# Autocollimator Calibration for Synchrotron Metrology: Advancing from Plane to Solid Angle

Ralf D. Geckeler, Oliver Kranz, Andreas Just, Michael Krause

***PTB - Physikalisch-Technische Bundesanstalt, Germany***

# Precision Form Measurement with Autocollimators

ESAD
Extended Shear Angle Difference

**PTB, Ger**
Physikalisch-Technische Bundesanstalt, Braunschweig

BESSY

**HZB / BESSY II, Ger**
Helmholtz-Zentrum Berlin für Materialien und Energie

**NMIJ, Japan***
National Metrology Institute of Japan, Tsukuba

**LOFT, US**
Large Optics Fabrication & Testing Group, Arizona

**Traceable to PTB**
**Primary Angle Standard**
**WMT 220**

**ALS, US**
Advaced Light Source, Berkeley

**DLS, UK**
Diamond Light Source, Didcot

**APS, US***
Advanced Photon Source, Argonne

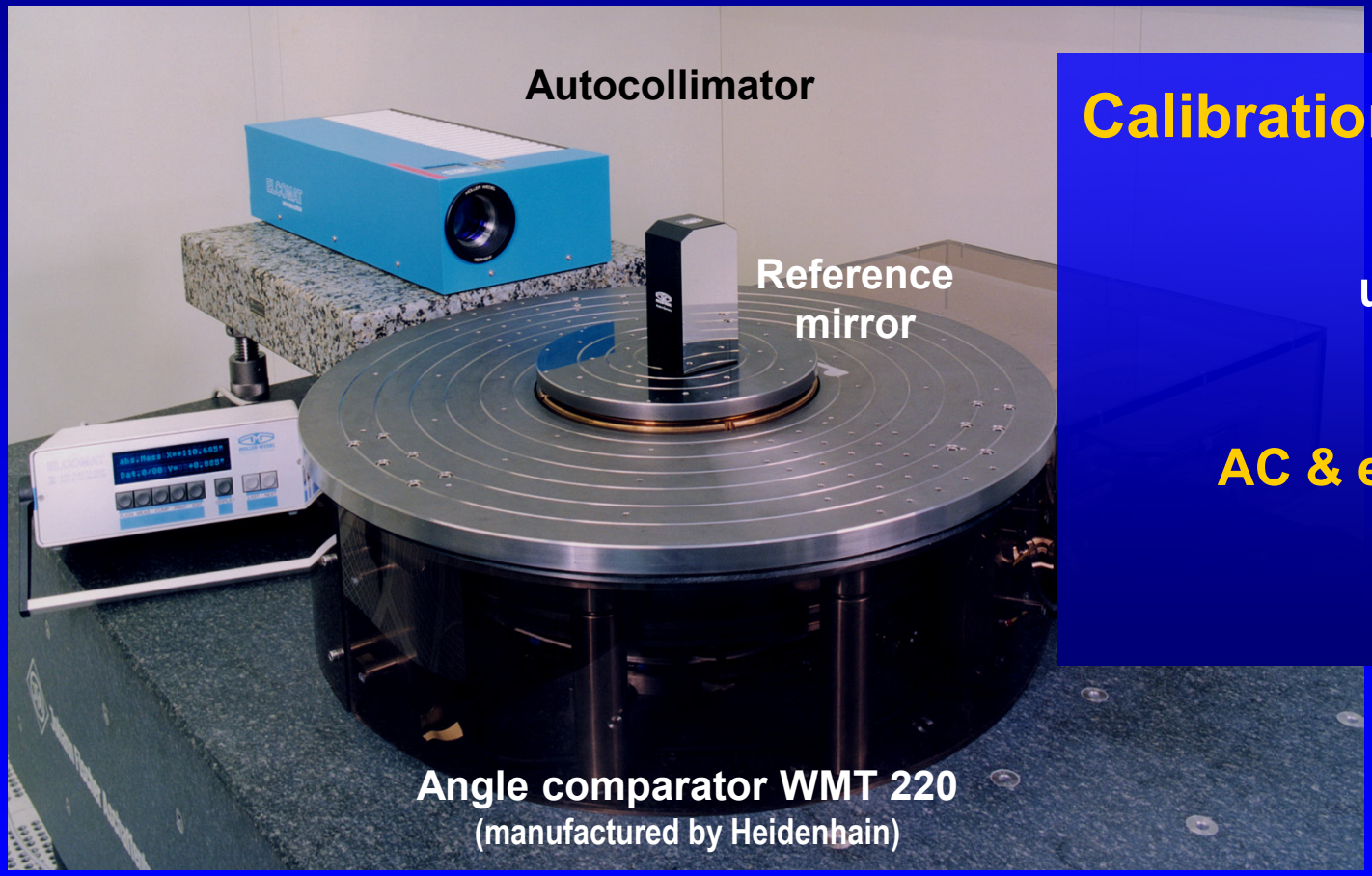
**ALBA, Spain***
Barcelona

**Spring8, Japan***
Super Photon Ring-8 GeV, Hyogo

(* under development)

# Primary Angle Standard of PTB
# Comparator WMT 220

**5.23 *Angle Metrology*, located in clean room facility**




## Calibration uncertainty

**WMT 220**

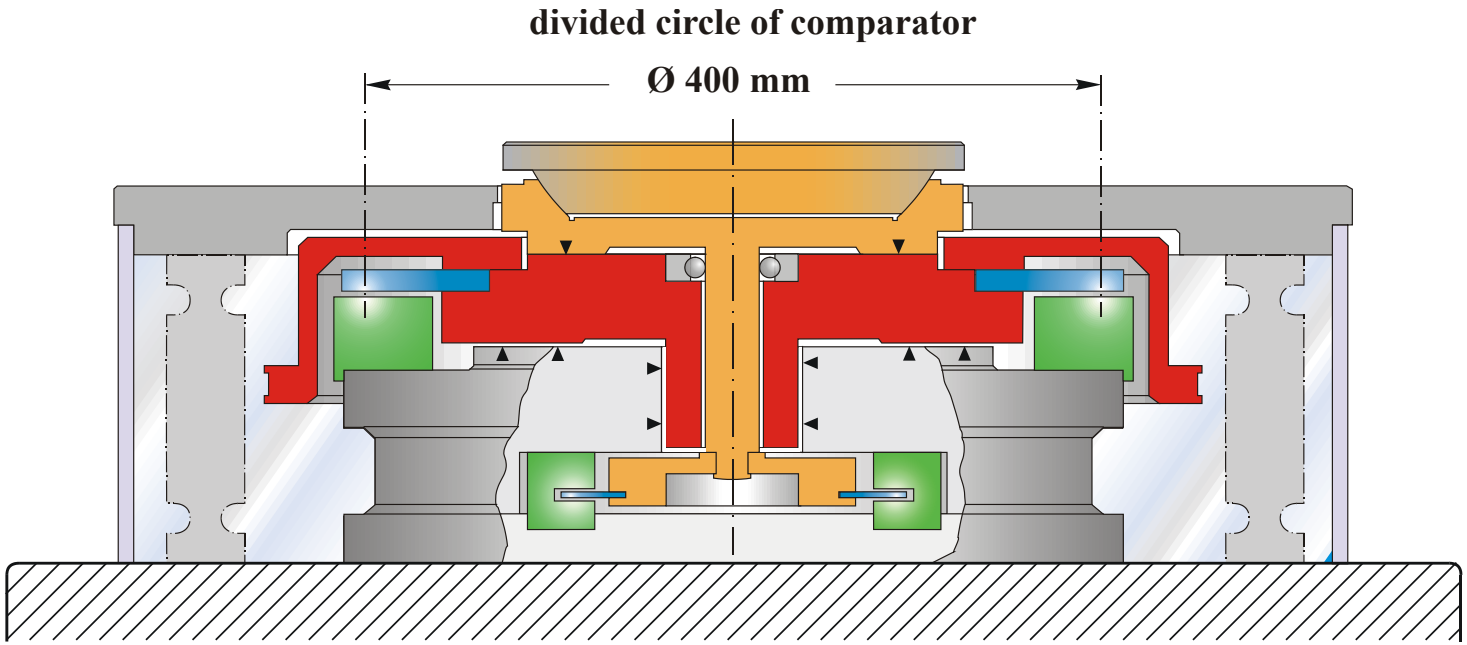
$u_{WMT}$ = 1 milliarcsec
(5 nrad)

**AC & encoders (CMC)**

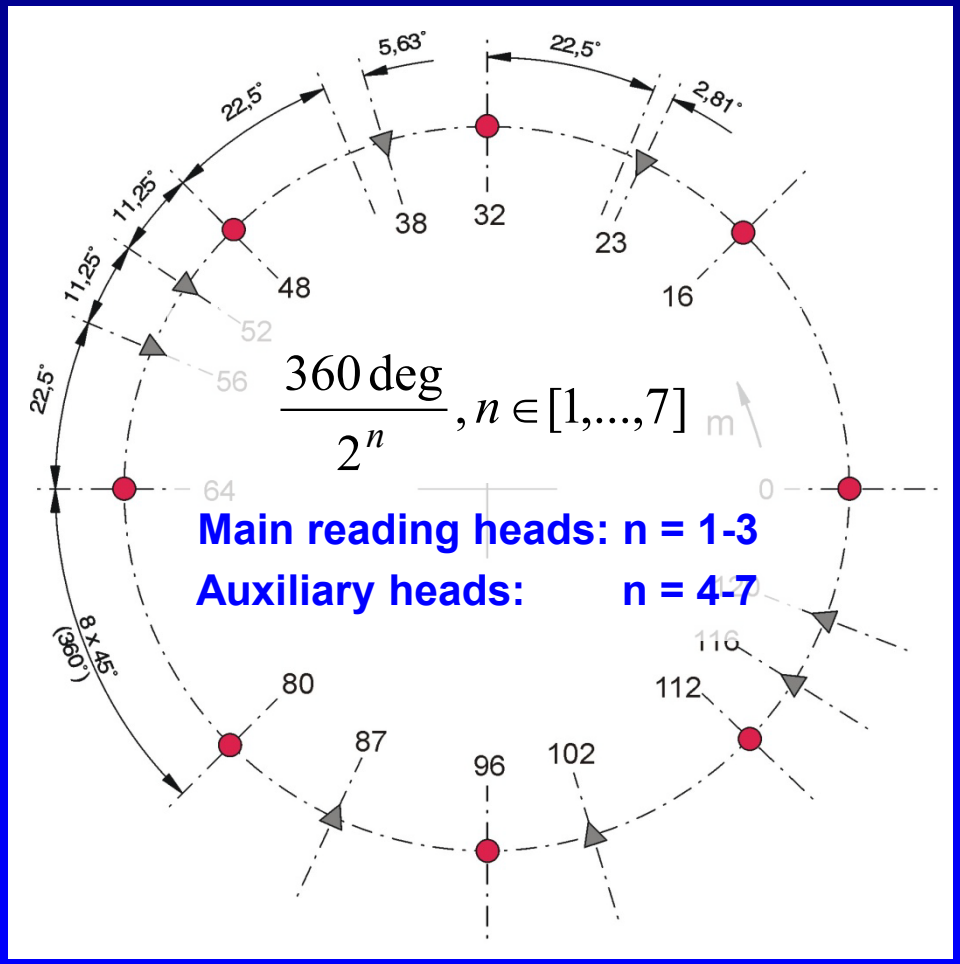
u = 5 milliarcsec
(24 nrad)

# Primary Angle Standard – Comparator WMT 220

| | |
|---|---|
| Grating & signal period: | $2^{17}$ & $2^{18}$ in $2\pi$ rad (10 & 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

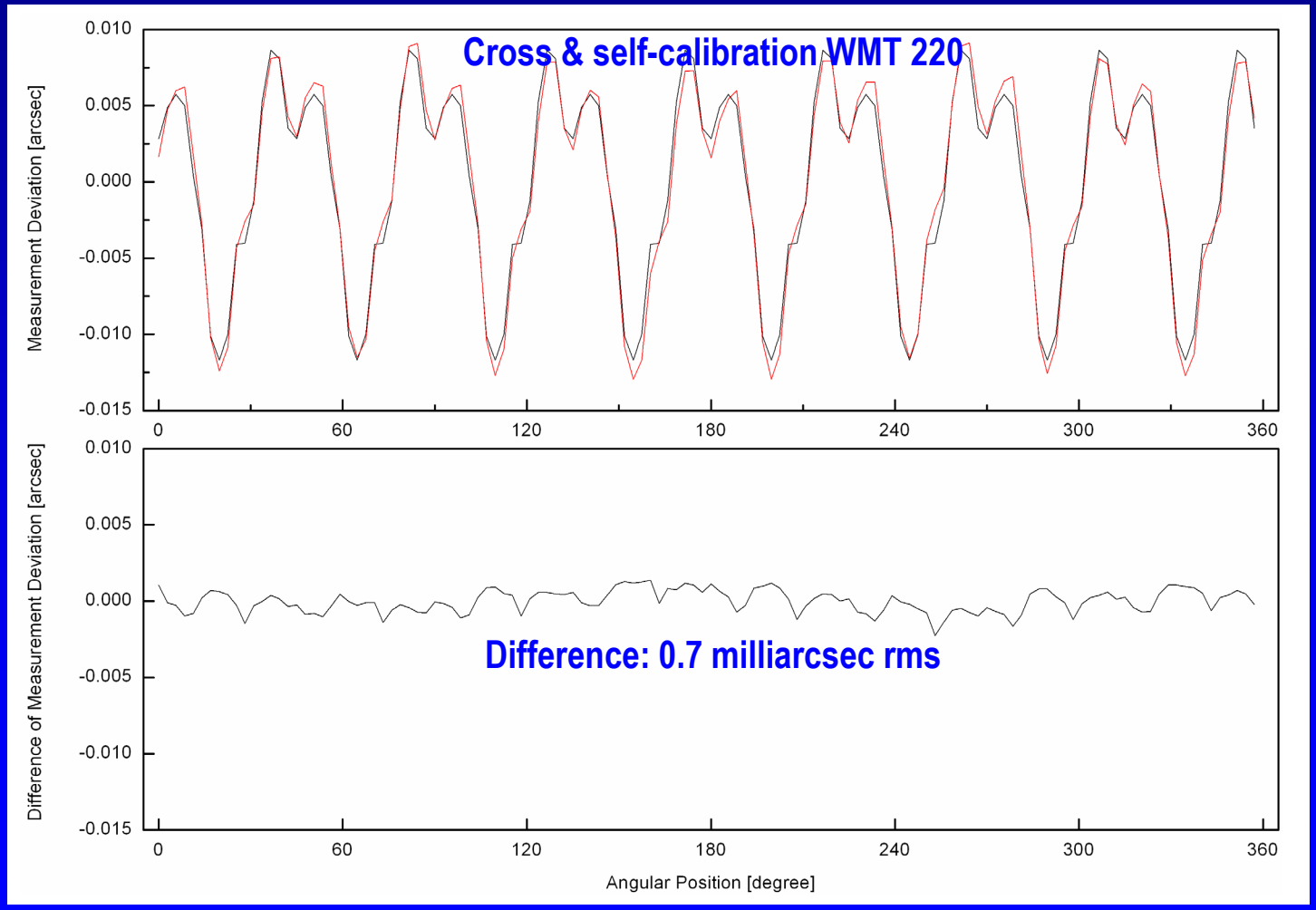
## Calibration

> Cross-calibration

> Self-calibration

# Cross- and Self-Calibration WMT 220

## Difference: 0.00074 arcsec rms = 0.74 milliarcsec rms (3.6 nrad rms)




n=128

# Digression: Angle Metrology and the SI

## SI - Le Système International d'Unités

**> Unit of plane angle, *radian*, is derived from base unit *meter***

**> *radian* = *m* / *m***

angle = arc length divided by radius (e.g., sine bar)

Practically, the radius (base length) can not be measurend adequately!

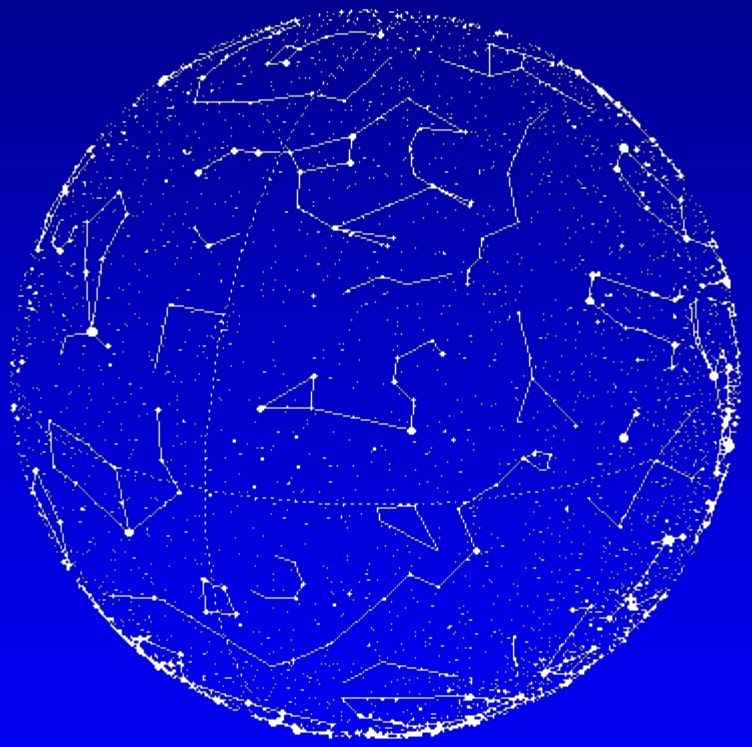
## Alternative

**> Division of full circle ($2\pi$ as a natural, error-free standard)**

**> Provides angles at nanoradian ($10^{-9}$ rad) uncertainty level**

# 2D Angle Measurement

## Advancing from plane angle to *solid* angle



### Relevance

> Form measurement
- Synchrotron metrology
- Flatness standards at NMIs

> AC manufacturers

> Precision engineering

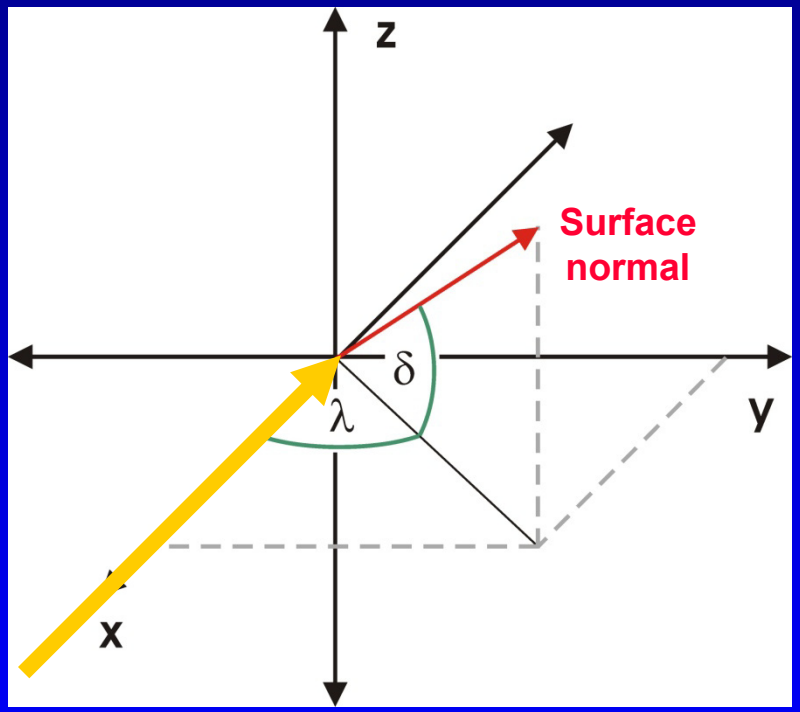
### Challenges

> Measurement speed ($n^2$)

> Traceability*

* '… property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.'
ISO / IEC Guide 99:1993: International vocabulary of metrology (VIM), definition 6.10.

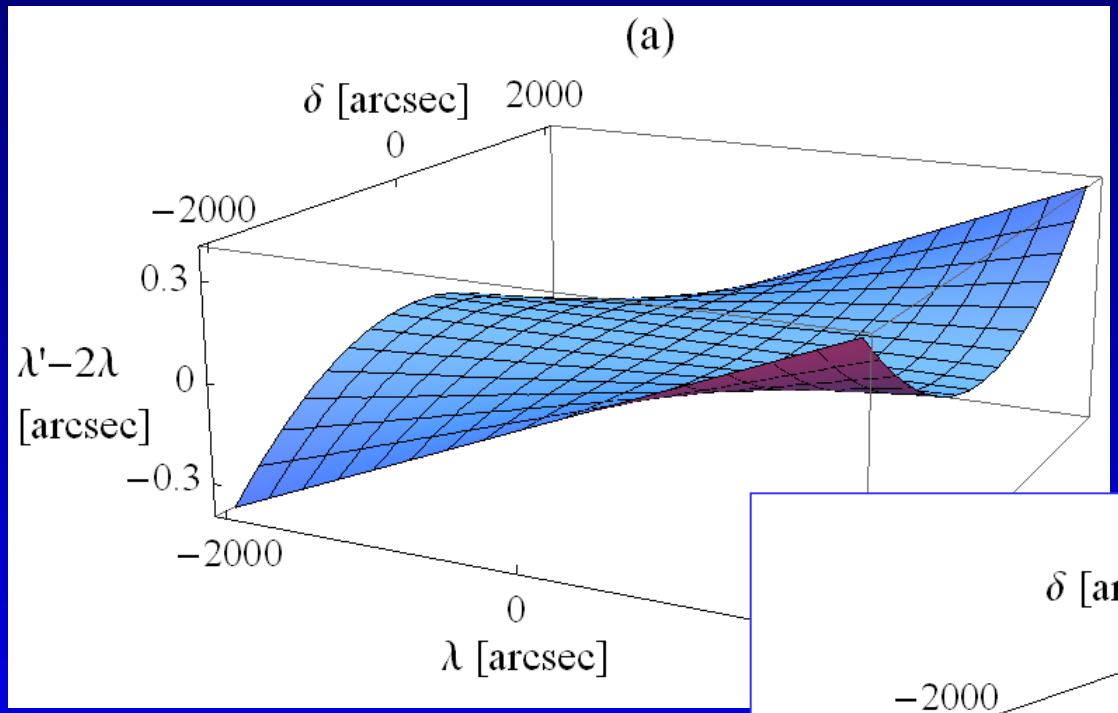
# Reflection at Surfaces in 2D

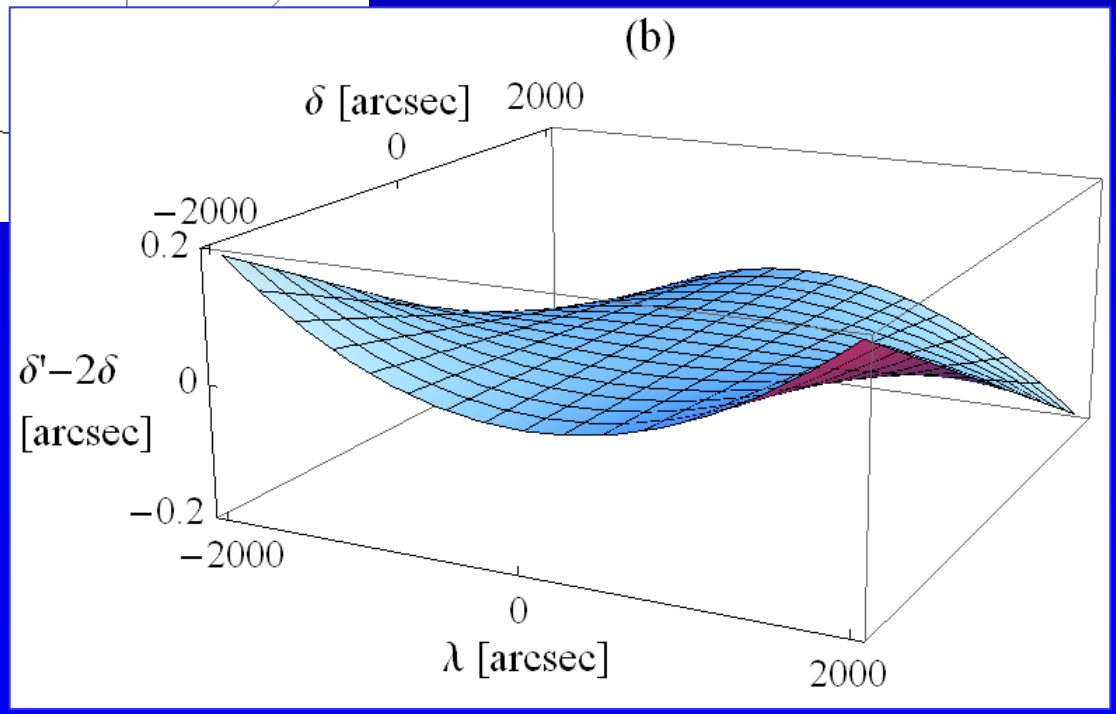



## Beam reflection angles

**Crosstalk** between longitudinal & sagittal reflection angle

# Crosstalk between Reflection Angles

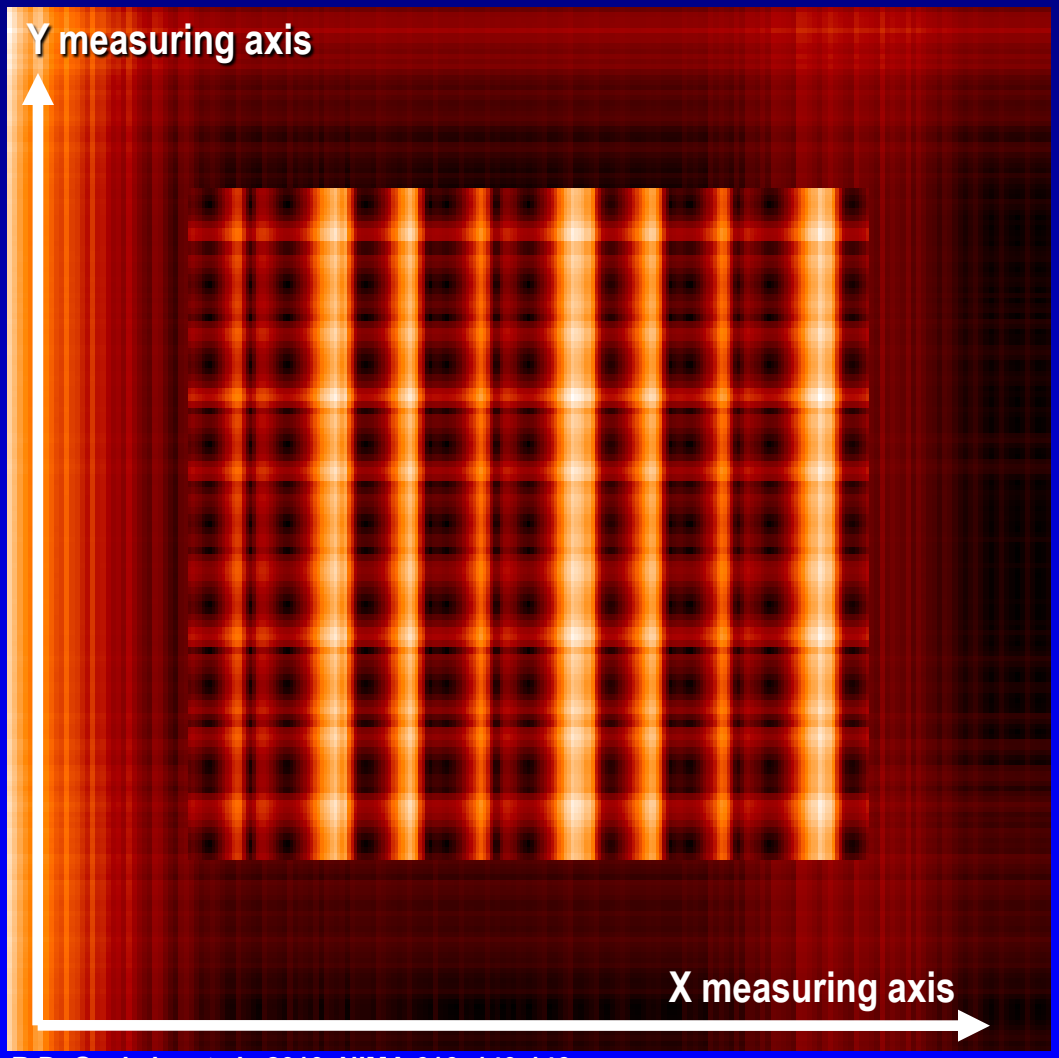



**(a) Sagittal angle error**

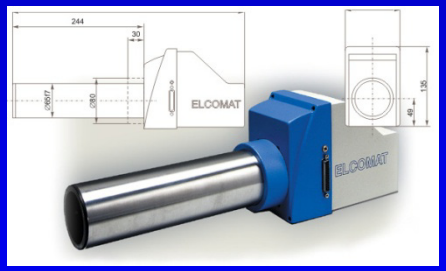
**(b) Longitud. angle error**
(relevant error)

# 2D Autocollimator Calibration: Simulation




R.D. Geckeler et al. 2010, NIMA 616, 140-146

**Important note:**
**AC axes operate independently - AC does not measure spherical angular coordinates**

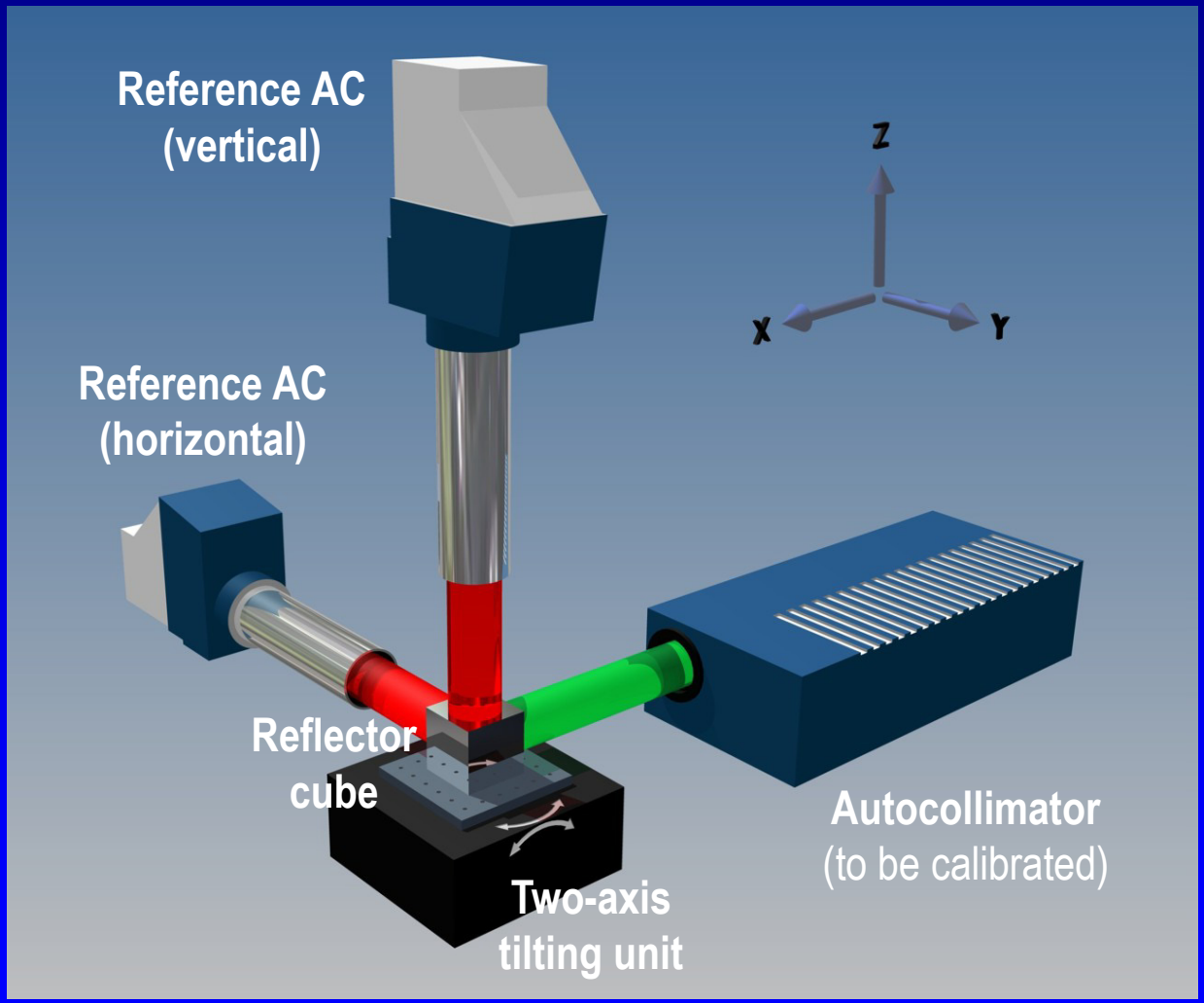



**Simulation from real 1D AC calibrations**

**Angle deviations (pv)**
**Full frame: 0.68 arcsec (3.3 µrad)**
**Insert: 0.07 arcsec (0.3 µrad)**

# SA²C – *Solid Angle* Autocollimator Calibrator

**Advancing from plane angle to *solid* angle**




## Solid angle

> [ ± > 1000 arcsec ]²

## Positioning: fast & precise

> Duration: < 1 s
> 10 x faster than WMT220
> Repeatability: ±0.02 arcsec

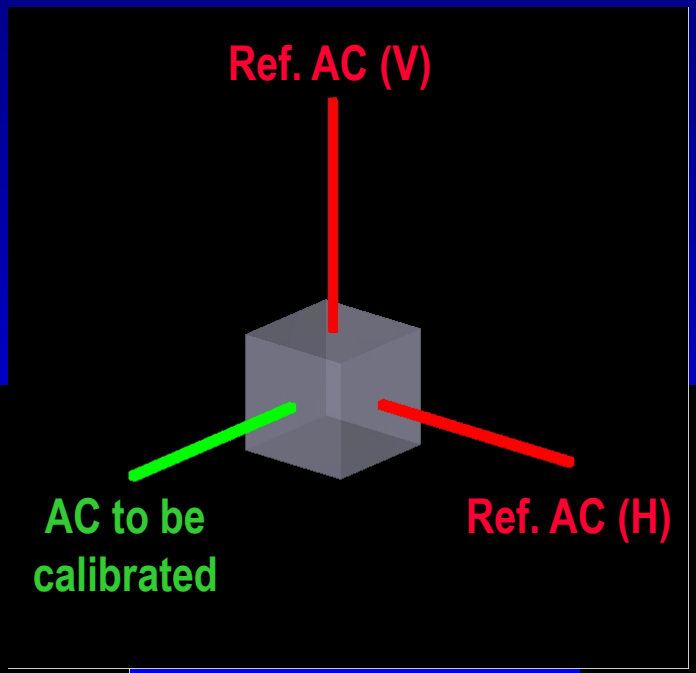
## Reference AC

> Decoupling measurement horizontal & vertical angle
> Uncertainty: 0.005 arcsec

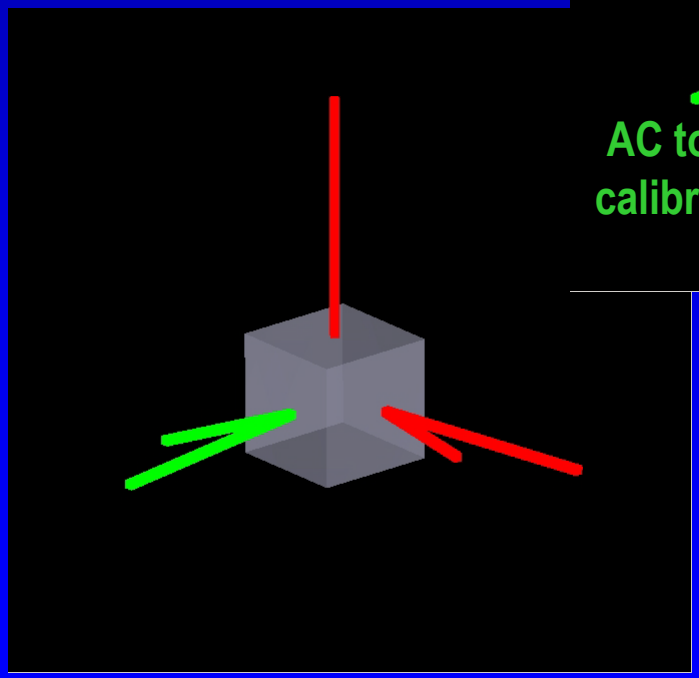
## Traceability

> PTB primary angle standard (plane angle) WMT220

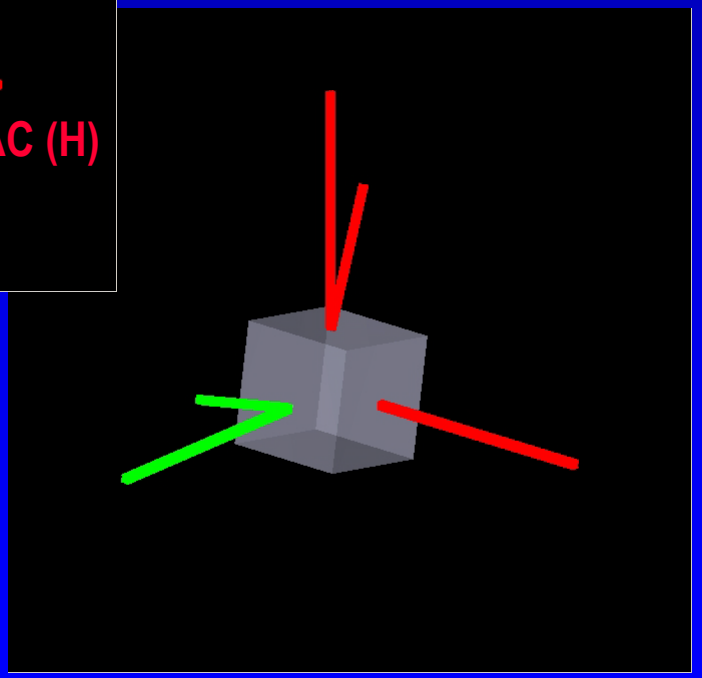
# Decoupling of Measurement Axes: 2D = 2 x 1D!



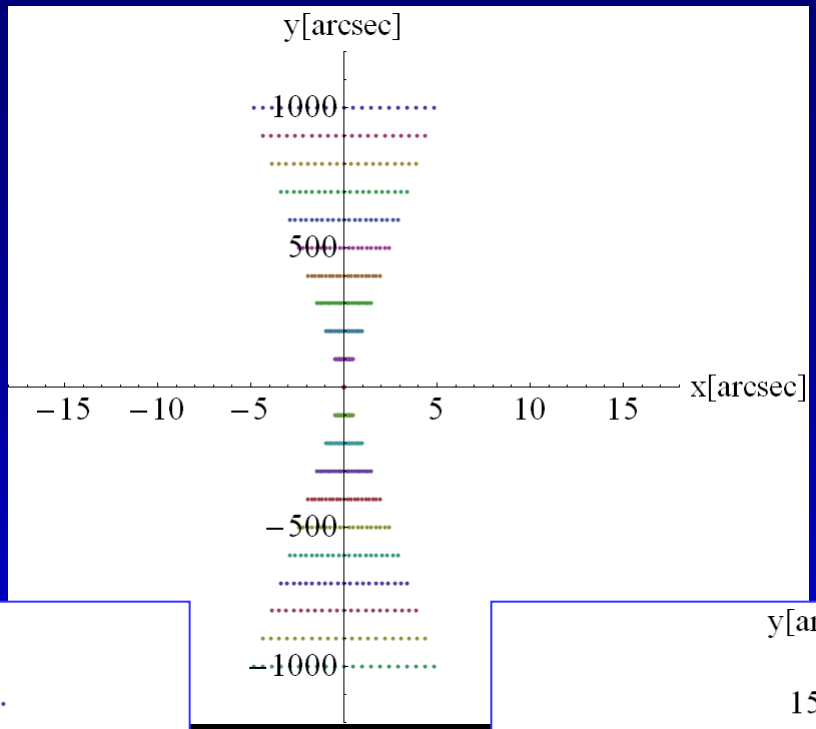

Yaw rotation
Ref. AC (H) engaged

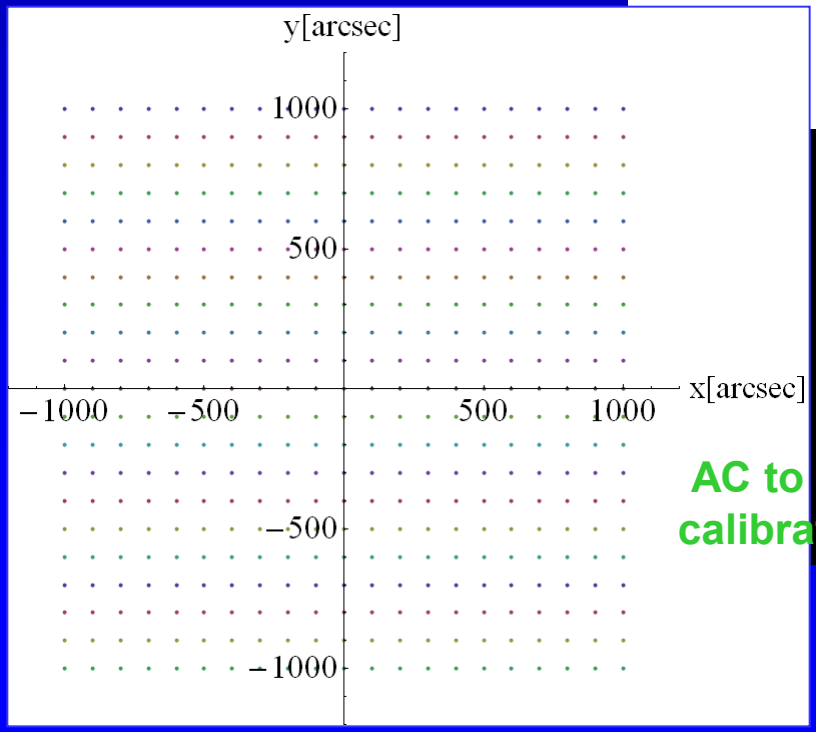


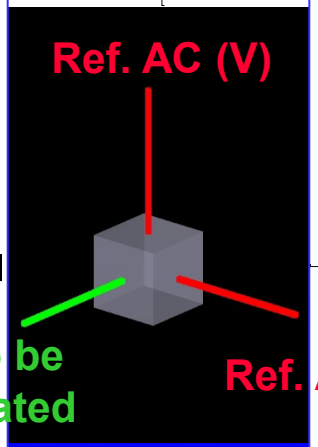
Pitch rotation
Ref. AC (V) engaged

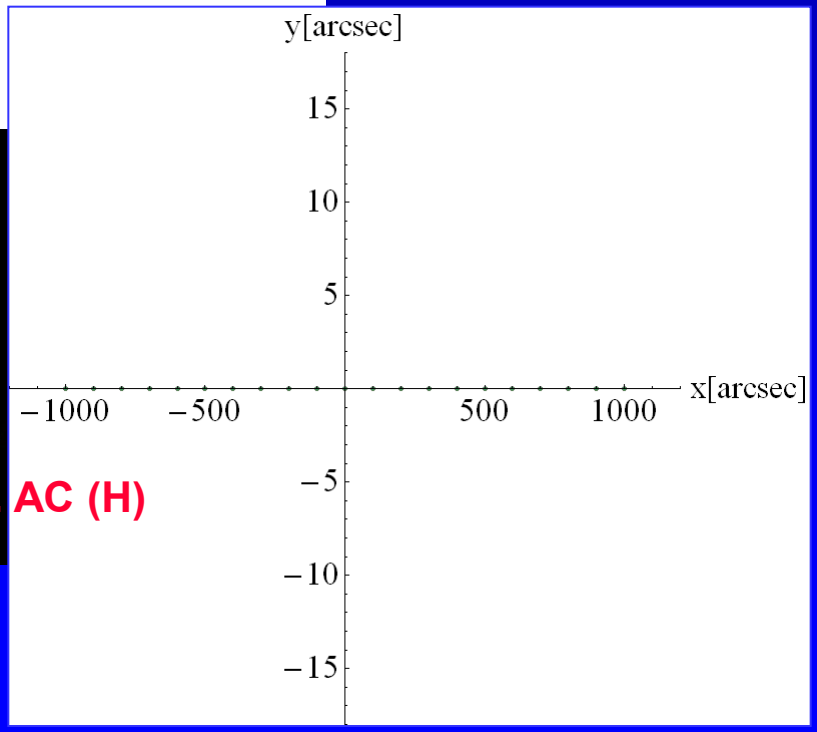


# Crosstalk of AC Measuring Axes



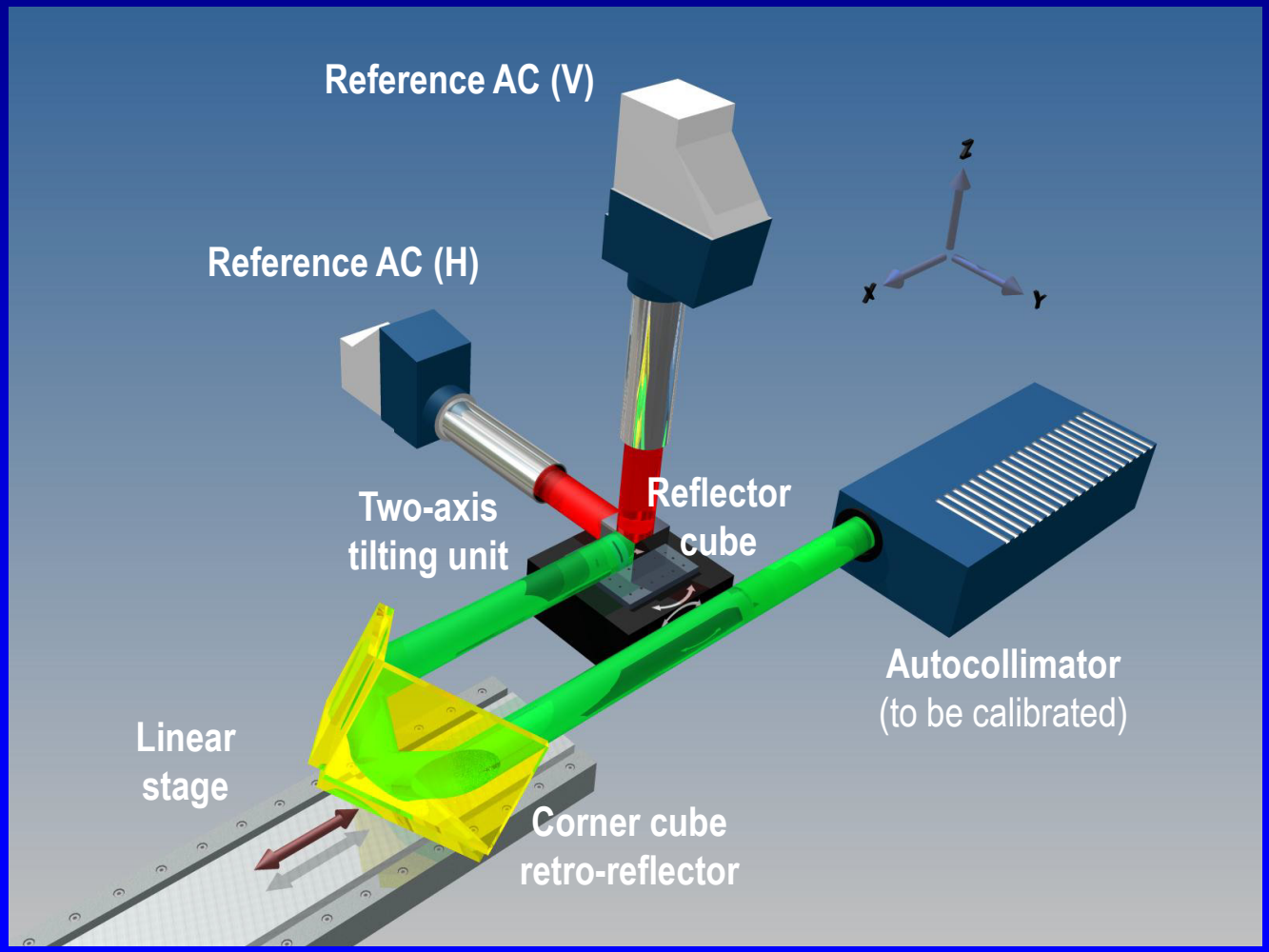



# SA²C – *Solid Angle* Autocollimator Calibrator

## Advancing from plane angle to *solid* angle

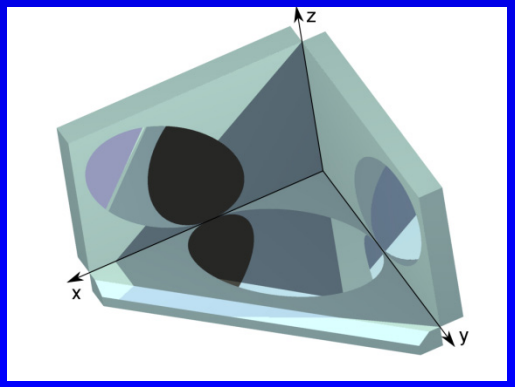



## Extension:

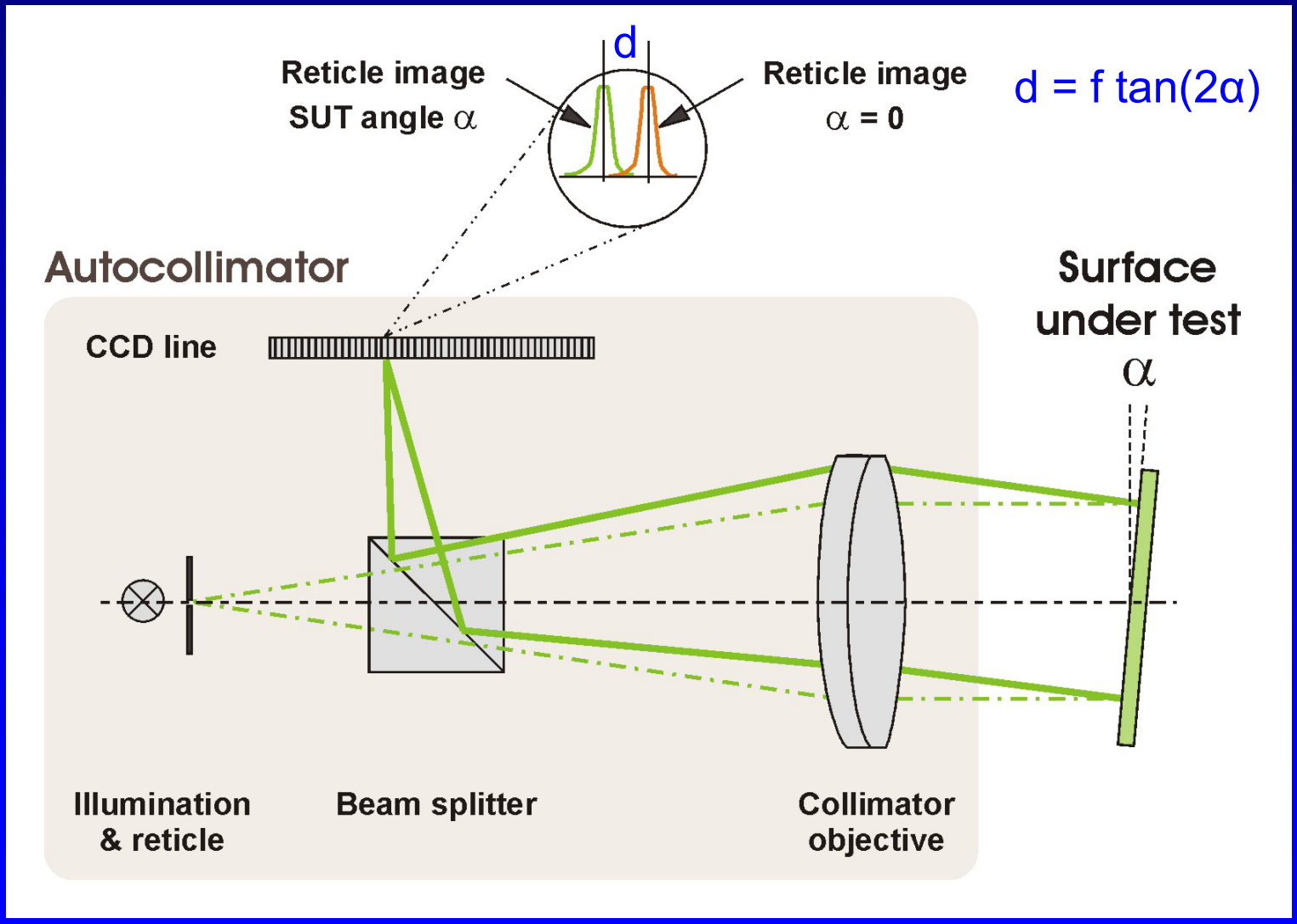
## Corner cube retro-reflector

> Flexible AC path length up to 1.5 m (synchrotron optics)

> Dynamic change of path length



# Electronic Autocollimator (AC): Principle



# AC Angle Response: *External* Parameters

## Aperture stop

> Diameter & shape

> Position

- Longitudinal: along AC's optical axis
- Lateral: perpendicular to optical axis

## Surface under test (SUT)

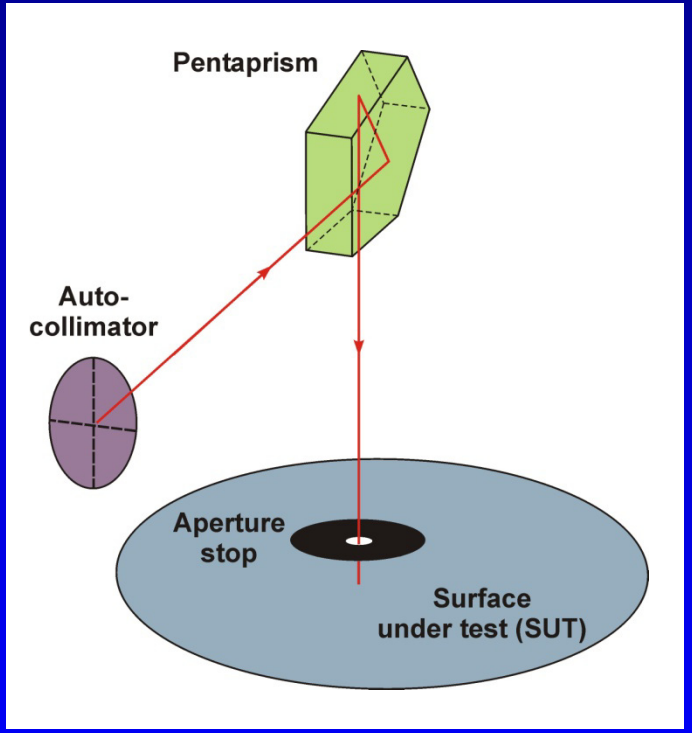
> Reflectivity

> Curvature

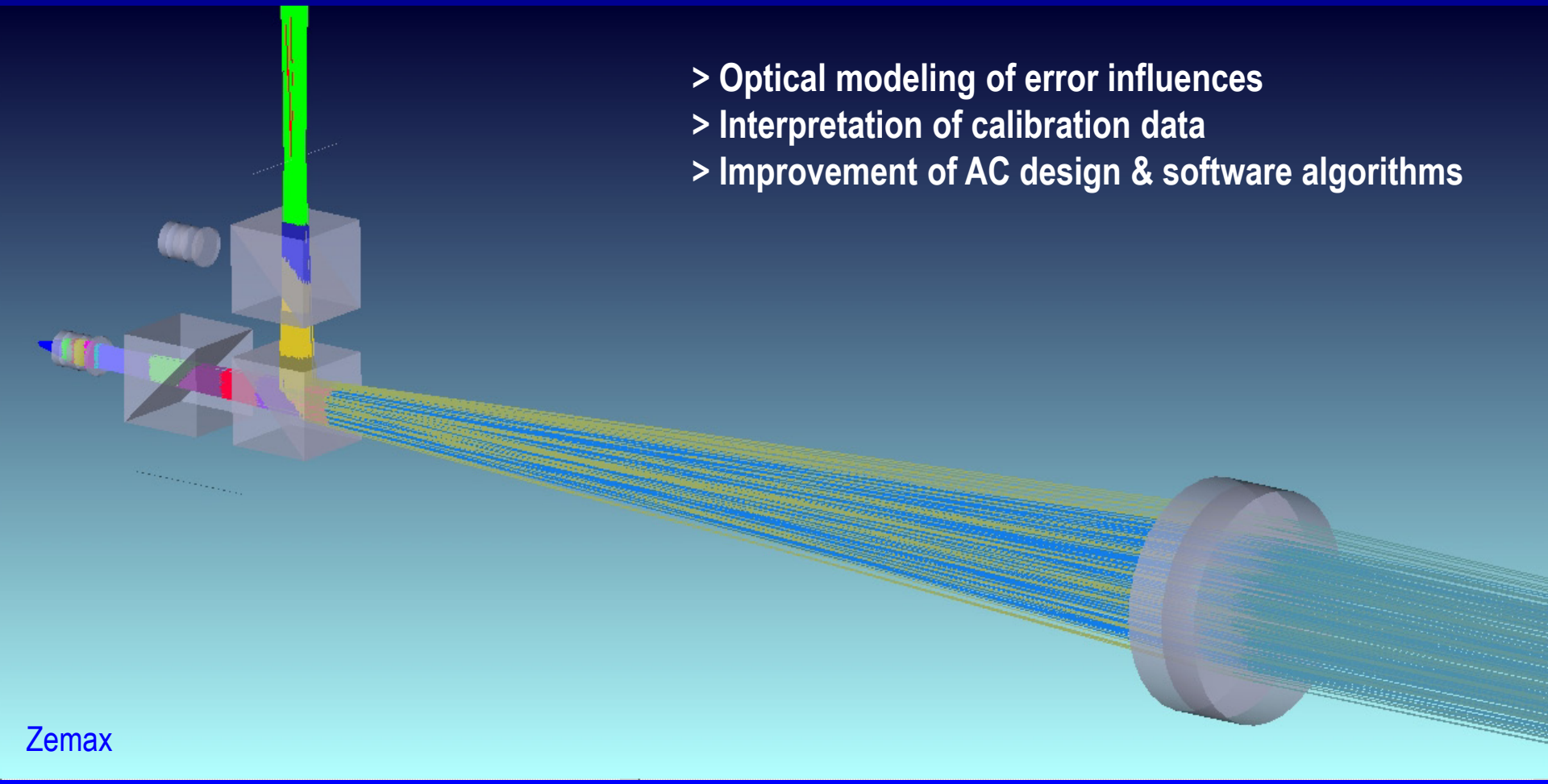
> Beam path length (AC to SUT)

> Sagittal slope

- Cross-talk AC measuring axes
- 2D calibration



# Optical Ray Tracing of Autocollimator



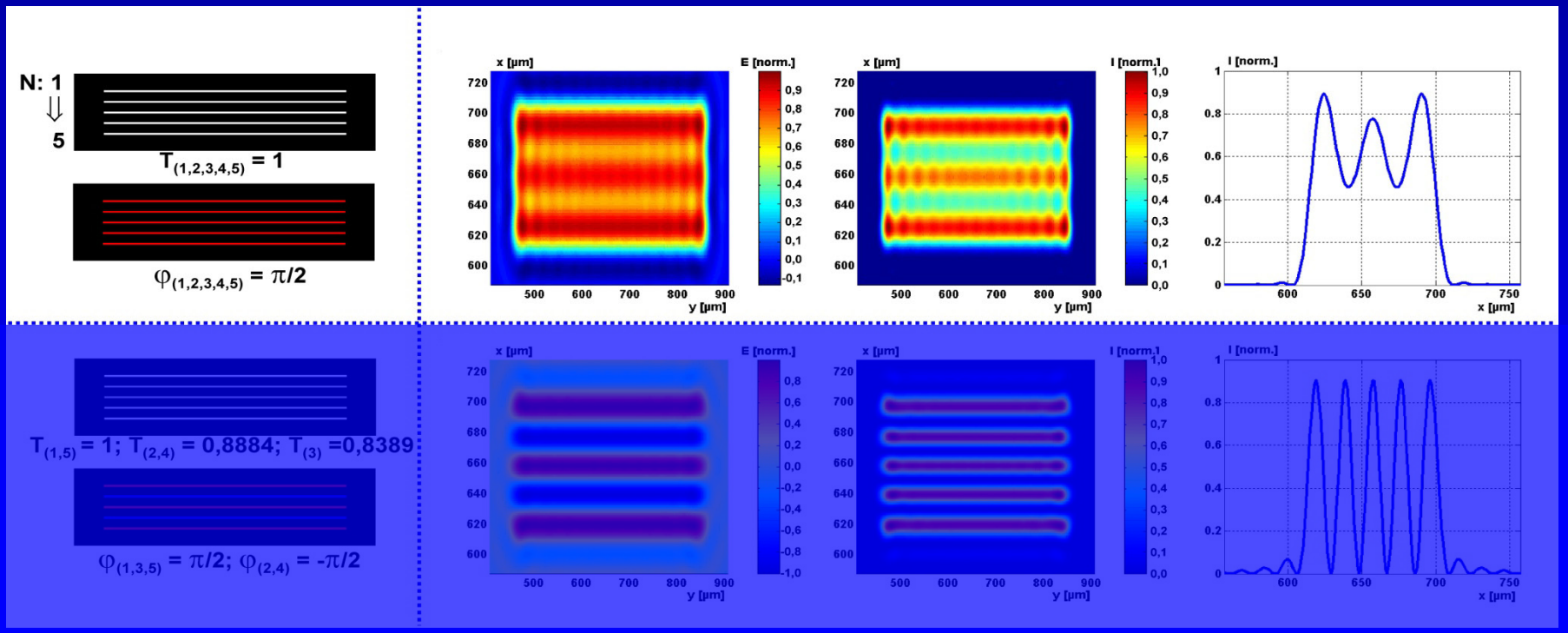
> Optical modeling of error influences
> Interpretation of calibration data
> Improvement of AC design & software algorithms

Zemax

# Phase-Shifting Reticles (PSR)

## Objective: Improve AC performance at small (1 mm) apertures

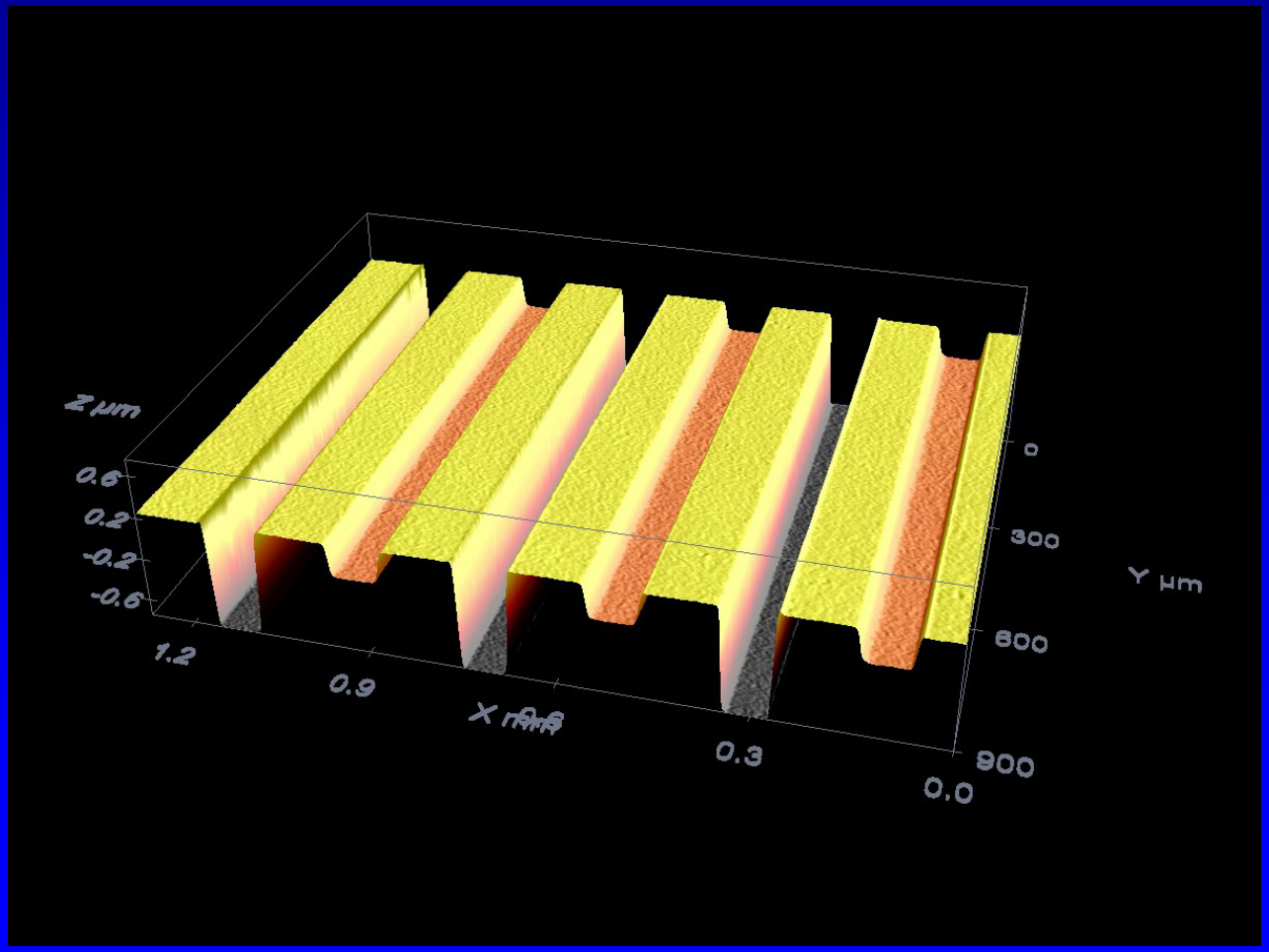
| Reticle transmission & phase | E field | Intensity | Intensity (profile) |
|---|---|---|---|




Patent G. Fütterer 2006; collaborative project with Möller-Wedel Optical, Wedel, Germany

# Phase-Shifting Reticles (PSR)

**Objective: Improve AC performance at small (1 mm) apertures**




## Topography Map

> 720 nm difference in groove depth

> Effective phase shift of $\pi$ (transmission)

## Status

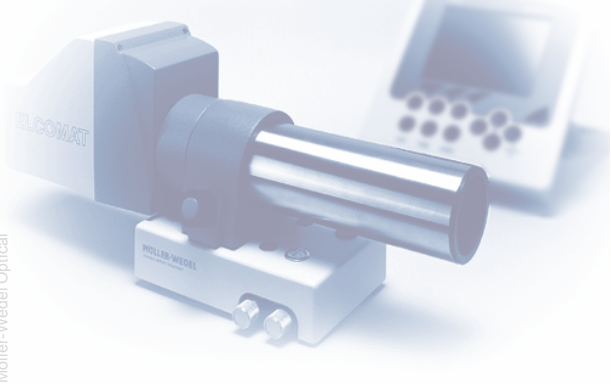
> PSR integration with autocollimator in progress at MWO

## Autocollimator Calibration

- Just et al. (2003), Metrologia
- Geckeler et al. (2002), Techn. Messen.

**NMIs, DAkkS, manufacturers, users**

**EURAMET.L-K3.2009 key comparison**




Möller-Wedel Optical

## Small Apertures

- Fütterer (2007), Proc. SPIE
- Fütterer (2006), Patent
- Fütterer (2005), Proc. SPIE

**Möller-Wedel Optical**

**- Phase-shifting reticles**

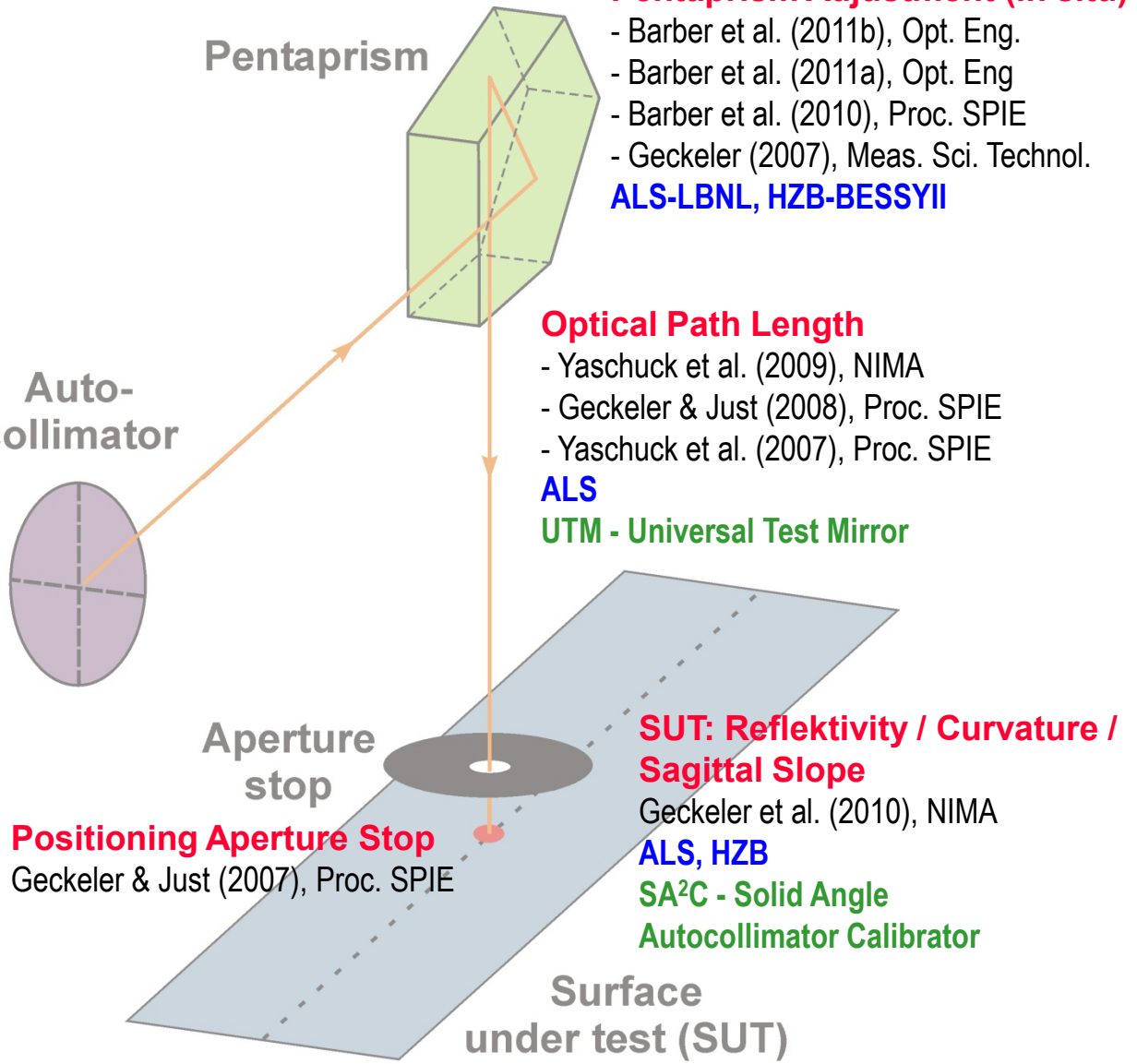
**- Ray tracing**

**- PhD student**

## THz Autocollimators

Hils et al. (2008), Optics Express

**Univ. Frankfurt**




## Pentaprism Adjustment (in situ)

- Barber et al. (2011b), Opt. Eng.
- Barber et al. (2011a), Opt. Eng
- Barber et al. (2010), Proc. SPIE
- Geckeler (2007), Meas. Sci. Technol.

**ALS-LBNL, HZB-BESSYII**

## Optical Path Length

- Yaschuck et al. (2009), NIMA
- Geckeler & Just (2008), Proc. SPIE
- Yaschuck et al. (2007), Proc. SPIE

**ALS**

**UTM - Universal Test Mirror**

## Positioning Aperture Stop

Geckeler & Just (2007), Proc. SPIE

## SUT: Reflektivity / Curvature / Sagittal Slope

Geckeler et al. (2010), NIMA

**ALS, HZB**

**SA²C - Solid Angle Autocollimator Calibrator**