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Proposal for a Universal Test Mirror for Characterization of Slope Measuring Instruments

Valeriy V. Yashchuk,[a)] Wayne R. McKinney,[a)] Tony Warwick,[a)]
Tino Noll,[b)] Frank Siewert,[b)] Thomas Zeschke,[b)] Ralf D. Geckeler [c)]

[a)] Lawrence Berkeley National Laboratory, Berkeley, California, 94720
[b)] BESSY mbH, Albert-Einstein-Str. 15, 12489 Berlin, Germany
[c)]Physikalische-Technische Bundesanstalt Braunschweig (PTB),
Bundesallee 100, 38116 Braunschweig, Germany

vvyashchuk@lbl.gov

Outline

- *Motivation:*

  Systematic errors and requirements for precise calibration

  Limitations of the existing calibration methods

  "Enjoy your achievements as well as your plans"

  Max Ehrmann, "Desiderate" (1948)

- *Concept of a Universal Test Mirror and optimal calibration algorithm*

- *Design consideration for a Universal Test Mirror*

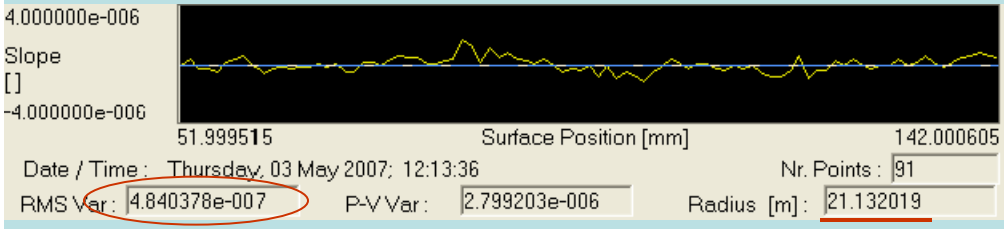
- *Conclusions*

Systematic errors and requirements for precise calibration

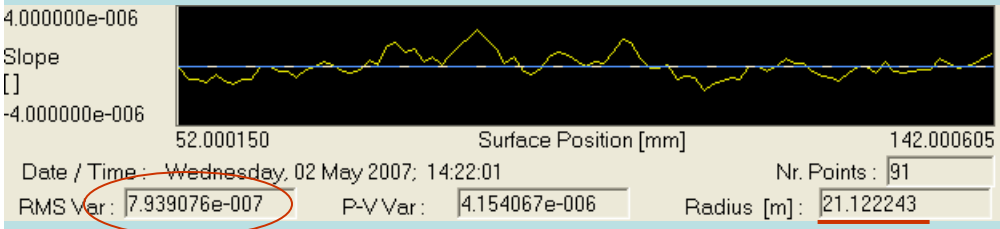
1. High performance calibration must account for peculiarities of optics under test and an experimental arrangement.

2. Calibration method must be universal, applicable to variety of optics and experimental arrangements

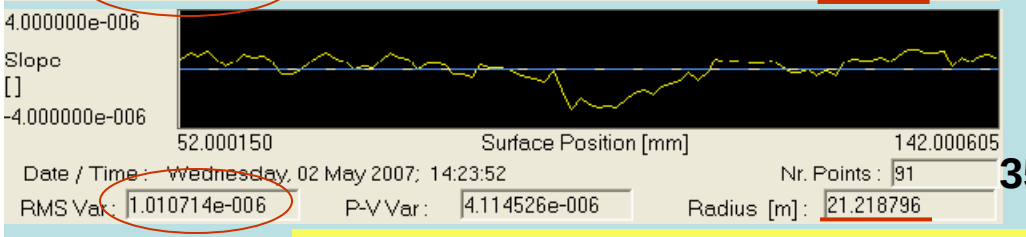
*Grating blank measured with upgraded ALS LTP-II *)*



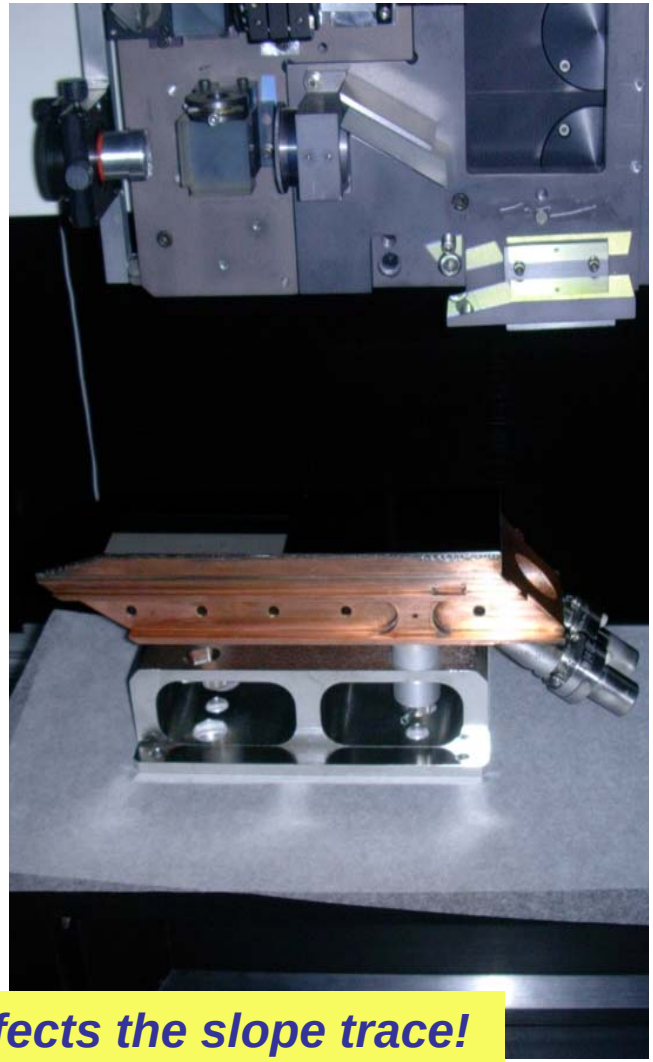
50mm



150mm



350mm

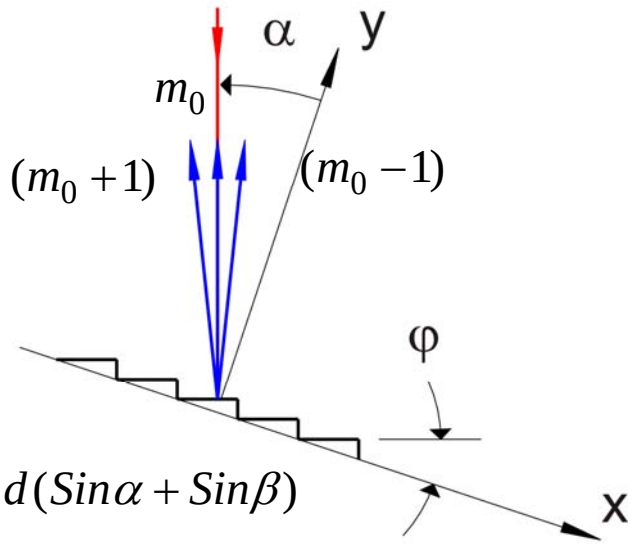


The distance to the surface under test affects the slope trace!

) J. L. Kirschman, E. E. Domning, K. D. Franck, S. C. Irick, A. A. McDowell, W. R. McKinney, G. Y. Morrison, B. V. Smith, T. Warwick, V. V. Yashchuk, "Flat-field calibration of CCD detector for Long Trace Profiler," SPIE Proc.* ***6704**-18 (2007) – this conference*

Limitations of the existing calibration methods

Calibration with a diffraction grating [1)]



$$m\lambda = d(Sin\alpha + Sin\beta)$$

Littrow configuration: $\alpha = \beta = \varphi$

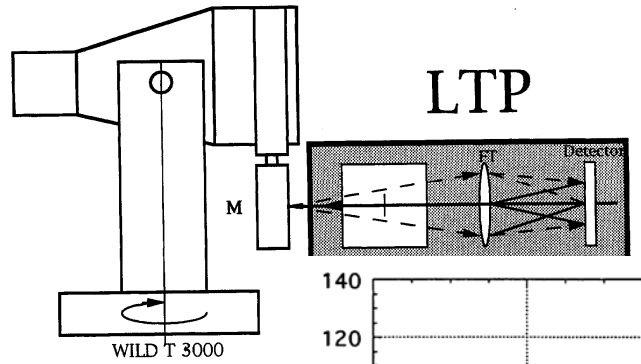
$$m_0 = {2d}/{\lambda}\, Sin\varphi$$

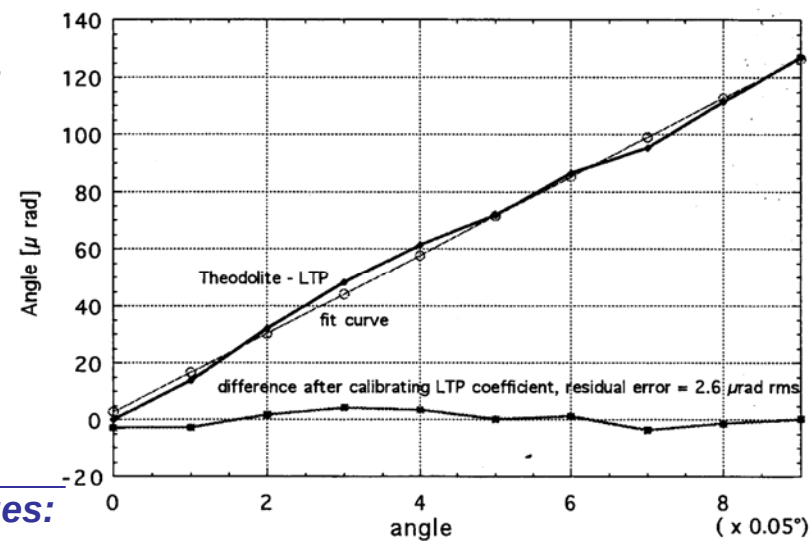
Disadvantages:

- ***provides linear approximation of the calibration***
- ***limited number of calibration points***
- ***depends on fabrication accuracy of the grating***
- ***requires calibration of the laser wavelength***

[1)] S. C. Irick, *Angle calibration of the long trace profiler using a diffraction grating,* Light Source Note LSBL-160 (Berkeley, 1992).

Calibration with a high resolution (0.03”) theodolite [2)]





Disadvantages:

- ***provides linear approximation of the calibration***
- ***depends on position of the reference mirror***
- ***manual operation, therefore limited number of calibration points***
- ***requires precise calibration of the theodolite***

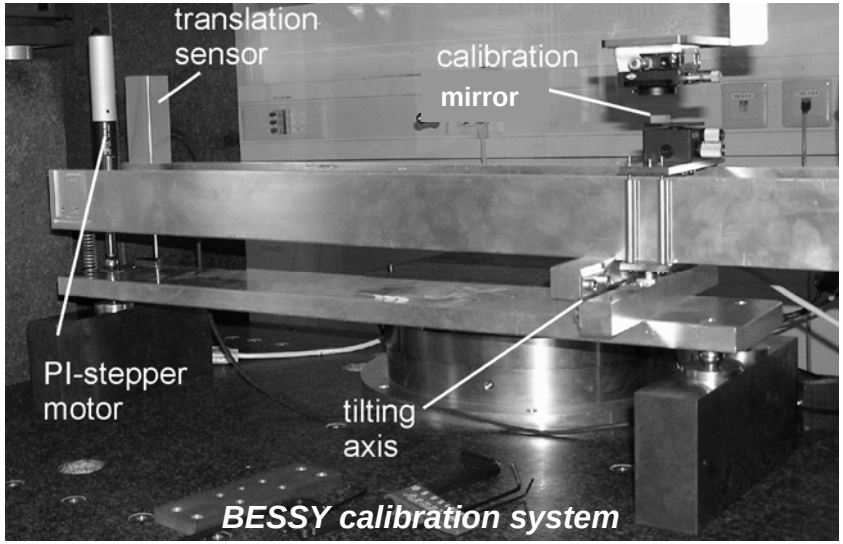
[2)] Shinan Qian, G. Sostero, P.T. Takacs, *Precision calibration and systematic error reduction in the long Trace profiler, Opt. Engineering 39(1), 304-10 (1999).*

High performance of the NOM is due to very careful calibration!

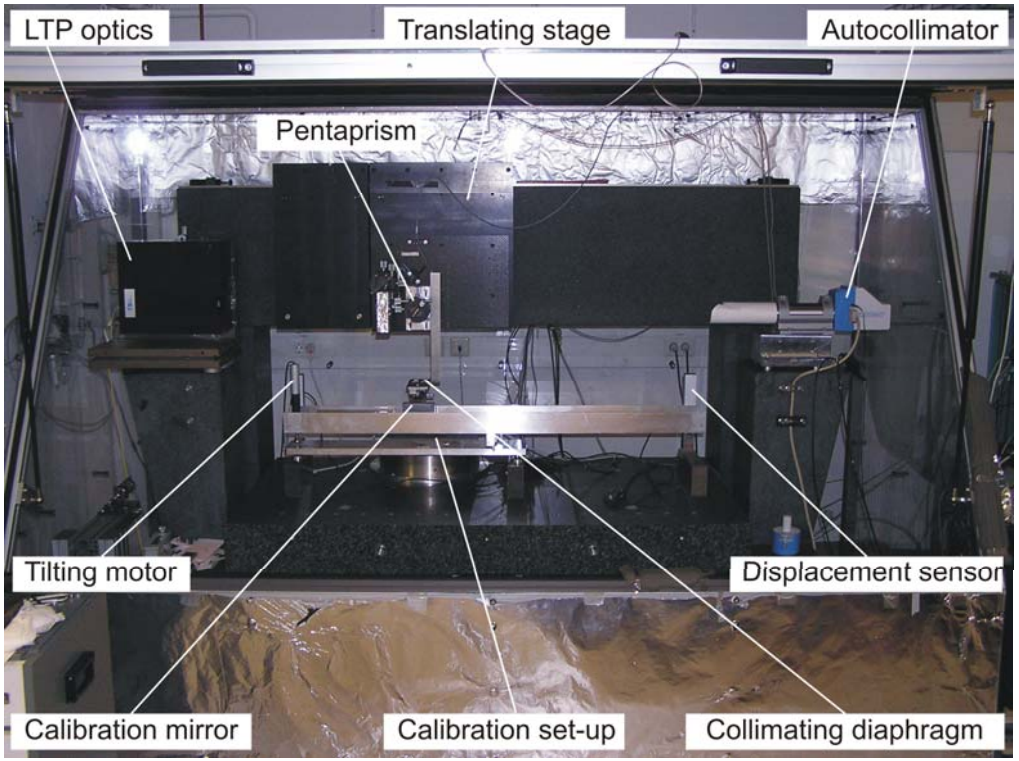
The BESSY NOM provides the world-best sensitivity to surface slope measurements:

~0.25 μrad (rms) for a significantly curved mirror and

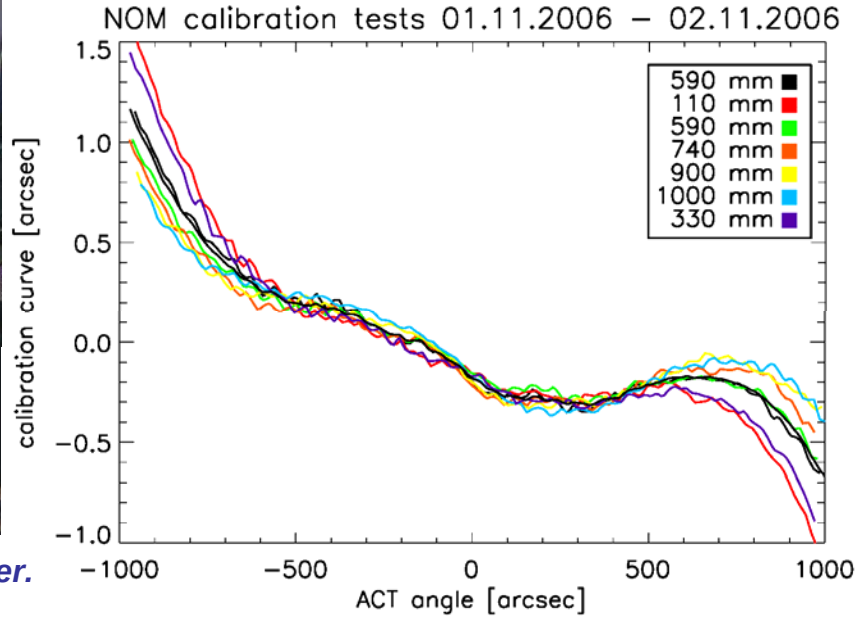
~0.05 μrad (rms) for a flat mirror.



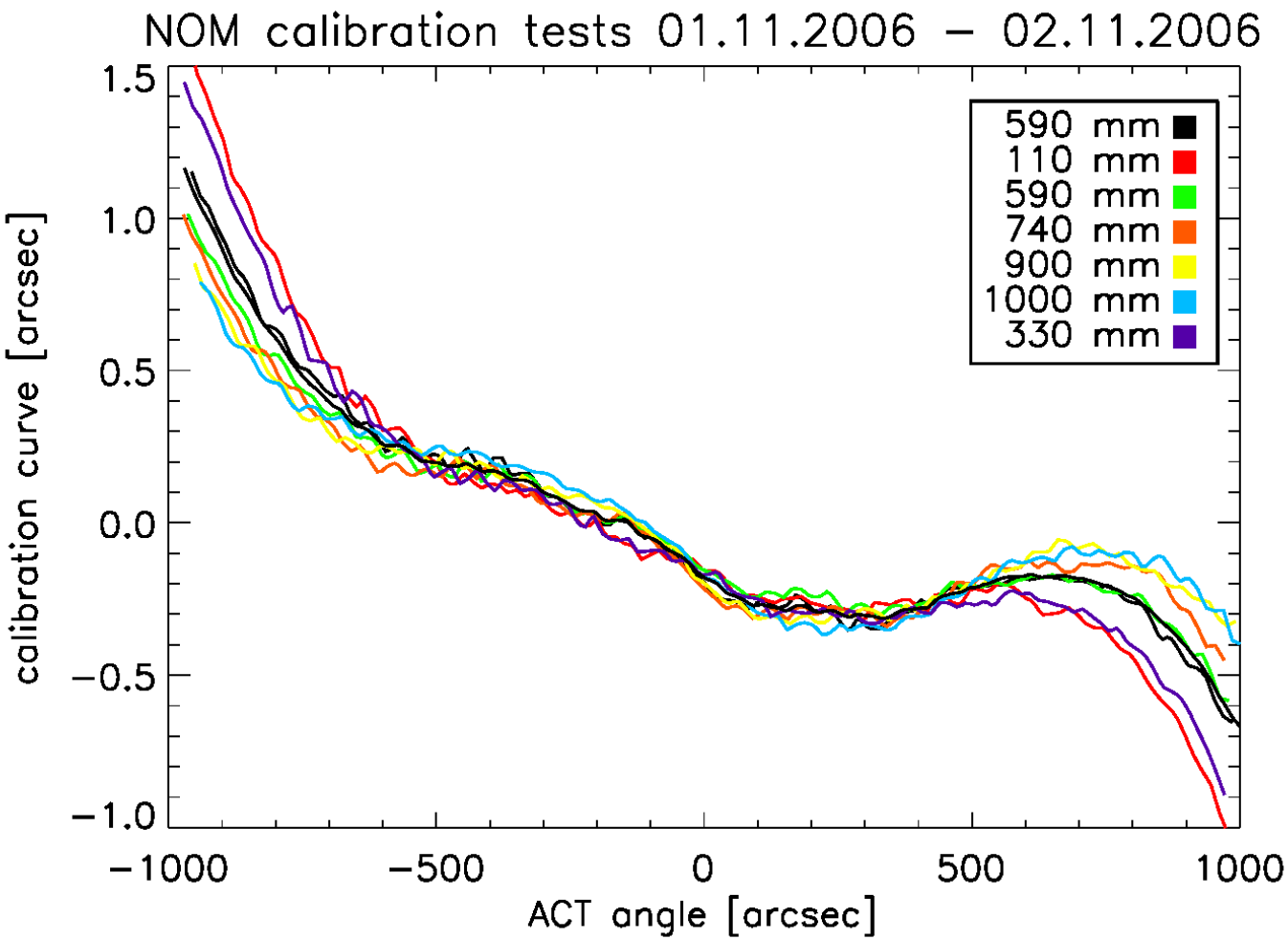
BESSY calibration system



BESSY calibration set-up installed for calibration of the NOM profiler.

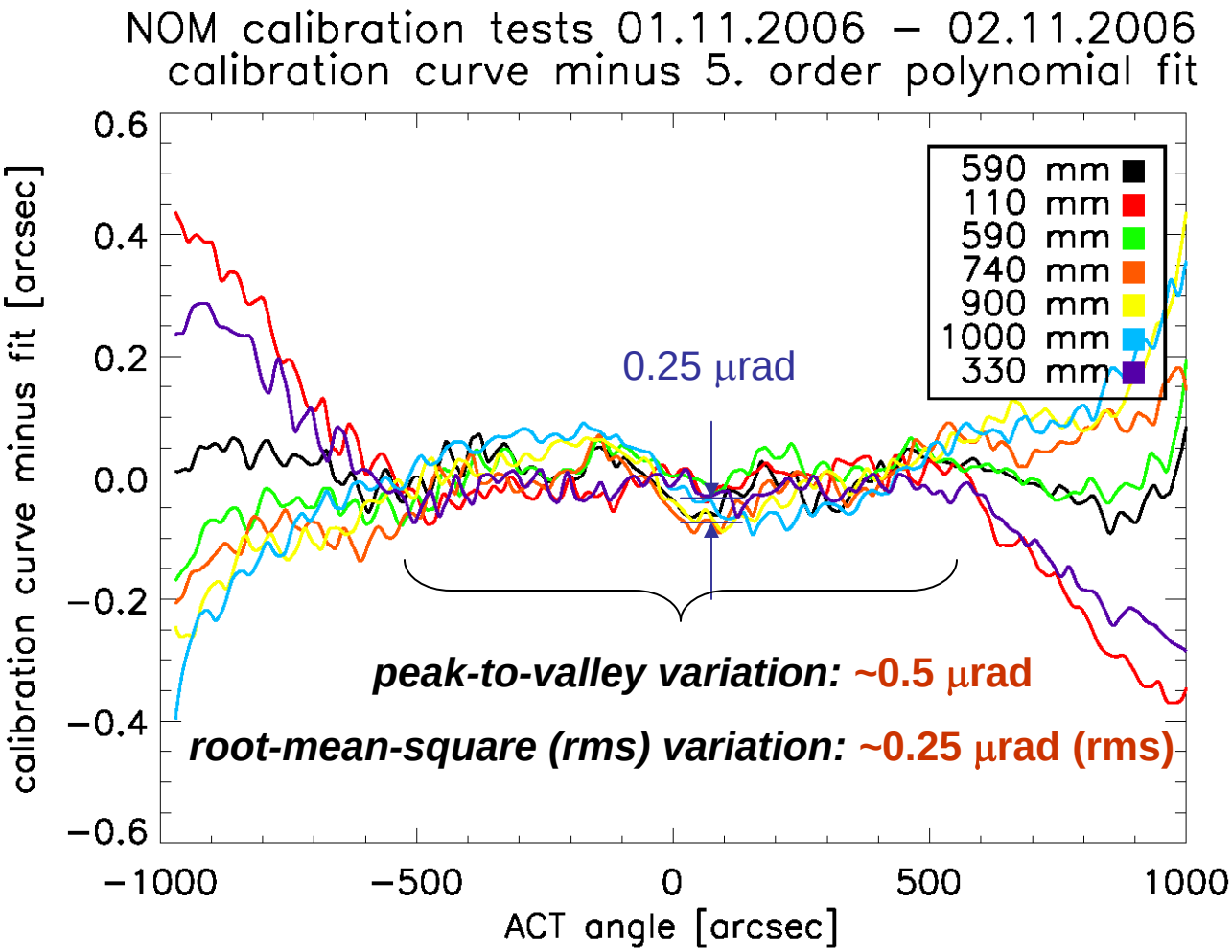


Importance of non-linear calibration!!!



Calibration curves of the NOM autocollimator arm obtained at different positions of the calibration mirror. A calibration curve represents the difference between the slope angle measured with the NOM and the tilting angle of the calibration mirror as a function of the mirror tilting angle.

Importance of calibration with high spatial frequency



Calibration curves of the NOM autocollimator arm obtained at different positions of the calibration mirror.
Firth-order polynomial is subtracted.

Concept of
Universal Test/calibration Mirror (UTM)

Requirements:

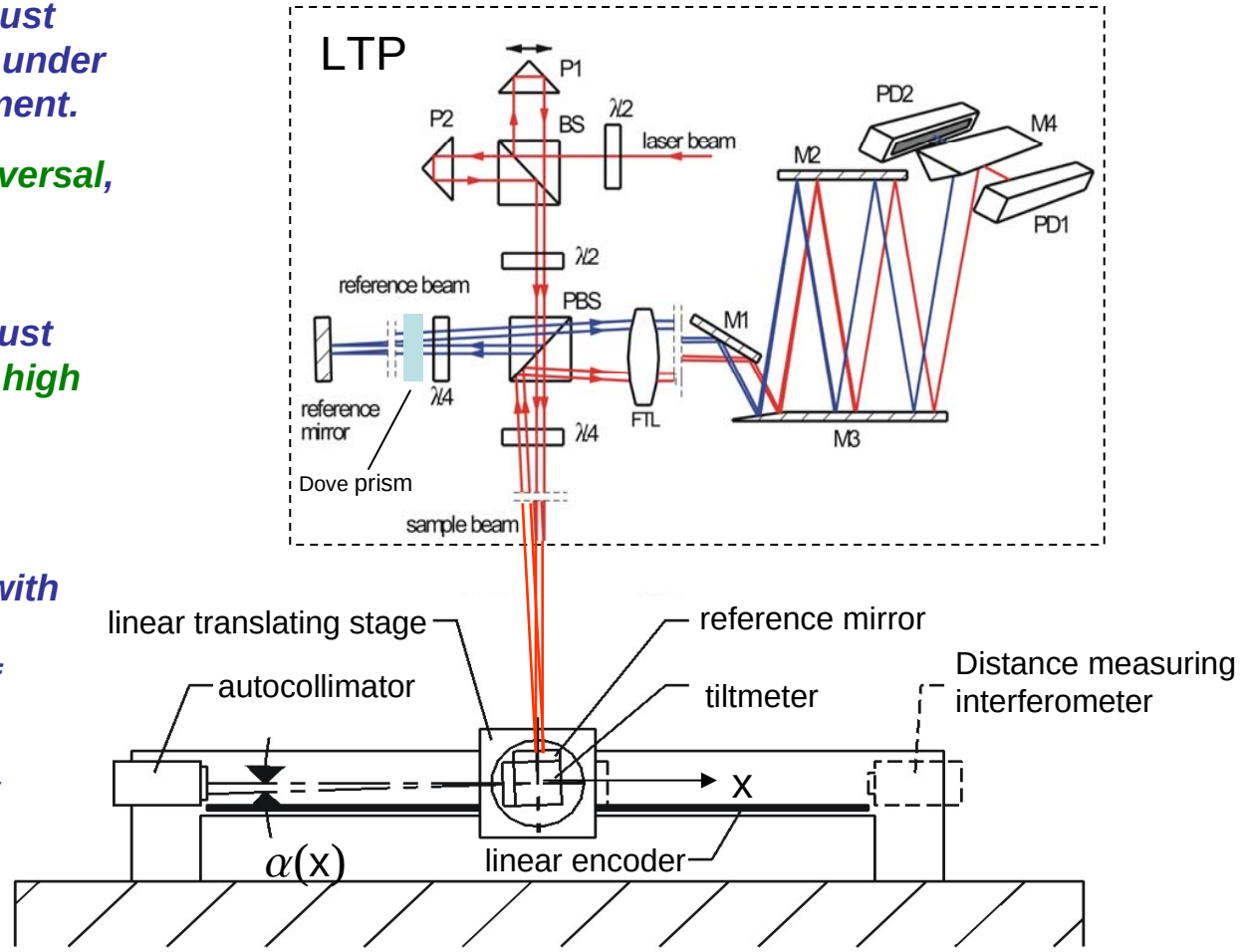
1. *High performance calibration must account for peculiarities of optics under test and an experimental arrangement.*

2. *Calibration method must be universal, applicable to variety of optics and experimental arrangements.*

3. *Dedicated calibration system must provide nonlinear calibration with high special frequency resolution.*

Idea:

- *Generate a specific test surface with an 'ideal' quality and with a shape absolutely identical to the shape of the surface under test (SUT).*
- *Can be accomplished with a very high quality mirror and extremely precise translation and tilt controls*



An extremely precise tilting stage (accuracy <0.05 µrad) is the cornerstone of a UTM system

Optimal calibration algorithm

Random-noise-free measurement with the mirror under test

No more measurements with the mirror under test;

All other measurements are made with the UTM system in order to find a unique trace of systematic errors and estimate error of the finding.

Even after the first test measurement, the error of the finding has to be much smaller than the systematic error.

1. Measure slope trace $\alpha_{MIRR}(t)$ with the mirror under test:

$$\alpha_{MIRR}(x) = \alpha_{SUT}(x) + \alpha^{M}_{SYS}(x)$$

2. Use slope trace $\alpha_{MIRR}(t)$ as a "defined figure" (DF) for the first UTM scan: $\alpha_{DF,1}(x) = \alpha_{MIRR}(x)$

3. Simultaneously and synchronously scan the UTM and the LTP with $\alpha_{DF,1}(x)$ to measure:

$$\alpha_{TEST,1}(x) = \alpha_{DF,1}(x) + \alpha^{T}_{SYS,1}(x) \quad \textit{or}$$

$$\alpha_{TEST,1}(x) = [\alpha_{SUT}(x) + \alpha^{M}_{SYS}(x)] + \alpha^{M}_{SYS}(x) + \delta\alpha^{M}_{SYS,1}(x) \quad \boxed{\alpha^{M}_{SYS}(x) >> \delta\alpha^{M}_{SYS,1}(x)}$$

and find first approximation for systematic error of the measurement with the mirror:

$$\alpha^{T}_{SYS,1}(x) = \alpha_{TEST,1}(x) - \alpha_{DF,1}(x) \approx \alpha^{M}_{SYS}(x)$$

4. For the second iteration, the DF function is

$$\alpha_{DF,2}(x) = \alpha_{MIRR}(x) - \alpha^{T}_{SYS,1}(x) = \alpha_{SUT}(x) + \delta\alpha_{SUT,2}(x) = \underline{\alpha_{SUT}(x) - \delta\alpha_{SYS,1}(x)}$$

5. The next measurements with the UTM gives:

$$\alpha_{TEST,2}(x) = \alpha_{DF,2}(x) + \alpha^{T}_{SYS,2}(x) = \alpha_{MIRR}(x) - \alpha^{T}_{SYS,1}(x) + \alpha^{T}_{SYS,2}(x) \quad \textit{or}$$

$$\alpha_{TEST,2}(x) = \alpha_{SUT}(x) + \delta\alpha_{SUT,2}(x) + \alpha^{M}_{SYS}(x) + \delta\alpha^{M}_{SYS,2}(x)$$

and use rms variation of

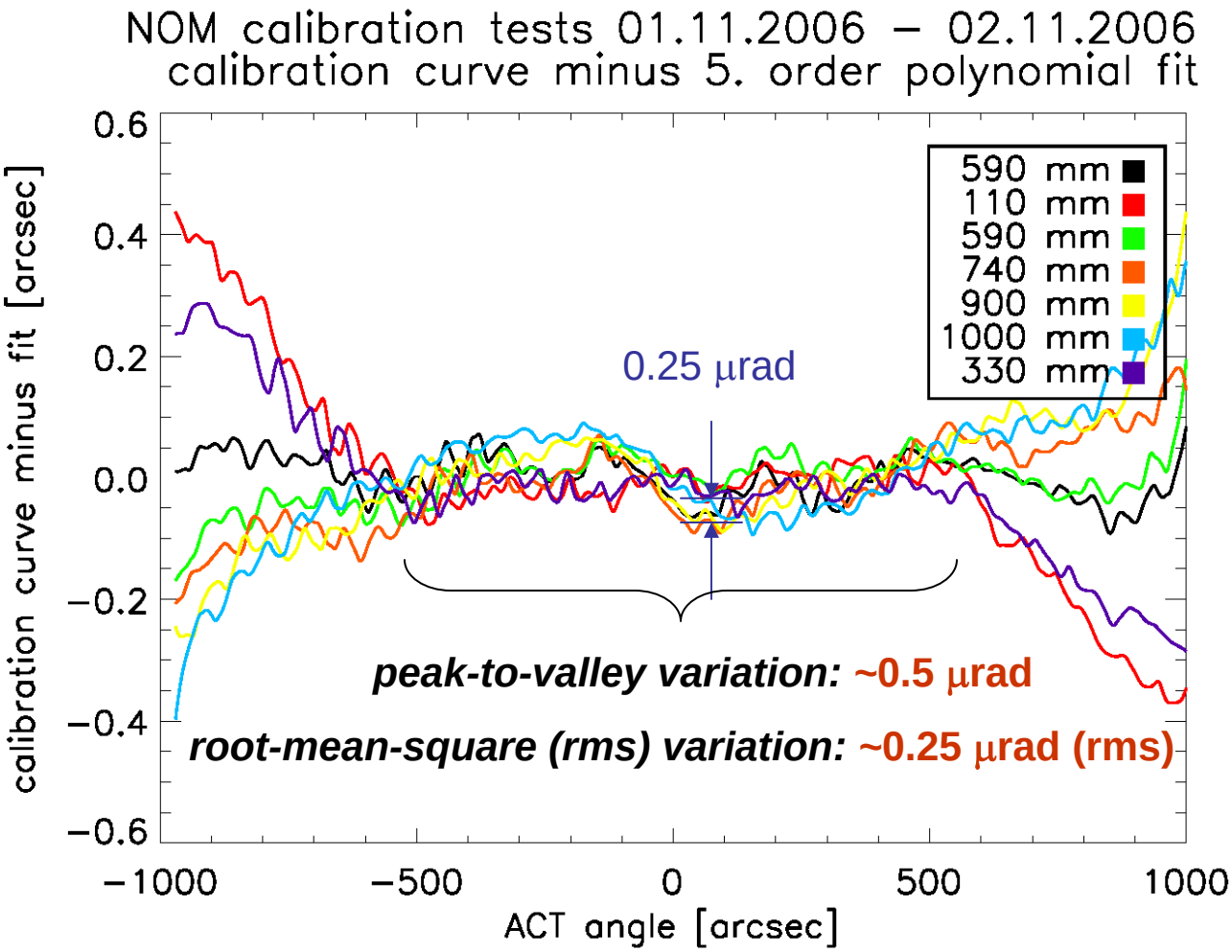
$$\boxed{\delta\alpha_{2,1} = \alpha_{TEST,2}(x) - \alpha_{MIRR}(x) = \alpha^{T}_{SYS,2}(x) - \alpha^{T}_{SYS,1}(x) \approx \alpha^{T}_{SYS,2}(x) - \alpha^{T}_{SYS,1}(x) + \delta\alpha^{M}_{SYS,2}(x) = \delta\alpha_{SUT,2}(x)}$$

6. Find the next DF function and perform measurement with the UTM

$$\alpha_{DF,3}(x) = \alpha_{MIRR}(x) - \alpha^{T}_{SYS,2}(x) \quad \ldots$$

$$\boxed{rms(\delta\alpha_{N+1,N}) \to 0}$$

Importance of calibration with high spatial frequency



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$$\boxed{\delta\alpha_{2,1} = \alpha_{TEST,2}(x) - \alpha_{MIRR}(x) = \alpha^{T}_{SYS,2}(x) - \alpha^{T}_{SYS,1}(x) \approx \alpha^{T}_{SYS,2}(x) - \alpha^{T}_{SYS,1}(x) + \delta\alpha^{M}_{SYS,2}(x) = \delta\alpha_{SUT,2}(x)}$$

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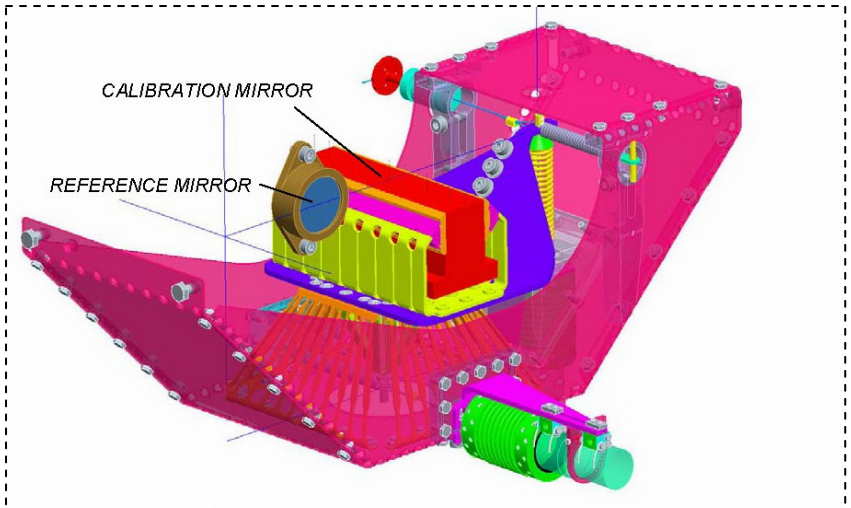
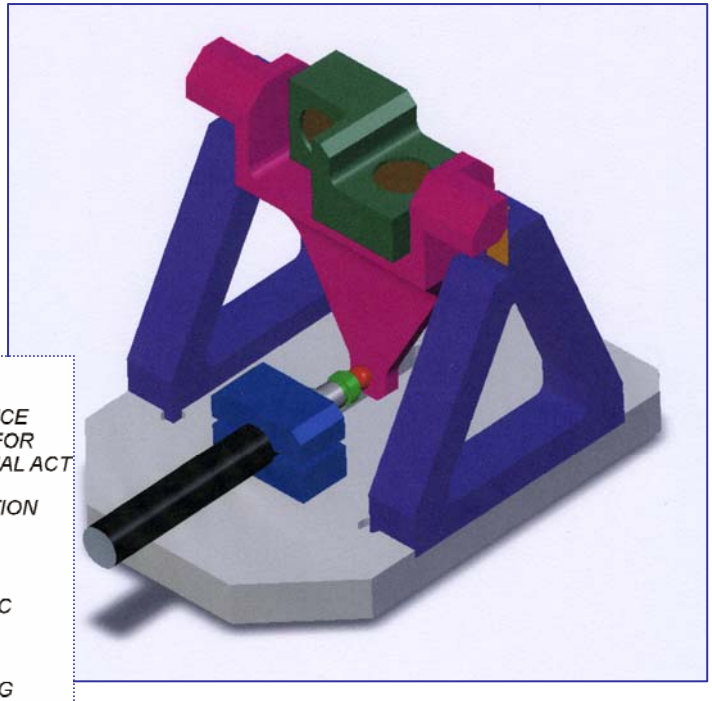
$$\boxed{rms(\delta\alpha_{N+1,N}) \to 0}$$

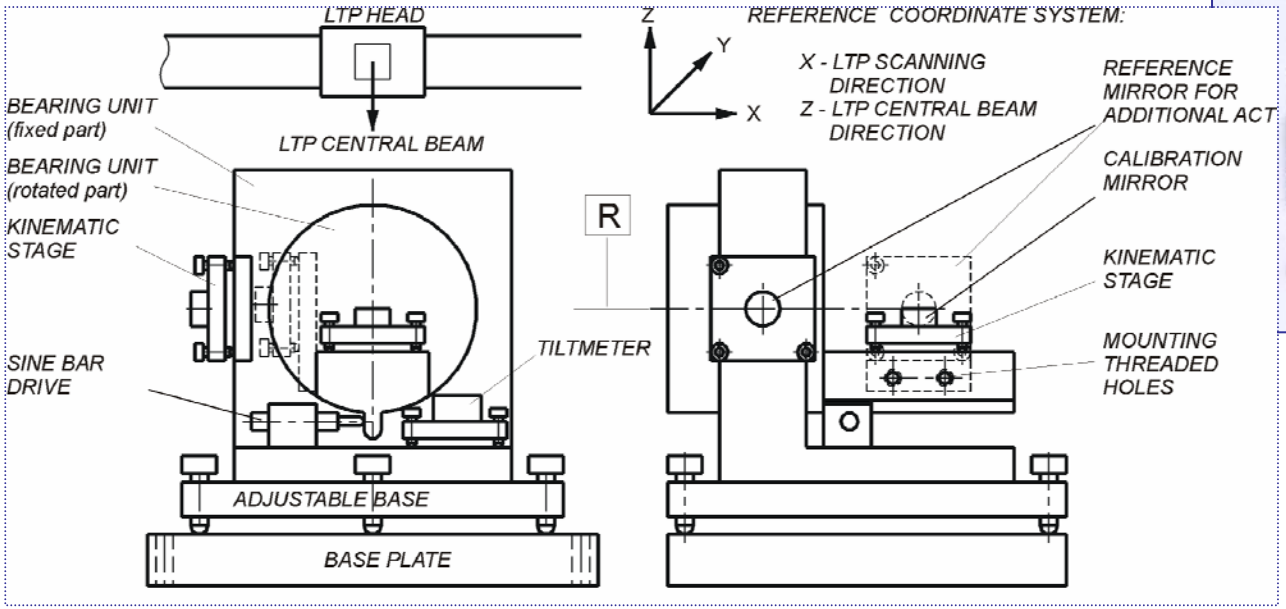
Current developments



Mirror adjustment system designed at BESSY for an X-ray Autocorrelator set-up. The system is planned to be used as a prototype of the UTM calibration mirror tilting/aligning stage developed under ALS-BESSY collaboration.

High-precision tilt stage is under development at the ALS in collaboration with BESSY and PTB





must provide an accuracy of

<0.05 µrad

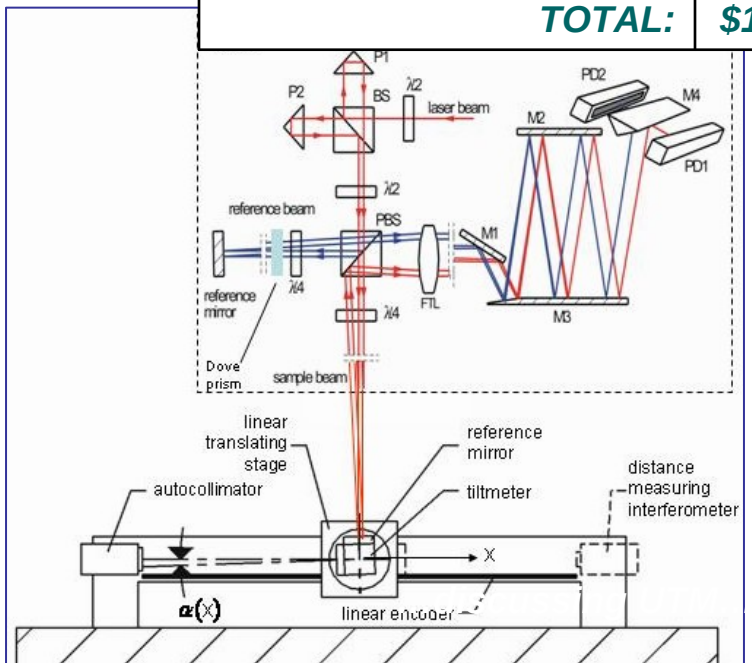
at the range of tilting angles of

±20 mrad

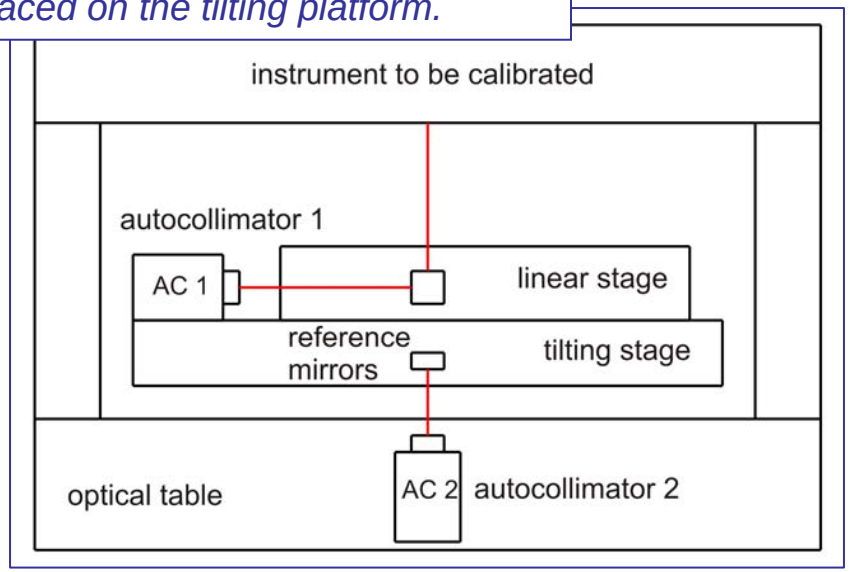
Developing the UTM

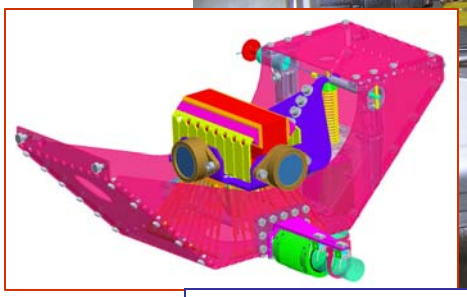
Estimated resources required to design and fabricate an UTM

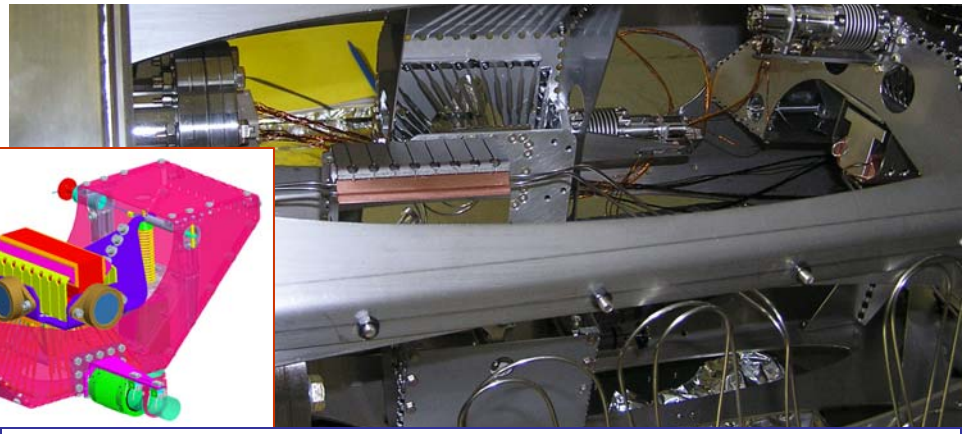
Components	Price
Linear translating stage	$30K
Tilting stage	$30K
Autocollimator	$50K
Tiltmeter	$8K
Reference mirrors	$8K
Control system	$10K
TOTAL:	$136K



UTM with linear translation stage placed on the tilting platform.







X-ray autocorrelation set-up as a prototype of a high performance tilting stage

Developing the UTM

PTB

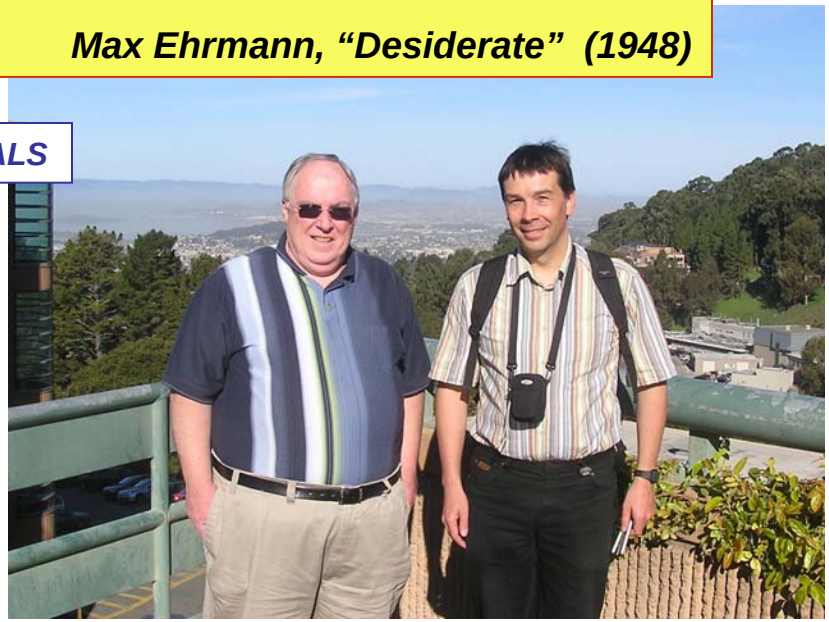
"Enjoy your achievements as well as your plans"

Max Ehrmann, "Desiderate" (1948)

BESSY

...discussing UTM...

ALS



Conclusions

✓ *A new conception for calibration and test of slope measuring instruments has been proposed and its possible realization in a Universal Test Mirror (UTM) mirror has been analyzed.*

✓ *The potential of the proposed UTM system are:*

- *calibration of an instrument specifically for certain optics;*
- *measurement of a universal multi-parametric calibration of an instrument;*
- *characterization of a slope profiler in the spatial-frequency domain;*
- *calibration for stitching measurements with very curved optics;*
- *measurement with significantly curved optics with a 'null' slope measurement mode*

✓ *Development of the UTM system requires state-of-the-art mechanical design and very precise manufacturing, utilizing united experiences, resources, and capabilities of the collaboration.*

✓ *Collaboration is open for creative collaboration with everyone interested in the development and use of the UTM technique.*

✓ *The collaboration assumes that the developed and approved UTM design will be available for the entire optical metrology community under the assumption that all further developments of the UTM system must be available for all users of the UTM technique.*

WELCOME ON BOARD!

Acknowledgements

*The authors are grateful to **D.E., Rob Duarte, Steve Irick, Nicholas Kelez, Jonathan Kirschman, Alastair MacDowell, Howard Padmore, and Peter Takacs** for useful discussions.*

V.V.Y. wishes to particularly acknowledge BESSY, and its staff, for their collaboration, kind hospitality, and encouragement during his visit of October-November 2006, when much of this work was accomplished, and measurements were taken with the NOM.

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Gene Church: "Remember Einstein's dictum: Things should be made as simple as possible, but no simpler!"
V.V.Y.: "This is probably why he did not accept quantum theory: it is too simple compared to his general relativity!"

THANKS!

Optical Metrology Laboratory
Experimental Systems Group
Advanced Light Source
Lawrence Berkeley National Laboratory

August 30, 2007