430 mm</td>
<td>low</td>
<td>Y</td>
<td>±600 ±500 ±1500</td>
<td>0.2^a 5 50</td>
</tr>
<tr>
<td>ALS</td>
<td>UTM (Universal Test Mirror)</td>
<td>Elcomat 3000</td>
<td>15 mm</td>
<td>250 mm</td>
<td>low</td>
<td>X / Y</td>
<td>±1000 ±10</td>
<td>10 0.1</td>
</tr>
<tr>
<td>ALS</td>
<td>DLTP (Developm. Long Trace Profiler)</td>
<td>Elcomat 3000</td>
<td>2.5 mm</td>
<td>330 / 550 mm</td>
<td>high</td>
<td>X / Y</td>
<td>±1000 ±10</td>
<td>10 0.2 0.02 0.2 0.2</td>
</tr>
<tr>
<td>PTB</td>
<td>TMS (Traceable Multi-Sensor)</td>
<td>Elcomat 3000</td>
<td>18 / 5 / 3 mm</td>
<td>250 / 350 / 440 / 560 mm</td>
<td>low / high</td>
<td>X / Y</td>
<td>±1000 ±20 600-1000</td>
<td>20 0.2 0.2</td>
</tr>
</tbody>
</table>

(a): Unique 4 week experimental calibration run
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AC Angle Deviations: External Parameters

Aperture stop
- Diameter & shape
- Position
  - longitudinal: along AC’s optical axis
  - lateral: perpendicular to optical axis

Surface under test (SUT)
- Reflectivity
- Curvature
- Effective path length (between AC and SUT)
- Sagittal slope (cross-talk AC measuring axes)

2D calibration possible?
AC Calibration: Distance Aperture - SUT

Distance aperture - reflecting surface 0, 300, 390 mm
AC Calibration: Distance Aperture - SUT

Periodic angle deviations:

> Vignetting distorts image of reticle pattern on CCD

> Evaluation of sub-pixel location of image on CCD; Intra-pixel Quantum Efficiency (QE) variation

AC = 4 milliarcsec


> AC aperture: 5 mm diam.
> SUT distance: 400 mm
> SUT coating: none
> Sampling: 0.1 arcsec
> Std. uncertainty: \( u_{AC} = 4 \) milliarcsec
AC Calibration: Lateral Displacement of Aperture

Lateral displacement $\pm 5$ mm
AC Calibration: Lateral Displacement of Aperture

Lateral displacement ±5 mm > slope of AC angle deviation: ±10^{-3}


> AC aperture: 5 mm diam.
> SUT distance: 400 mm
> SUT coating: none
> Sampling: 0.1 arcsec
> Std. uncertainty: u_{AC} = 4 milliarcsec
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AC Beam Path: Dependency on SUT Distance

Problem: Change in beam deflection = path length $\times$ angle
AC Beam Path: Dependency on SUT Distance

**Problem:** Change in beam deflection = path length x angle

Distance-dependent angle deviations by:
- Optical aberrations (objective, beam splitter …)
- Alignment errors (including CCD)

CCD out of focal plane: $\Delta \alpha \sim \alpha$
AC Angle Deviations: Distance-Dependency

Topography error from distance change 250 mm - 560 mm

- AC aperture 18 mm: Relative topography error \( \leq 5 \cdot 10^{-5} \)
- AC aperture 5 mm: Relative topography error \( \leq 4 \cdot 10^{-4} \)

SUT slope range \( \leq \pm 980 \) arcsec \((\pm 4.75 \) mrad\), e.g., radius 10 m, profile length 95 mm

Topography Error from AC Distance-Dependency

SUT slope range $\pm 980$ arcsec ($\pm 4.75$ mrad),
e.g., radius 10 m, profile length 95 mm

<table>
<thead>
<tr>
<th>Change in distance to SUT [mm]</th>
<th>Relative topography error $\times 10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 (250 - 350)</td>
<td>1</td>
</tr>
<tr>
<td>190 (250 - 440)</td>
<td>2</td>
</tr>
<tr>
<td>310 (250 - 560)</td>
<td>4</td>
</tr>
</tbody>
</table>

- Aperture 18 mm
- Aperture 5 mm
- Aperture 3 mm

- SUT coating: aluminum
- Calibration range $\pm 1000$ arcsec
- Sampling: 20 arcsec
### Topography Errors from AC Measurement Conditions

**SUT slope range**: ±980 arcsec (±4.75 mrad)

<table>
<thead>
<tr>
<th>Changed condition</th>
<th>Fixed condition(s)</th>
<th>Relative topography error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>AC aperture</strong></td>
<td><strong>SUT distance</strong></td>
</tr>
<tr>
<td>SUT reflectivity 4% (uncoated) to high (aluminum)</td>
<td>18 mm</td>
<td>560 mm</td>
</tr>
<tr>
<td>AC aperture 18 mm to 3 mm</td>
<td>-</td>
<td>440 mm</td>
</tr>
<tr>
<td>AC aperture 5 mm to 3 mm</td>
<td>-</td>
<td>440 mm</td>
</tr>
<tr>
<td>SUT distance 250 mm to 560 mm</td>
<td>18 mm</td>
<td>-</td>
</tr>
<tr>
<td>SUT distance 250 mm to 560 mm</td>
<td>5 mm</td>
<td>-</td>
</tr>
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SUT reflectivity high unless otherwise stated.
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2D Autocollimator Calibration (Simulation)

- Relevant to synchrotron metrology
- Extremely challenging (traceability)
- No NMI active in this area

Simulation from real 1D AC calibrations
Summary: Angle Metrology for Deflectometry

> **Primary angle standard WMT 220 at PTB**
  Std. uncertainty calibration $u_{WMT} = 1$ milliarcsec (5 nrad)

> **Flexible AC calibration according to user specification**
  Std. uncertainty AC calibration $u_{AC} = 5$ milliarcsec (24 nrad)

> **Deflectometric set-up influences AC calibration**
  - Aperture stop: Diameter, shape & position
  - SUT: Reflectivity, curvature, path length, sagittal slope
  - Measurement conditions = calibration conditions

> **Current / future challenges**
  - Distance-dependent effects
  - 2D calibration
Thank You very much:

For the opportunity to speak at the National Institute of Advanced Industrial Science and Technology (AIST).

For the privilege of Your attendance and attention.

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