APS Optics Metrology

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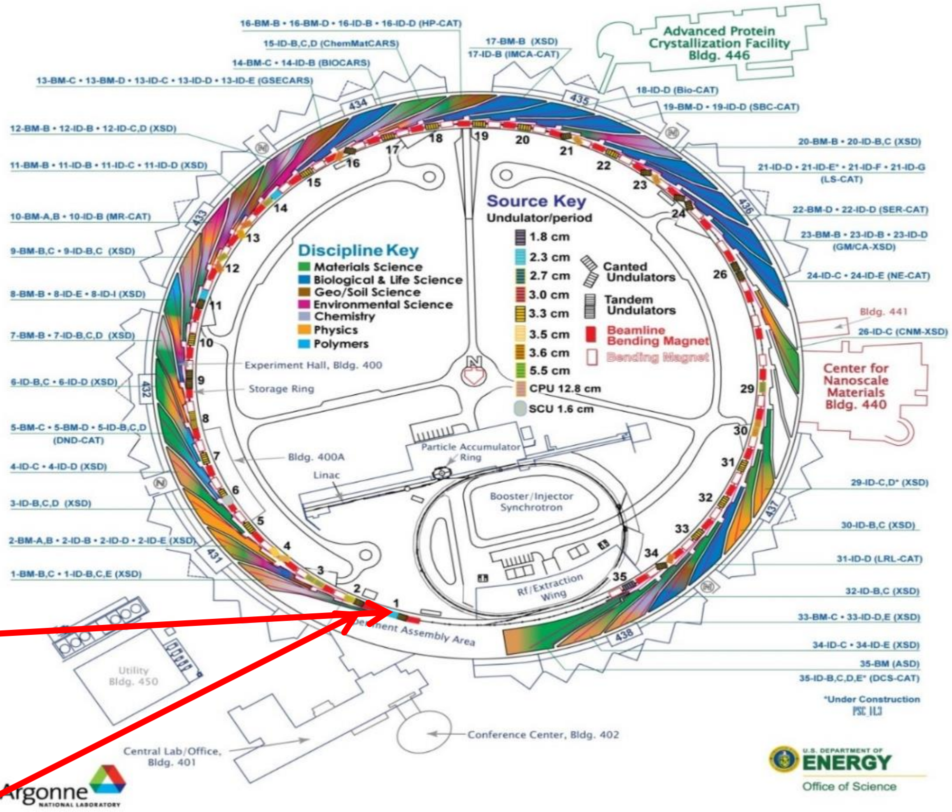
TWG meeting, October 15, 2015

Outline

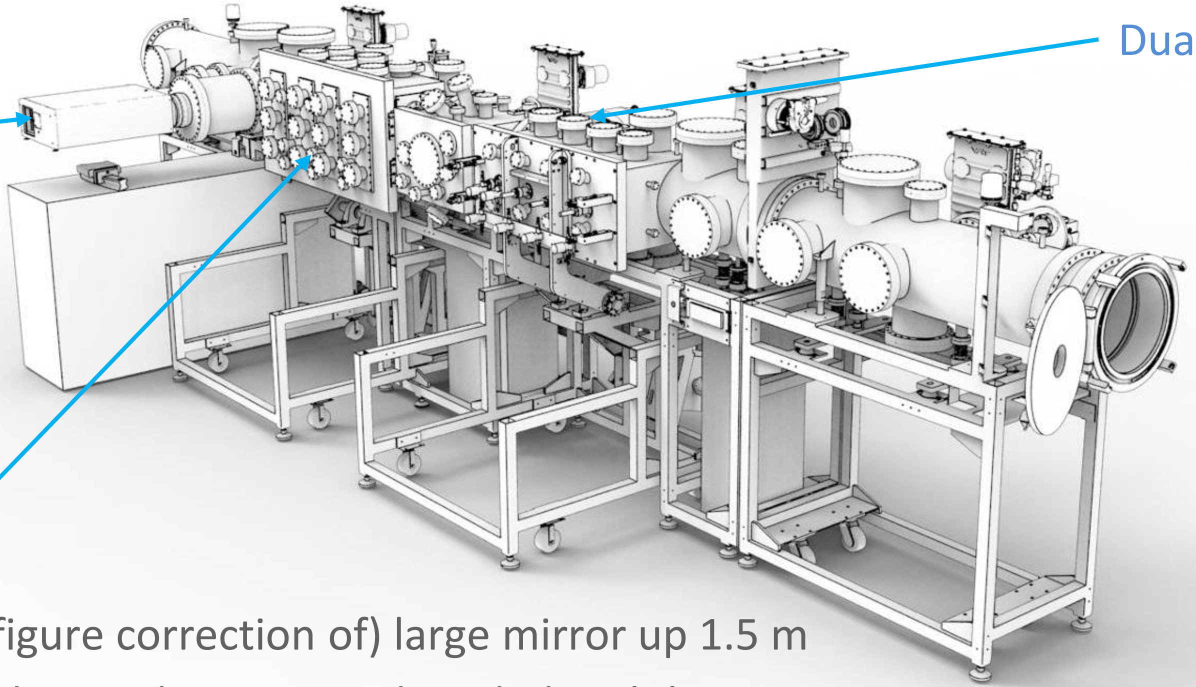
- Introduction
- Optical Metrology
- At-Wavelength Metrology
- Summary



1-BM

New Modular Deposition System with integrated In-situ Ion Beam Milling and Metrology

- Effective use of low-emittance will require optics with dramatically smaller figure errors and tailored surface profiles/
- APS in investing in a new deposition system that allow advanced thin film optics including.



In-situ dynamic Fizeau interferometer

Dual Ion mills

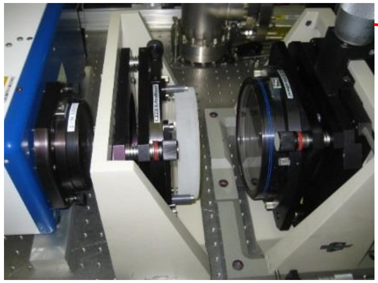
Deposition system with dynamic interferometer

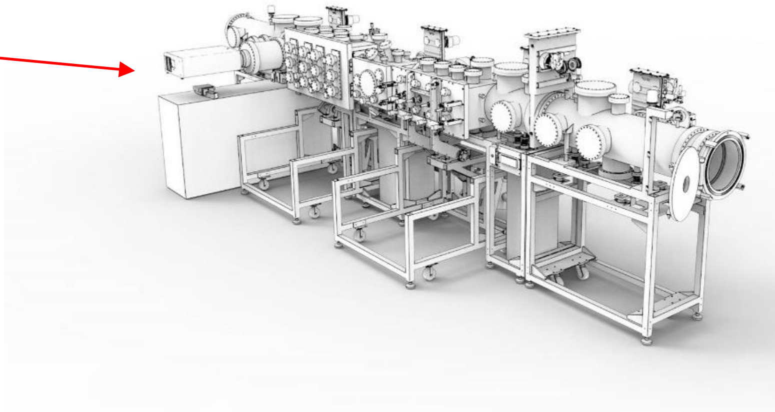
- Coating (figure correction of) large mirror up 1.5 m
- Fabricated coated mirrors and graded multilayer optics
- Delivery expected November. 2015

Lahsen Assoufid, APS Metrology updates, TWG Meeting, October 15, 2015

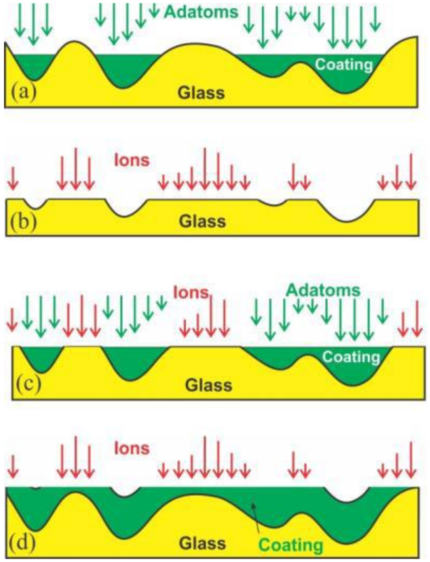
New Modular Deposition System with integrated In-situ Ion Beam Milling and Metrology

- The system includes a Fizeau interferometer for measurement of mirrors profile.
- Maintains the mirror under vacuum through the fabrication process
- Fast iteration rate for recoating/milling
- Ability to avoid oxidation (metals, etc.)





- **Extremely accurate registration between Fizeau and ion mills/coatings for accurate fabrication of optics**
- Coating (figure correction of) large mirror up 1.5 m
- Fabricated coated mirrors and graded multilayer optics

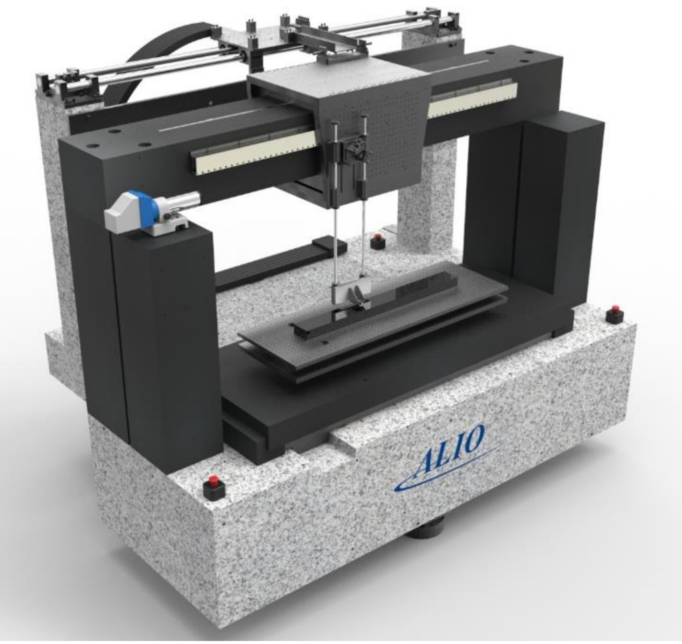


Surface correction techniques: (a) differential deposition, (b) ion-beam figuring, (c) combination, (d) ion-beam figuring of over-coating

(R. Conley)

Optical Metrology

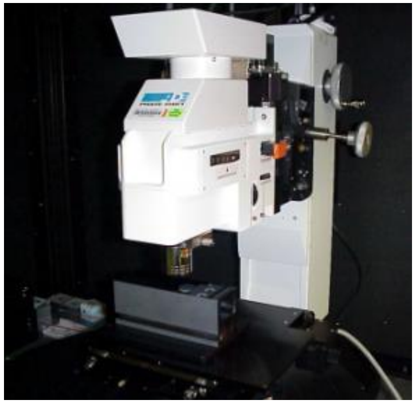
- Current capabilities:
  - New slope measuring system in the NOM configuration with <50 nrad precision on flat mirrors
  - Roughness and stitching microscope interferometer (MicroXAM RTS), < 0.05 nm height resolution
  - Laser Fizeau Interferometer (Wyko 6000), 150 mm aperture, <1 nm resolution.



The APS slope measuring profiler (2011-12)

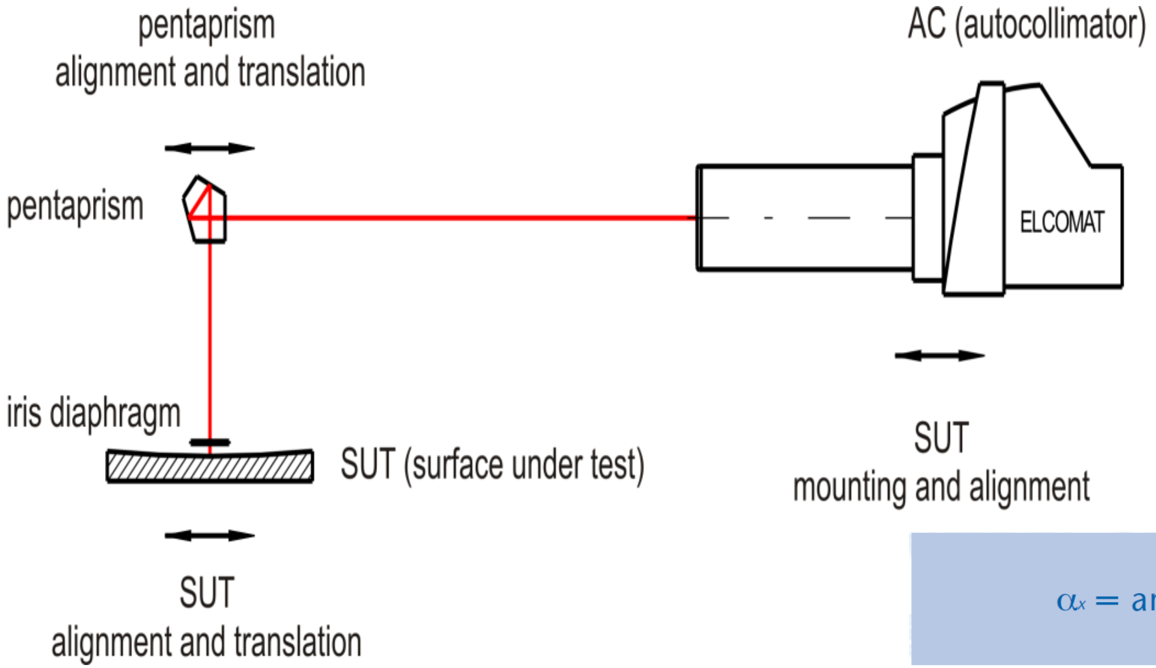
Wyko 6000 Interferometer (1994)

4-D Technology's FizCam for in-situ metrology (2015)



MicroXam RTS roughness/microstitching microscope (2006)

Autocollimator and a moving mirror pentaprism based slope profiler (NOM concept)



Elcomat 3000/8
http://www.moeller-wedel-optical.com/

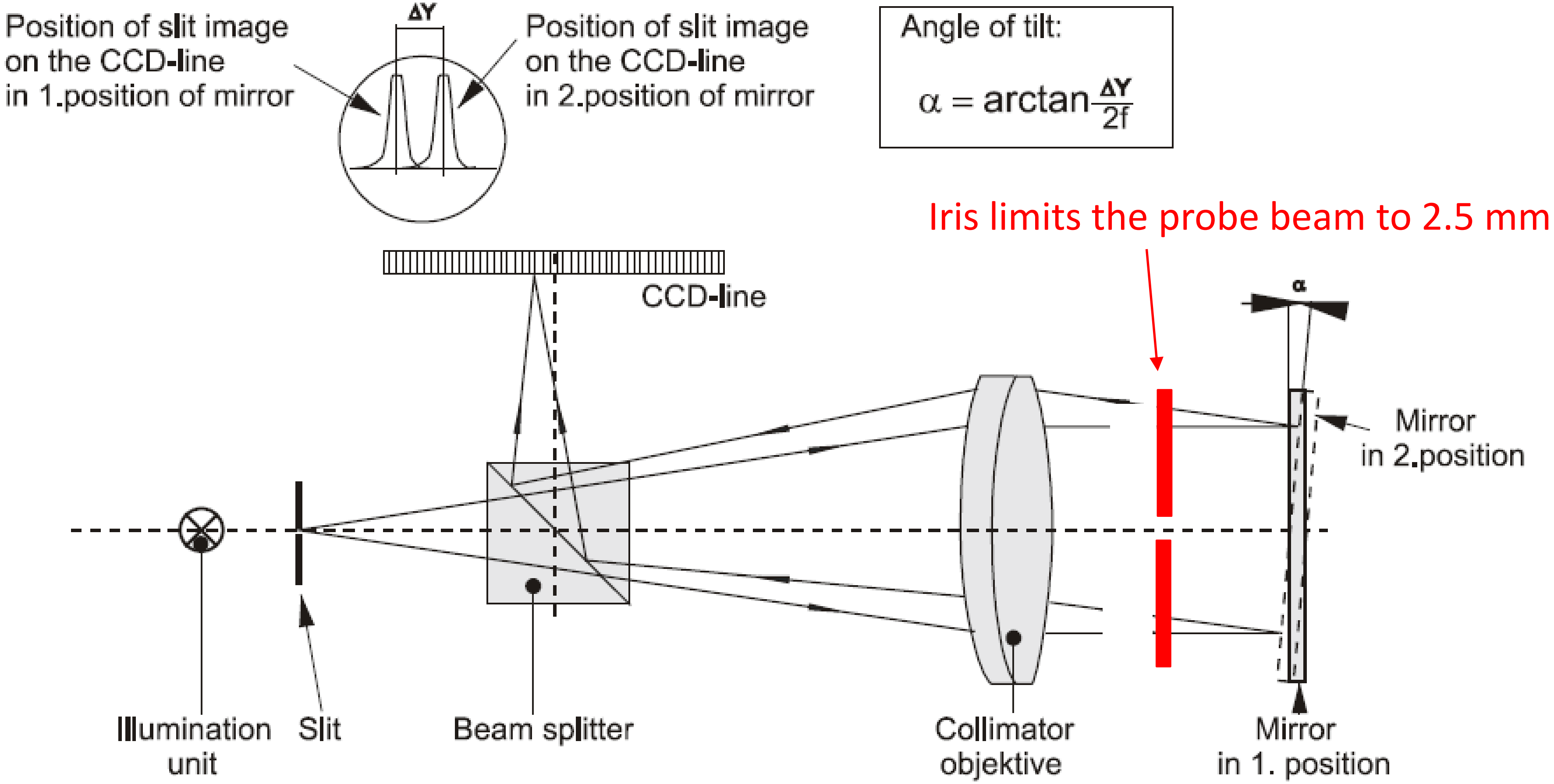
$$\alpha_x = \arctan\left(\frac{\Delta x}{2f}\right) \approx \frac{\Delta x}{2f}$$

$$\alpha_y = \arctan\left(\frac{\Delta y}{2f}\right) \approx \frac{\Delta y}{2f}$$

*F. Siewert, H. Lammert, T. Zeschke, Modern Developments in X-ray and Neutron Optics, Springer 2008

The image of an illuminated object, located in the rear focal plane of the collimator lens, is projected to infinity and reflected via mirror. The image is picked up by a light-sensitive receiver.

A slight alteration of the angle between the optical axis of the autocollimator and the mirror causes a deviation which can be determined very precisely.

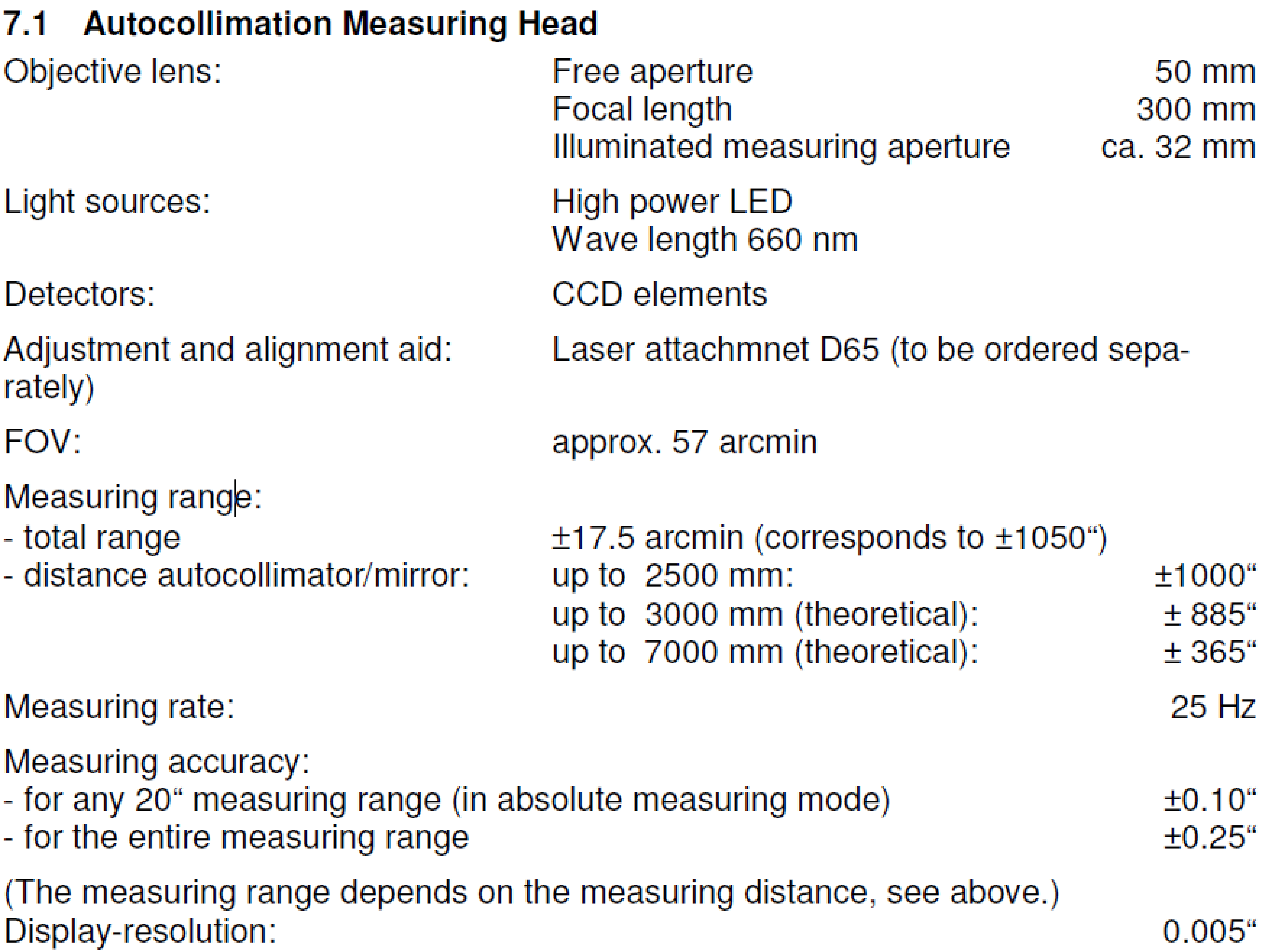


Angle of tilt:

$$\alpha = \arctan\frac{\Delta Y}{2f}$$

Iris limits the probe beam to 2.5 mm

Fig.2: Measuring principle of autocollimation



7.1 Autocollimation Measuring Head

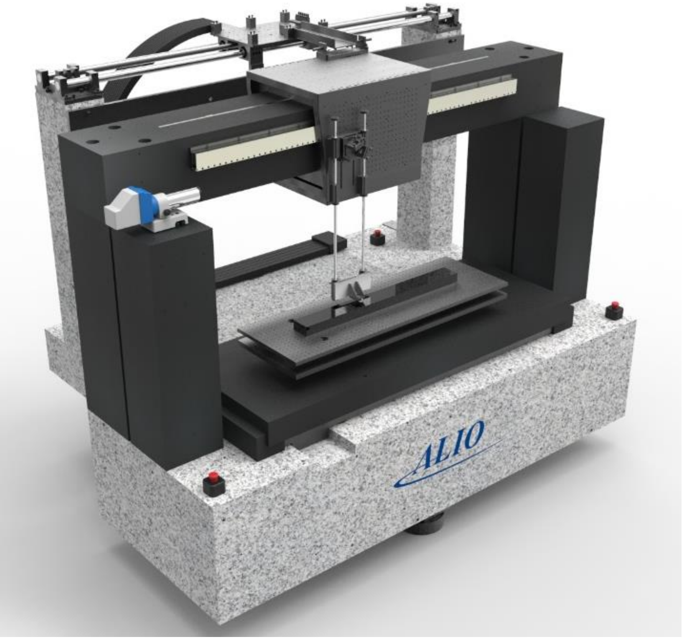
Objective lens:	Free aperture	50 mm
	Focal length	300 mm
	Illuminated measuring aperture	ca. 32 mm
Light sources:	High power LED Wave length 660 nm	
Detectors:	CCD elements	
Adjustment and alignment aid:	Laser attachmnet D65 (to be ordered separately)	
FOV:	approx. 57 arcmin	
Measuring range:		
- total range	±17.5 arcmin (corresponds to ±1050“)	
- distance autocollimator/mirror:	up to 2500 mm:	±1000“
	up to 3000 mm (theoretical):	± 885“
	up to 7000 mm (theoretical):	± 365“
Measuring rate:		25 Hz
Measuring accuracy:		
- for any 20“ measuring range (in absolute measuring mode)		±0.10“
- for the entire measuring range		±0.25“

(The measuring range depends on the measuring distance, see above.)

Display-resolution:	0.005“

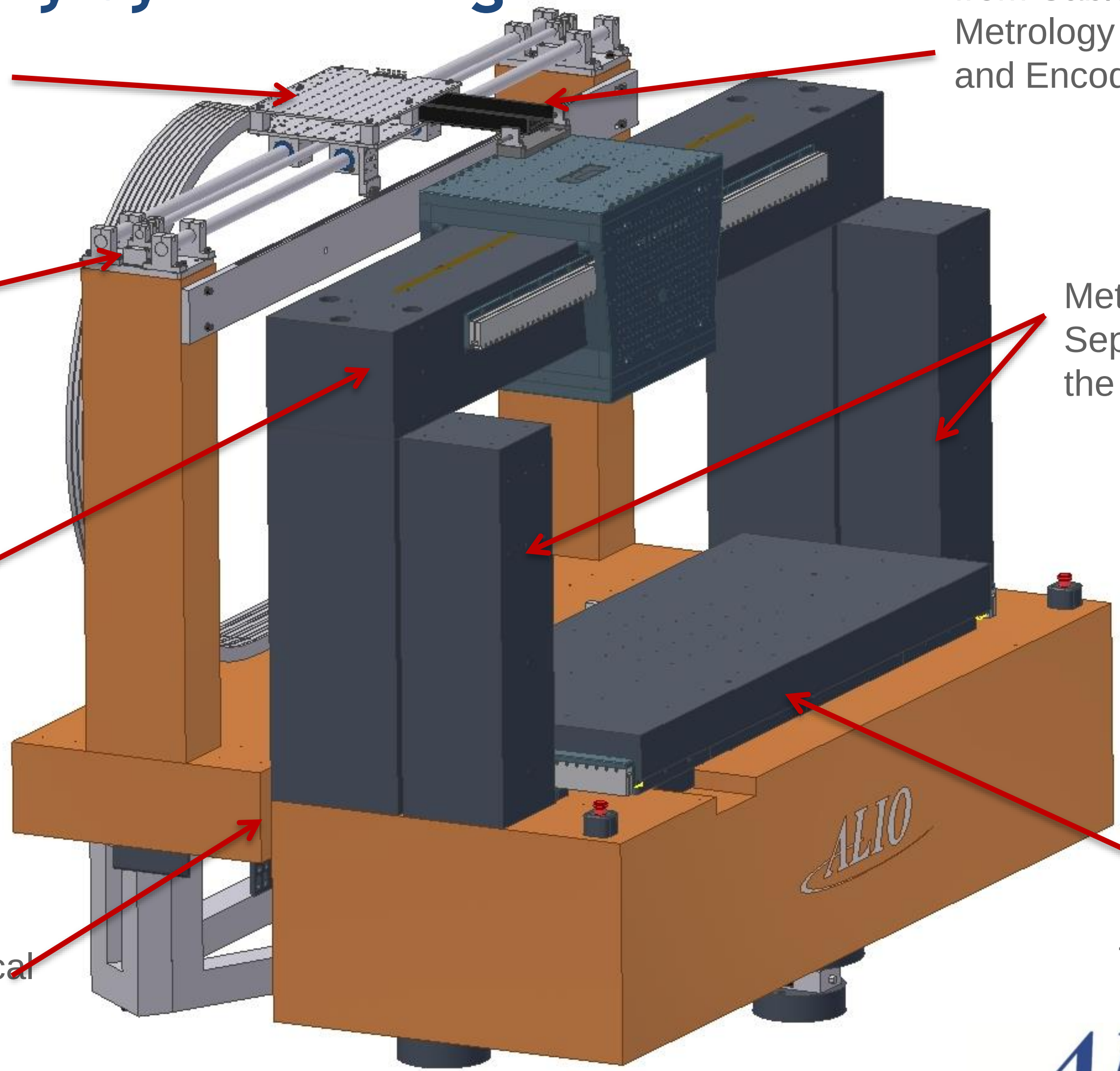
The APS slope measuring profiler design

- Gantry System:
  - Alio Industries (APS Design)
  - Scan length up 1.5 m
- Slope sensor
  - Autocollimator: Elcomat 3000/8, MÖLLER-WEDEL OPTICAL GmbH, model
  - Resolution ~ 50 nrad
- scanning opto-mechanics and mirror support table: APS
- Data acquisition: EPICS based, APS BCDA
- Data processing: Pyhton-based, APS



LTP 3-D drawing by O. Schmidt

The APS Slope Measuring Profiler: The Gantry System Design



Additional Mounting Location for Additional User Added Functionality.

Soft / Gentle Cable Loop from Cable Axis to Metrology Axis for Motor and Encoder Cables.

Cable axis

Metrology Risers Separate / Isolated from the Axis / Motion Risers

Metrology axis

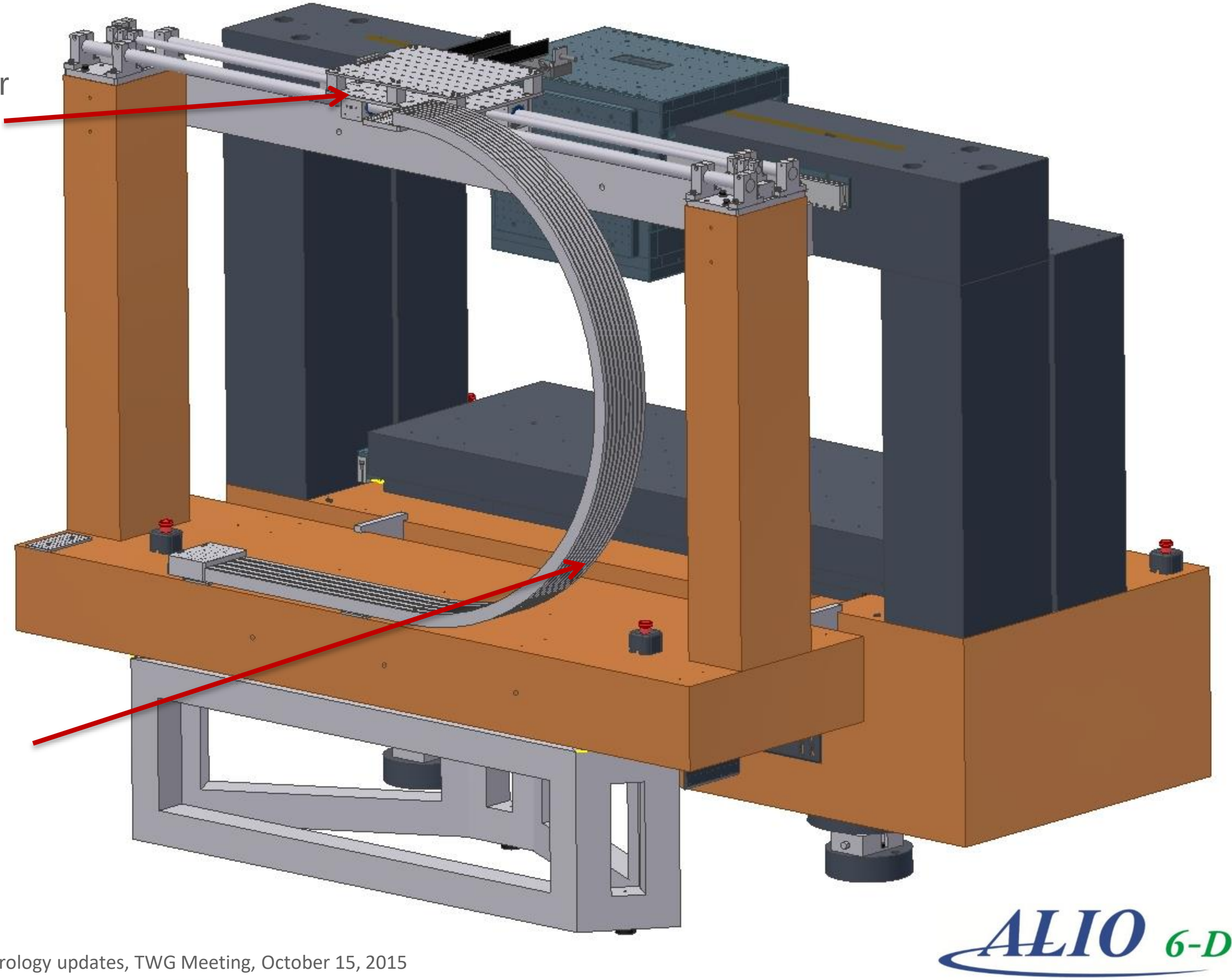
Positioning accuracy 50 nm. A factor of 2000 improvement over previous LTP

Mirror granite table

Cable Axis 100% Isolated from the Optical Carriage with Isolated Granite and Frame.

ALIO 6-D

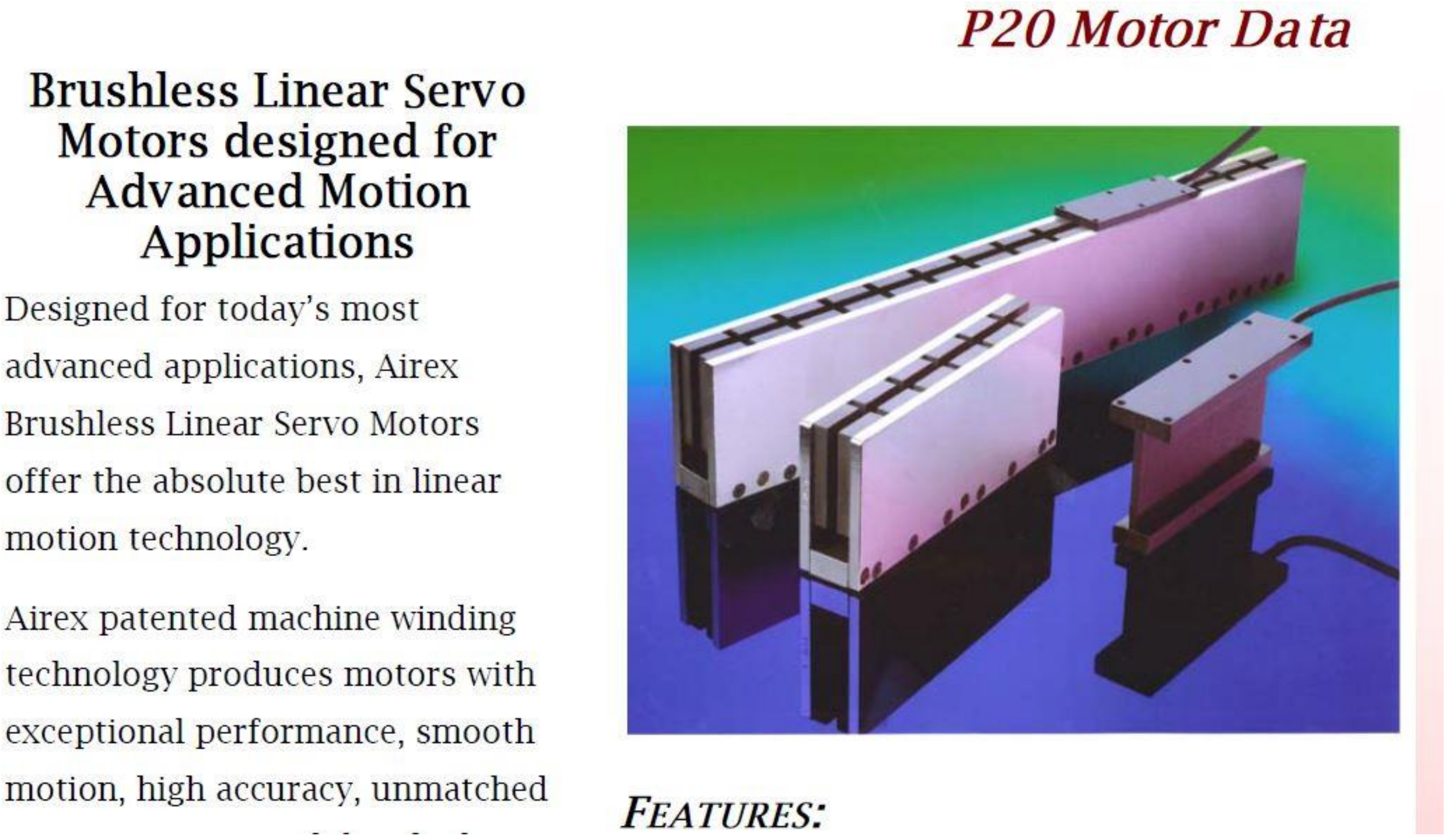
The APS Slope Measuring Profiler: The Gantry System Design



Completely Separate Air Bearing Servo Axis for Cable Axis. Axis Mirrors Motion of Optical Carriage Thus Isolating Cable Drag and Vibration.

Large Radius Cable Loop to Minimize Vibration and Drag.

Motion system



P20 Motor Data

Brushless Linear Servo Motors designed for Advanced Motion Applications

Designed for today's most advanced applications, Airex Brushless Linear Servo Motors offer the absolute best in linear motion technology.

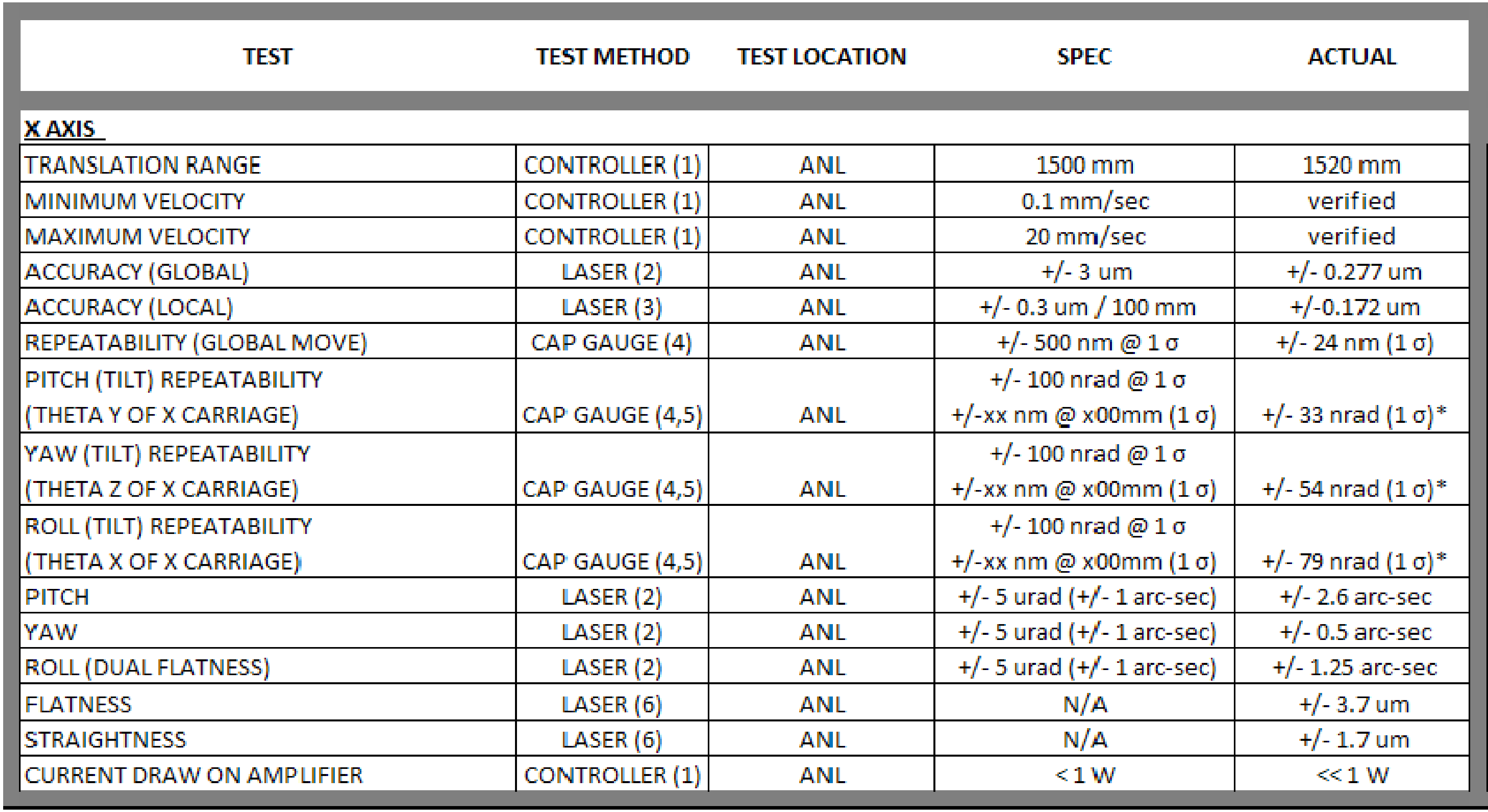
Airex patented machine winding technology produces motors with exceptional performance, smooth motion, high accuracy, unmatched

FEATURES:

http://www.airex.com/wp-content/Linear_Motr/P20%20Motor%20Data%20f.pdf

Motion system specs and test results

Table 1. Test results with specifications for the Long Trace Profiler system: X axis



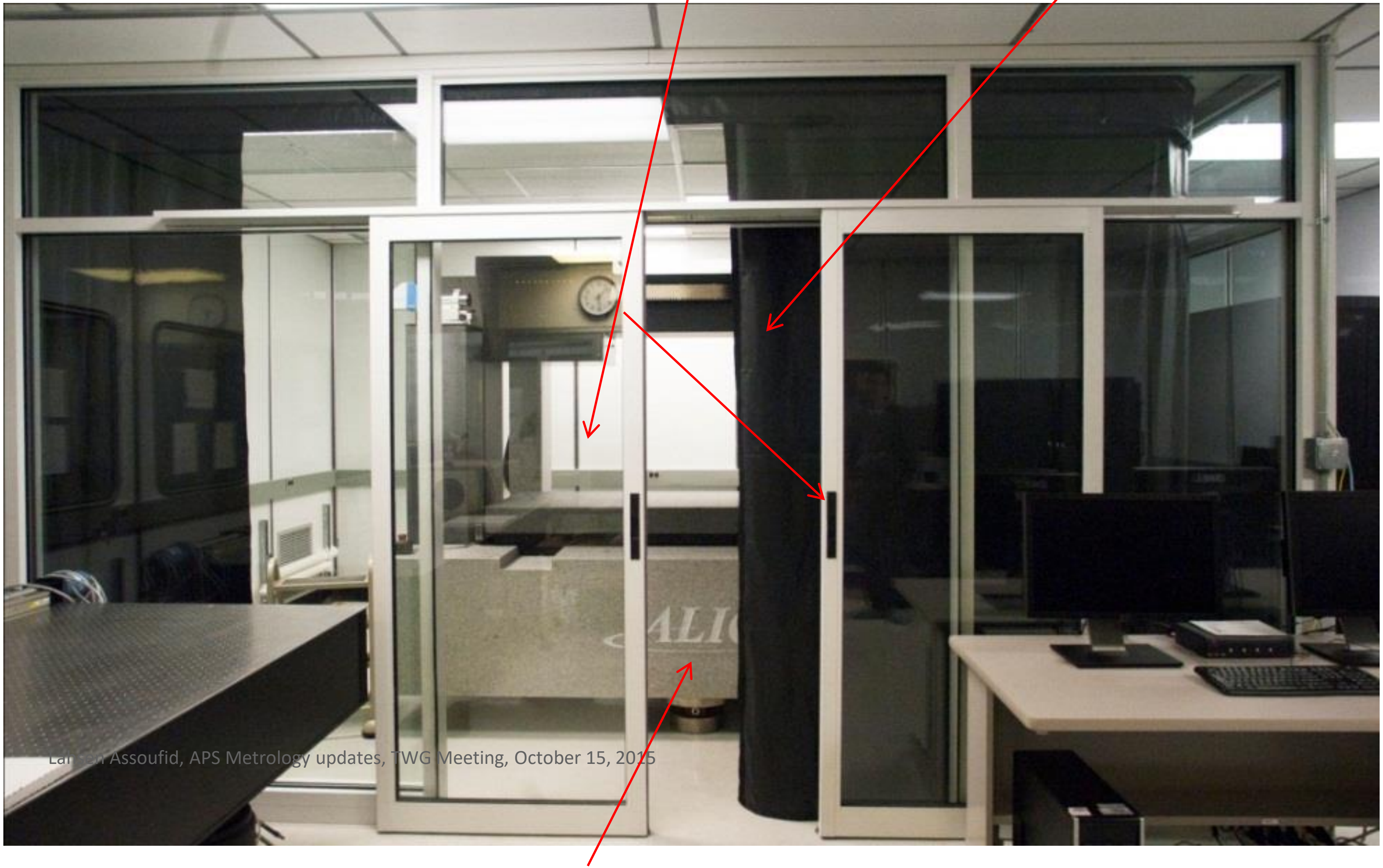
TEST	TEST METHOD	TEST LOCATION	SPEC	ACTUAL
X AXIS				
TRANSLATION RANGE	CONTROLLER (1)	ANL	1500 mm	1520 mm
MINIMUM VELOCITY	CONTROLLER (1)	ANL	0.1 mm/sec	verified
MAXIMUM VELOCITY	CONTROLLER (1)	ANL	20 mm/sec	verified
ACCURACY (GLOBAL)	LASER (2)	ANL	+/- 3 um	+/- 0.277 um
ACCURACY (LOCAL)	LASER (3)	ANL	+/- 0.3 um / 100 mm	+/-0.172 um
REPEATABILITY (GLOBAL MOVE)	CAP GAUGE (4)	ANL	+/- 500 nm @ 1 σ	+/- 24 nm (1 σ)
PITCH (TILT) REPEATABILITY (THETA Y OF X CARRIAGE)	CAP GAUGE (4,5)	ANL	+/- 100 nrad @ 1 σ +/-xx nm @ x00mm (1 σ)	+/- 33 nrad (1 σ)*
YAW (TILT) REPEATABILITY (THETA Z OF X CARRIAGE)	CAP GAUGE (4,5)	ANL	+/- 100 nrad @ 1 σ +/-xx nm @ x00mm (1 σ)	+/- 54 nrad (1 σ)*
ROLL (TILT) REPEATABILITY (THETA X OF X CARRIAGE)	CAP GAUGE (4,5)	ANL	+/- 100 nrad @ 1 σ +/-xx nm @ x00mm (1 σ)	+/- 79 nrad (1 σ)*
PITCH	LASER (2)	ANL	+/- 5 urad (+/- 1 arc-sec)	+/- 2.6 arc-sec
YAW	LASER (2)	ANL	+/- 5 urad (+/- 1 arc-sec)	+/- 0.5 arc-sec
ROLL (DUAL FLATNESS)	LASER (2)	ANL	+/- 5 urad (+/- 1 arc-sec)	+/- 1.25 arc-sec
FLATNESS	LASER (6)	ANL	N/A	+/- 3.7 um
STRAIGHTNESS	LASER (6)	ANL	N/A	+/- 1.7 um
CURRENT DRAW ON AMPLIFIER	CONTROLLER (1)	ANL	< 1 W	<< 1 W

Delivery of the gantry system: August 2011

Assembling and Installation: Sept – Oct. 2011

Construction of the Enclosure Nov. 2011

Enclosure construction: Dec. 2011



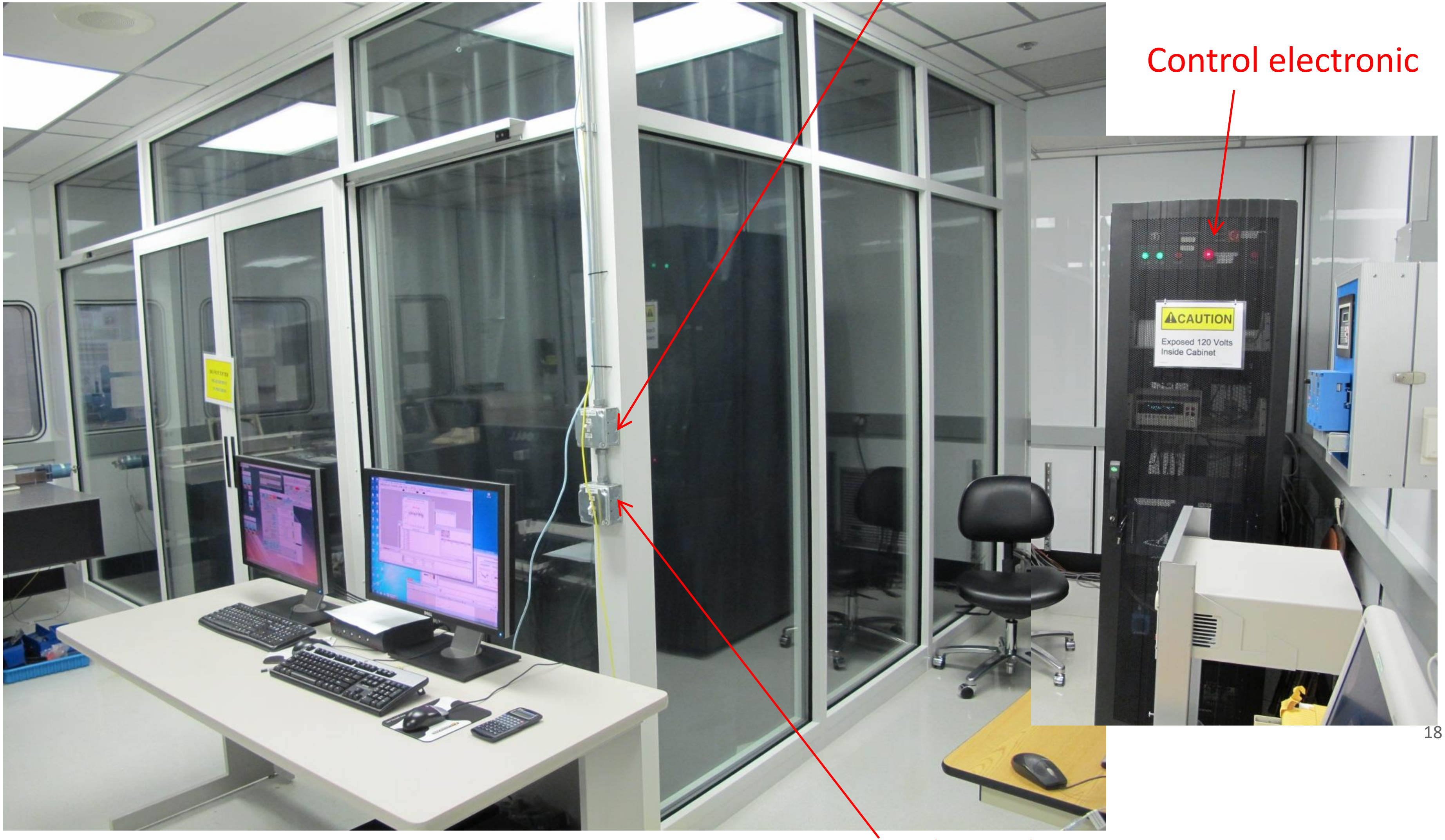
Laser curtain/visible light shield

Double sliding doors

Granite table supported on an industrial kinematic mount

Has a separate air handling control

Commissioning Jan. 2012

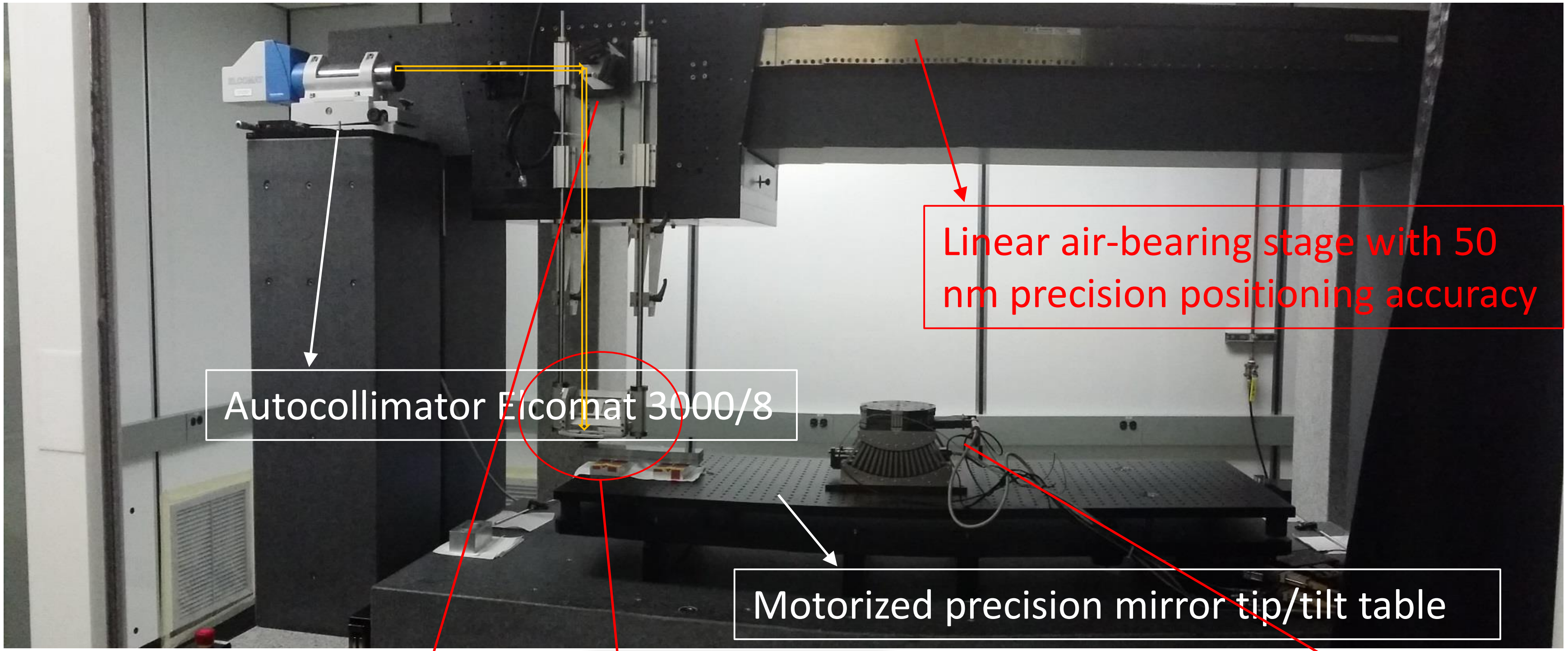


Light switch

Control electronic

Switch for air flow system (baffle)

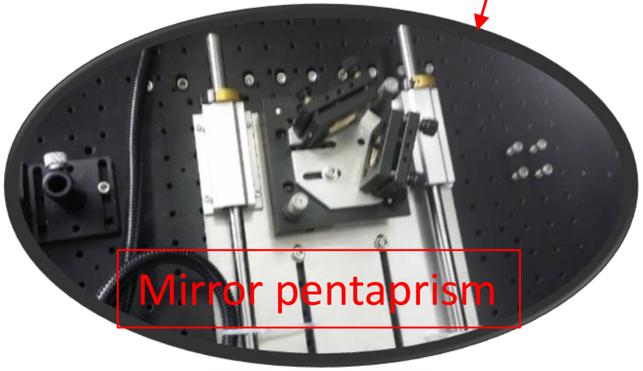
APS Slope Measuring Profiler in NOM Configuration



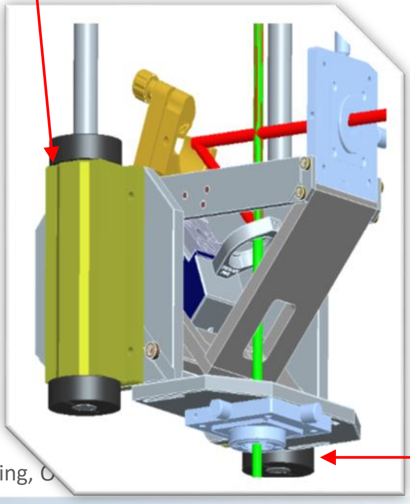
Linear air-bearing stage with 50 nm precision positioning accuracy

Autocollimator Elcomat 3000/8

Motorized precision mirror tip/tilt table



Mirror pentaprism

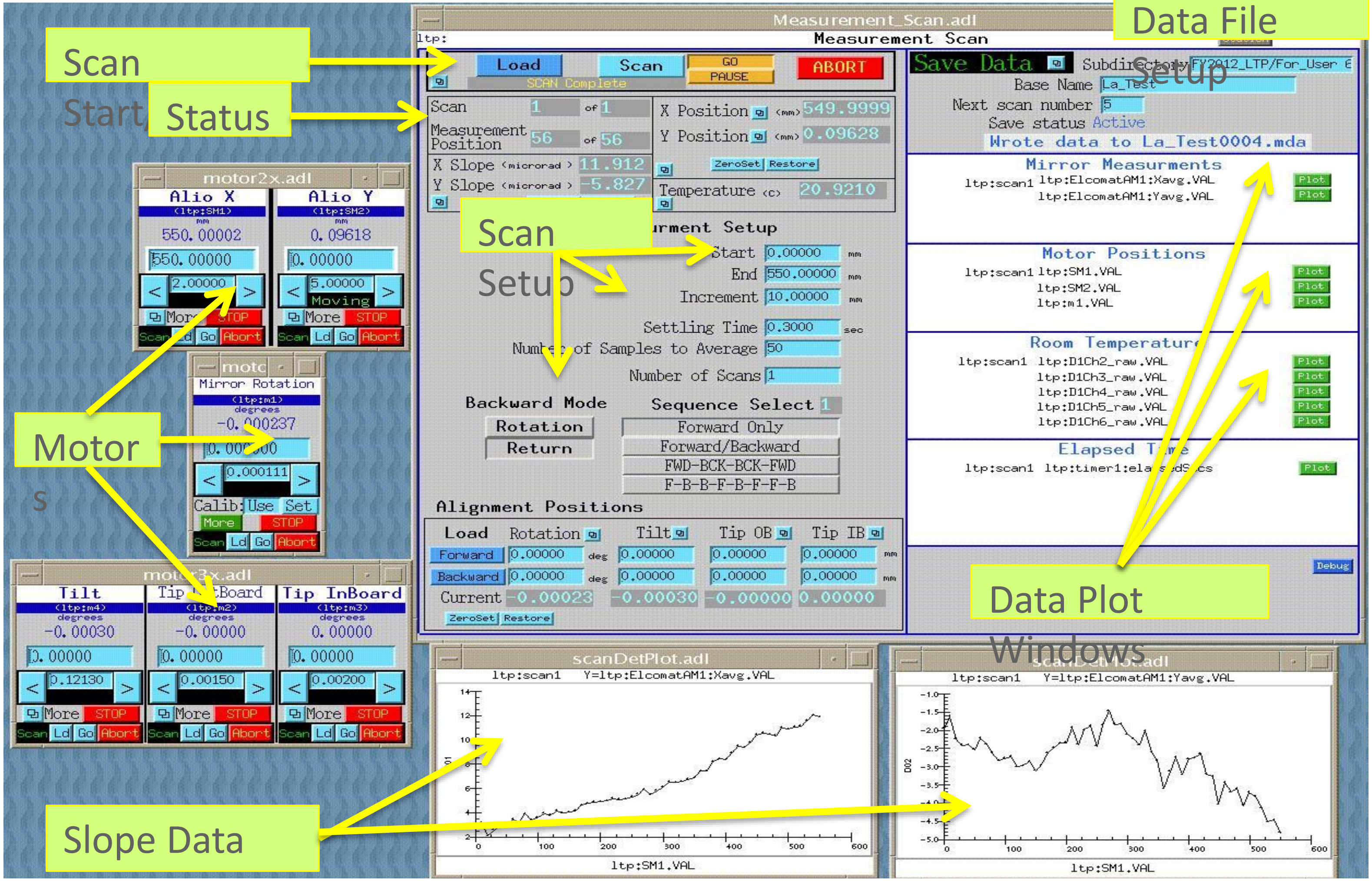


Mirror pentaprism for measurement of horizontal deflecting mirror

2.5 mm diam iris

Small angle generator for angle calibration and for curved mirror measurement by stitching

EPICS-based Data Acquisition (2011-12)



Scan Start/Status

Scan Setup

Motors

Slope Data

Data File Setup

Data Plot Windows

Measurement_Scan.adl

ltp: Measurement Scan

SCAN Complete

Scan 1 of 1

Measurement Position 56 of 56

X Position (mm) 549.9999

Y Position (mm) 0.09628

X Slope (microrad) 11.912

Y Slope (microrad) -5.827

Temperature (c) 20.9210

Start 0.00000 mm

End 550.00000 mm

Increment 10.00000 mm

Settling Time 0.3000 sec

Number of Samples to Average 50

Number of Scans 1

Sequence Select 1

Alignment Positions

Load	Rotation		Tilt	Tip OB	Tip IB	
Forward	0.00000	deg	0.00000	0.00000	0.00000	mm
Backward	0.00000	deg	0.00000	0.00000	0.00000	mm
Current	-0.00023		-0.00030	-0.00000	0.00000	

Save Data

Subdirectory FY2012_LTP/For_User 6

Base Name La_Test

Next scan number 5

Save status Active

Wrote data to La_Test0004.mda

Mirror Measurments

ltp:scan1 ltp:ElcomatAM1:Xavg.VAL

ltp:ElcomatAM1:Yavg.VAL

Motor Positions

ltp:scan1 ltp:SM1.VAL

ltp:SM2.VAL

ltp:m1.VAL

Room Temperature

ltp:scan1 ltp:D1Ch2_raw.VAL

ltp:D1Ch3_raw.VAL

ltp:D1Ch4_raw.VAL

ltp:D1Ch5_raw.VAL

ltp:D1Ch6_raw.VAL

Elapsed Time

ltp:scan1 ltp:timer1:elapsedSecs

motor2x.adl

Alio X (ltp:SM1) mm	Alio Y (ltp:SM2) mm
550.00002	0.09618
550.00000	0.00000
2.00000	5.00000
	Moving

Mirror Rotation (ltp:m1) degrees

-0.000237

0.000000

0.000111

motor3x.adl

Tilt (ltp:m4) degrees	Tip OutBoard (ltp:m2) degrees	Tip InBoard (ltp:m3) degrees
-0.00030	-0.00000	0.00000
0.00000	0.00000	0.00000
0.12130	0.00150	0.00200

scanDetPlot.adl

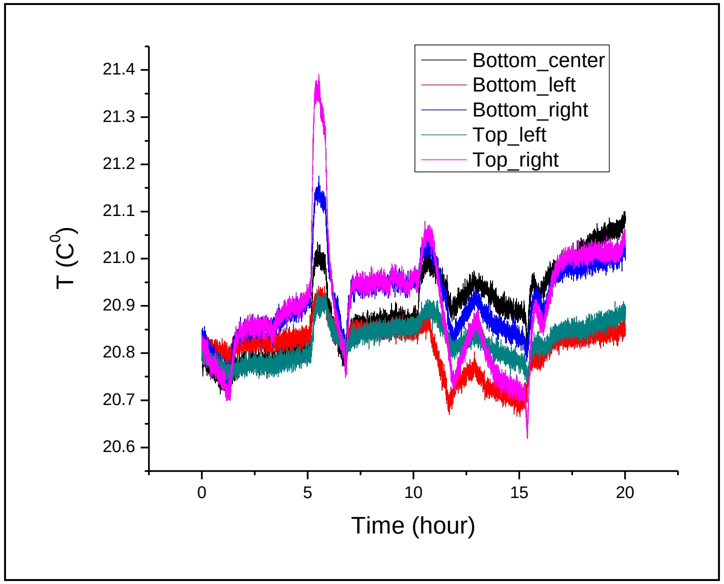
ltp:scan1 Y=ltp:ElcomatAM1:Xavg.VAL

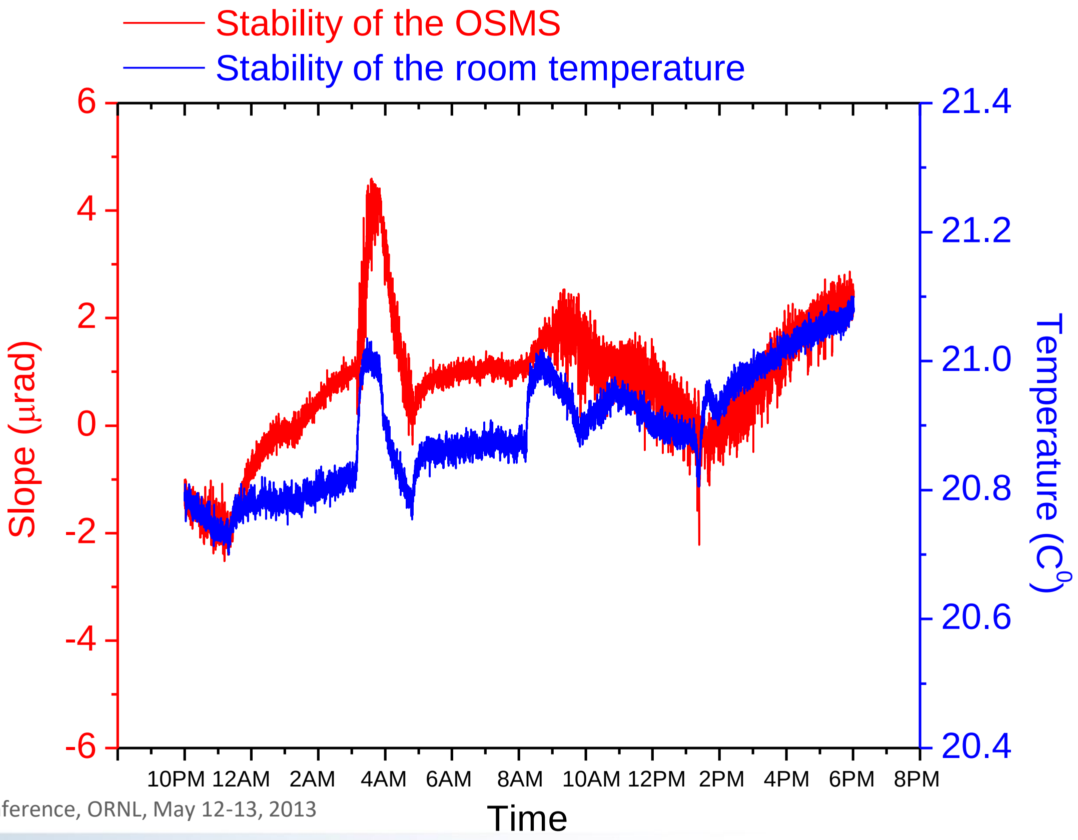
scanDetPlot.adl

ltp:scan1 Y=ltp:ElcomatAM1:Yavg.VAL

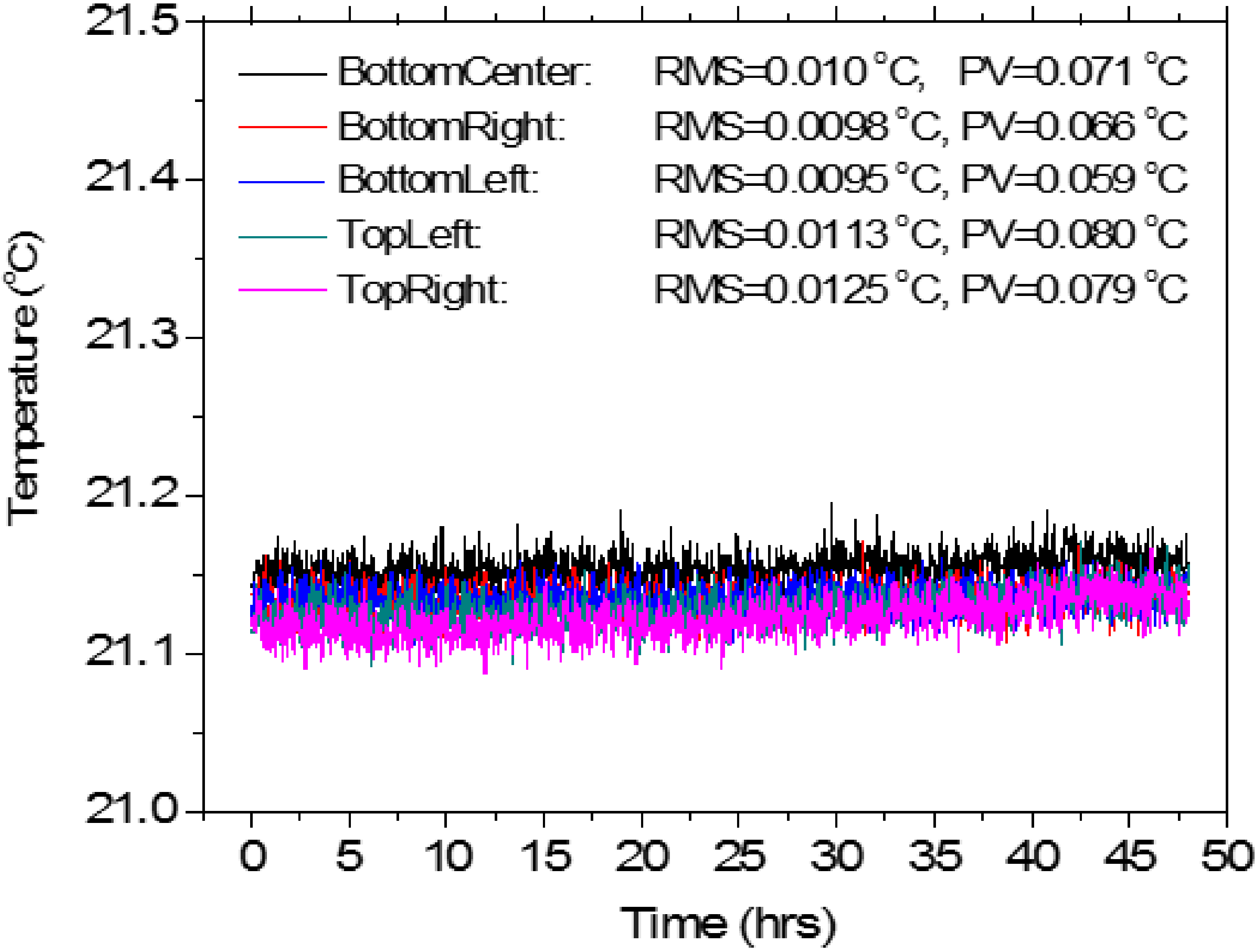
J. Sullivan, P. Jemian, L. Assoufid EPICS Based Data Acquisition (unpublished)

Stability of the APS OSMS vs. the stability of the room temperature in 20 hours

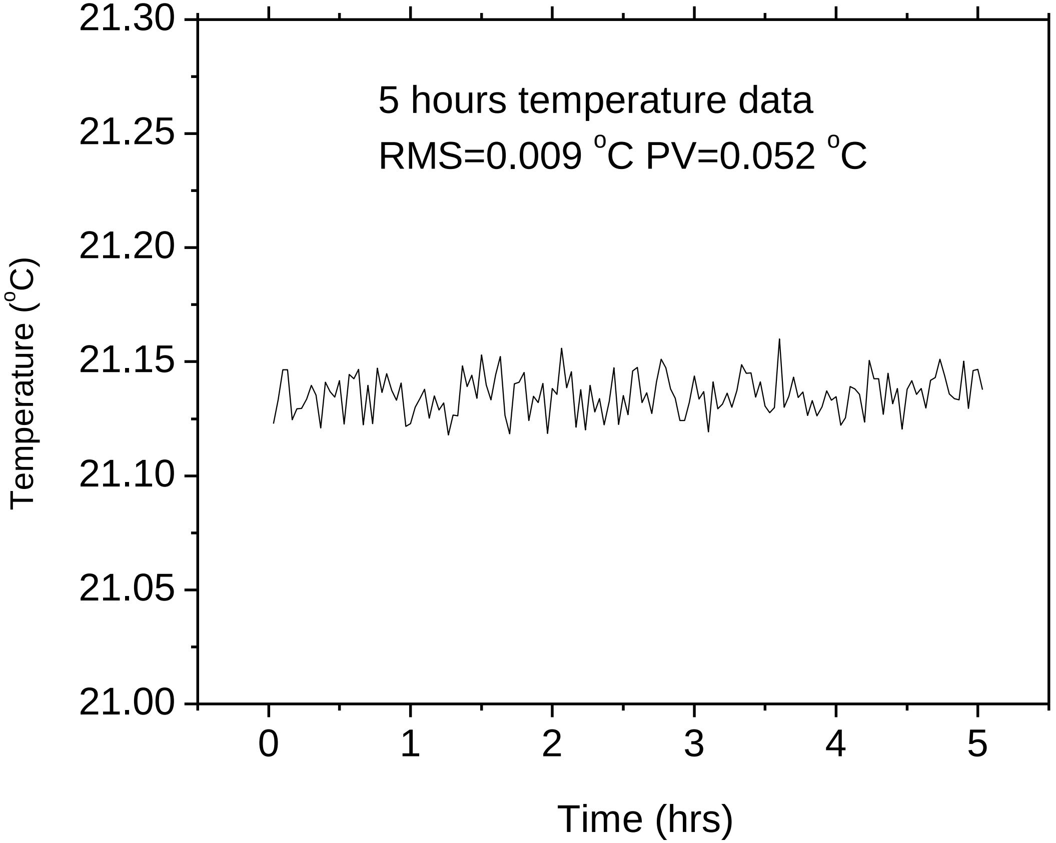


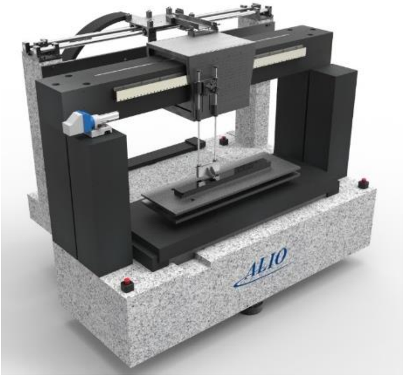


Temperature inside of the AC-LTP enclosure (48 hours from 5/23/2014 to 5/25/2014)



Temperature stability: 2015

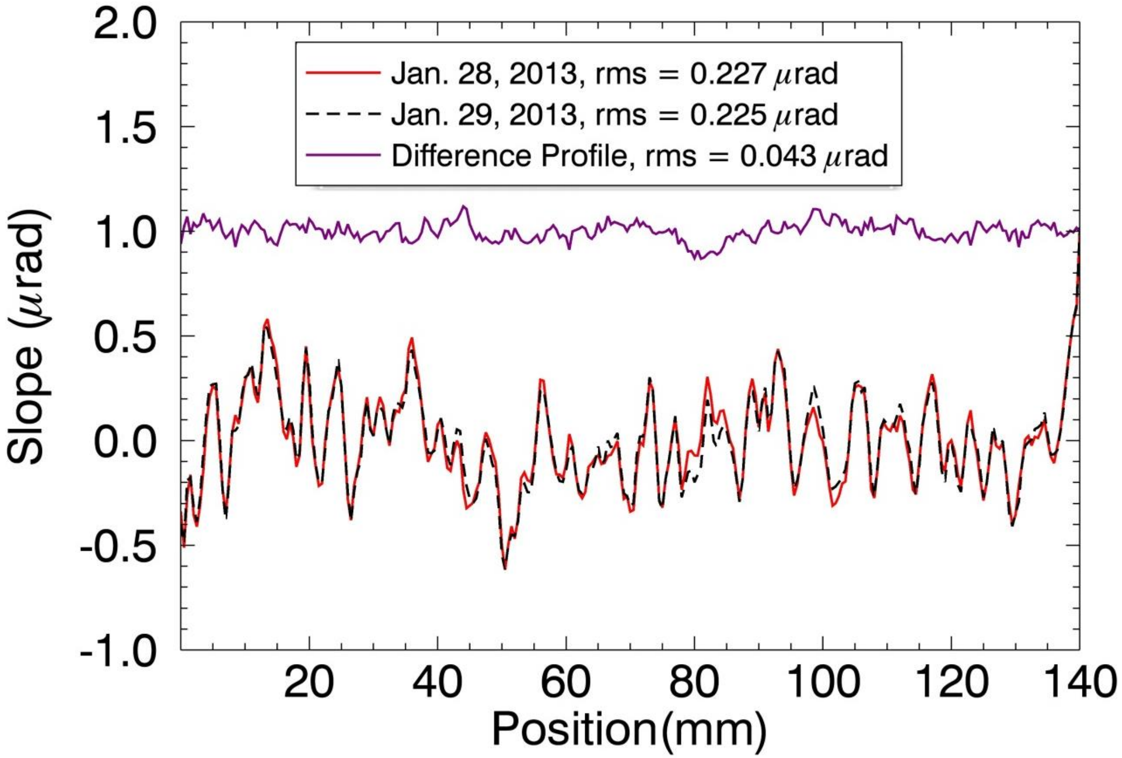


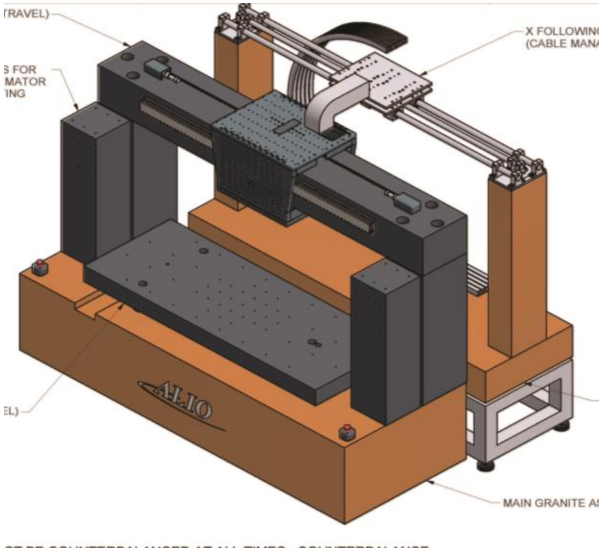


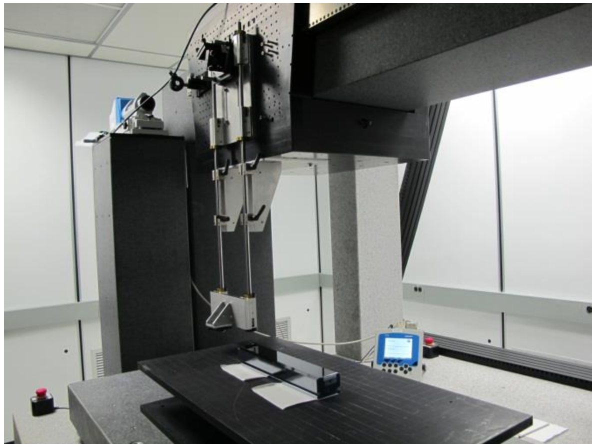
- Air handling system turned off
- Excellent temperature stability obtained within a few hours.
- Further improvement are expected to be achieved by adding another enclosure around the instrument.

New Slope Profiler: Repeatability and accuracy

- Test mirror: 140-mm Si, 0.2 µrad rms slope error
- Two different measurement taken at 1 day interval



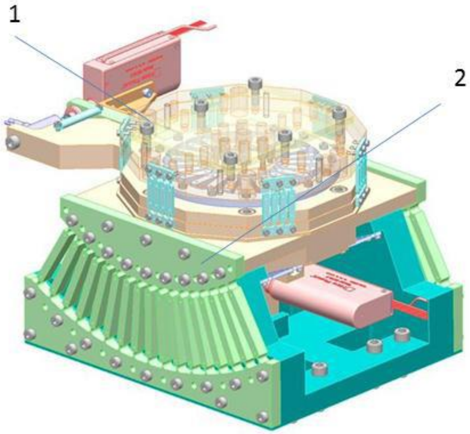




- **Repeatability: 43 nrad rms. A factor of 5 increase in accuracy compared to a standard LTP**

Recent In-house Developments and Implementations

- **New Python-based data processing software:** (OMEN)
- **Calibration**
  - Prototype of a small angle generation device for calibration was developed and tested:
    - Flexural stage (by D. Shu)
    - EPICS-based control and acquisition software (J. Sullivan)



- **Measurement of curved optics by stitching or calibration**
  - Automated tip/tilt stage and sub-aperture/segmented measurements
  - EPICS-based control and data acquisition software.
  - All developed in-house.

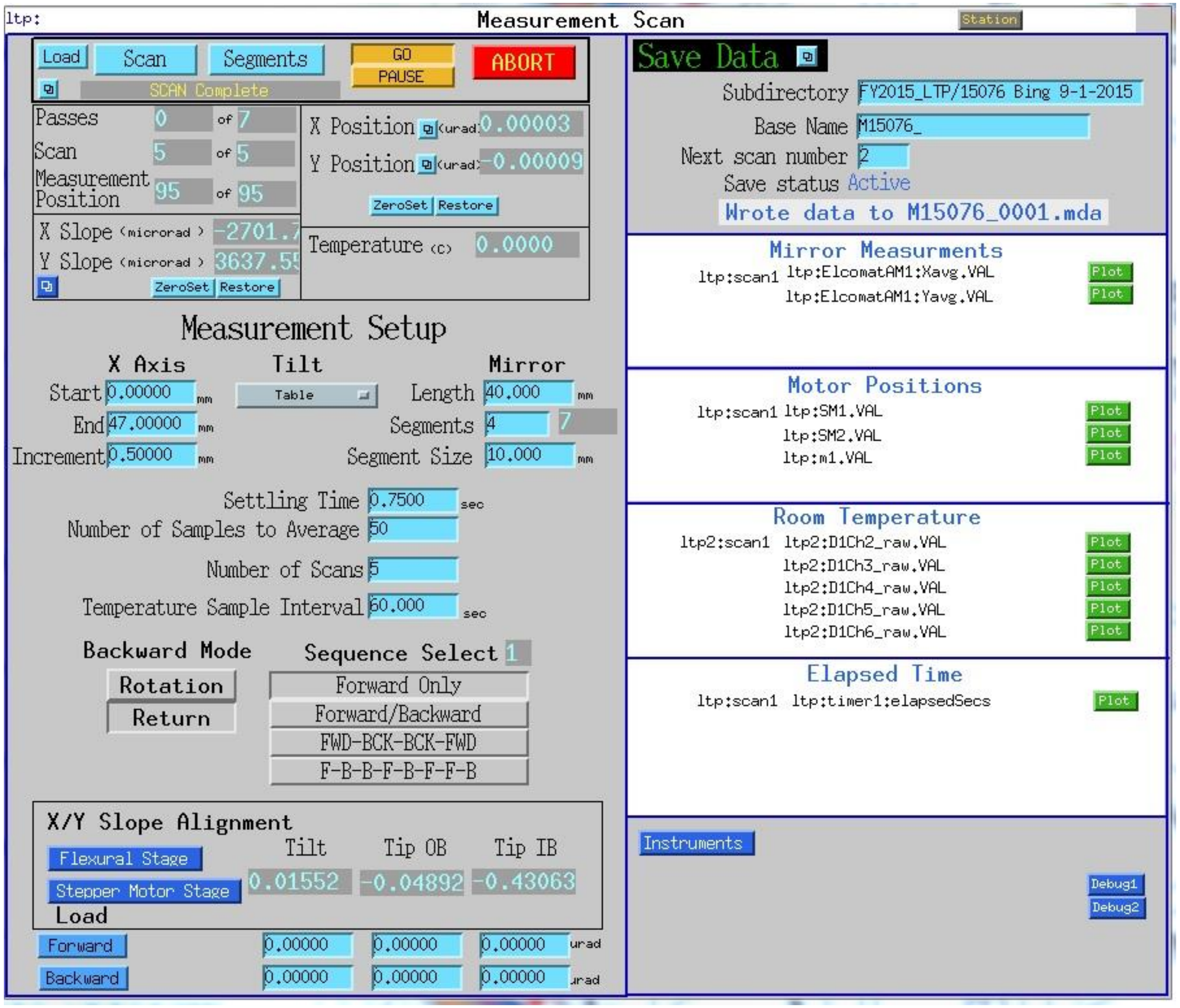
- Fine adjustment driven by a PZT with a maximum range ~0.6 mrad with 20 nrad resolution.
- Limitation: Coarse adjustment driven by a PicoMotor with a range of up to 9 mrad

Deming Shu, et al. SPIE Vol. 9206 (2014)

Automated tilting stage for subaperture scanning and stitching: EPICS user interface.

Completed August 2015

- In-house developed software for high precision mirror tilt and positioning for sub-aperture scanning and stitching.



ltp: Measurement Scan

SCAN Complete

Passes 0 of 7
Scan 5 of 5
Measurement Position 95 of 95
X Position (urad) 0.00003
Y Position (urad) -0.00009
X Slope (microrad) -2701.7
Y Slope (microrad) 3637.55
Temperature (c) 0.0000

Measurement Setup

X Axis
Start 0.00000 mm
End 47.00000 mm
Increment 0.50000 mm

Tilt
Table

Mirror
Length 40.000 mm
Segments 4 7
Segment Size 10.000 mm

Settling Time 0.7500 sec
Number of Samples to Average 50
Number of Scans 5
Temperature Sample Interval 60.000 sec

Backward Mode
Sequence Select 1

X/Y Slope Alignment
Tilt 0.01552
Tip OB -0.04892
Tip IB -0.43063
Load
Forward 0.00000 0.00000 0.00000 urad
Backward 0.00000 0.00000 0.00000 urad

Save Data
Subdirectory FY2015_LTP/15076 Bing 9-1-2015
Base Name M15076_
Next scan number 2
Save status Active
Wrote data to M15076_0001.mda

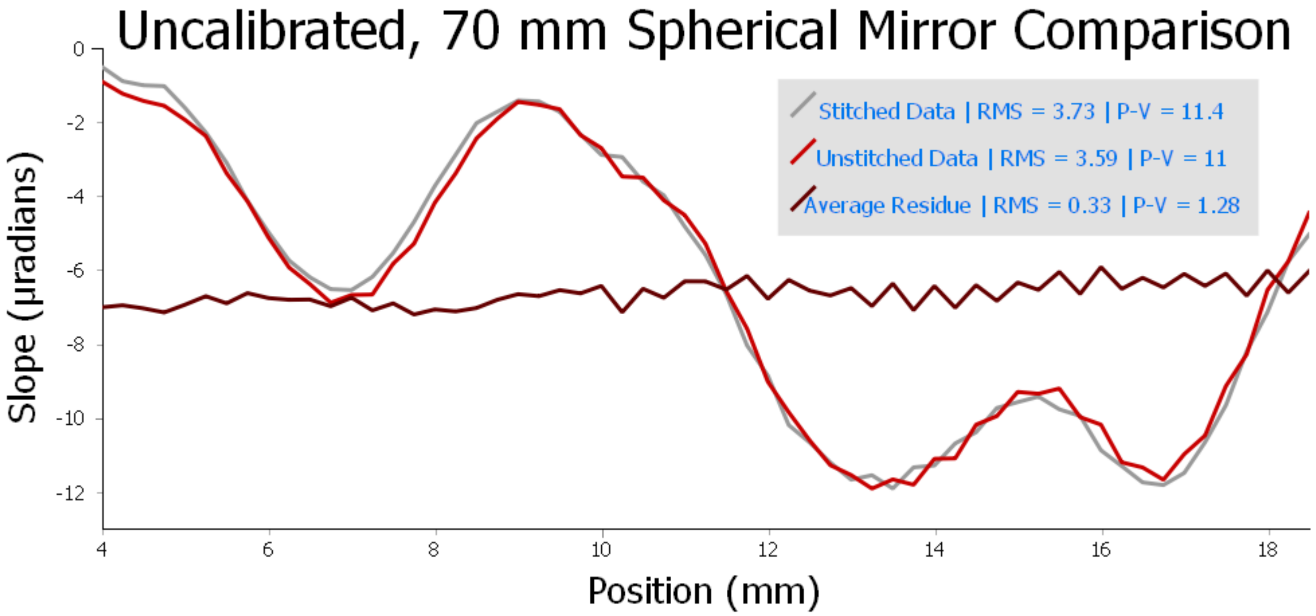
Mirror Measurments
ltp:scan1 ltp:ElcomatAM1:Xavg.VAL
ltp:ElcomatAM1:Yavg.VAL

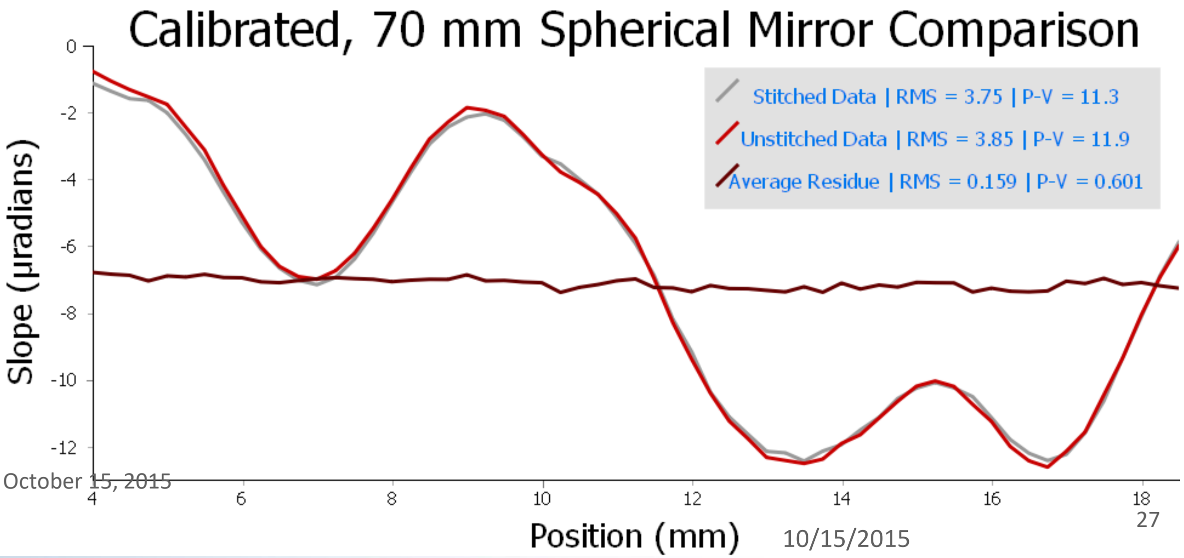
Motor Positions
ltp:scan1 ltp:SM1.VAL
ltp:SM2.VAL
ltp:m1.VAL

Room Temperature
ltp2:scan1 ltp2:D1Ch2_raw.VAL
ltp2:D1Ch3_raw.VAL
ltp2:D1Ch4_raw.VAL
ltp2:D1Ch5_raw.VAL
ltp2:D1Ch6_raw.VAL

Elapsed Time
ltp:scan1 ltp:timer1:elapsedSecs

Measurement of a Curved Mirror by Stitching: Comparison with Calibrated data


Uncalibrated, 70 mm Spherical Mirror Comparison


Calibrated, 70 mm Spherical Mirror Comparison

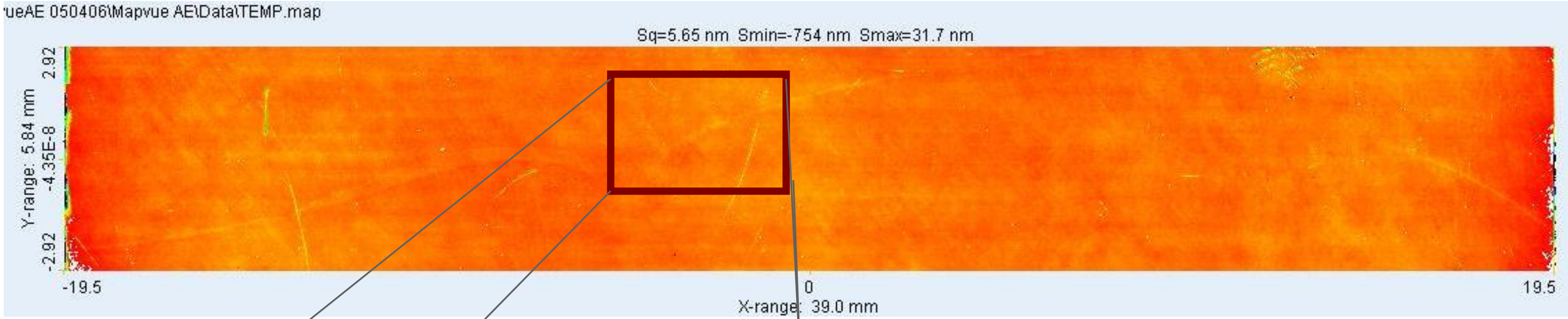
General issues about scanning deflectometric profilers

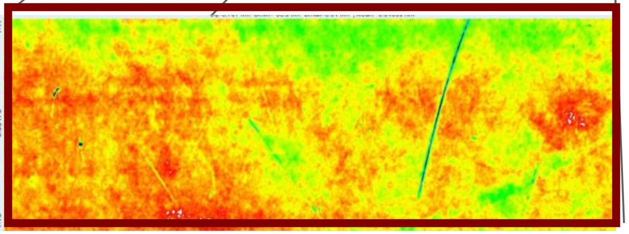
- Deflectometers (pencil beam LTP, NOM), are typically one dimensional profilers. Characterization of focusing optics generally requires two dimensional metrology tools. (Bender twist can not be easily “seen” with 1-D profilers)
- Scanning devices require long measurement time, which makes the measurement prone to drift error.
- Their variable optical path length make them prone to external perturbations
- Measurements can be affected by:
  - systematic/residual errors of scanning stage (in addition to aberrations of the internal optics)
  - Possible non linearity of the slope sensor
  - Environment effect: temperature stability, electronic and acoustic noise
- Very large (> a few km) and very small (<100m) radii of curvature are very challenging to measure

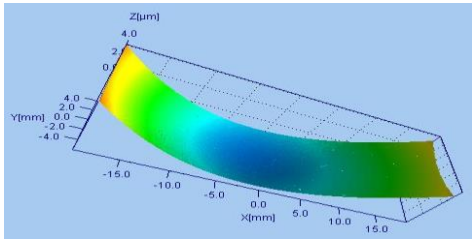
Autocollimator-based profilers limitations and needs

- Auto-collimator-based slope measuring profilers limitations:
  - Spatial sampling limited by the size of the probe beam (~2.5 mm).
  - Measurement of curved mirrors limited by the autocollimator dynamical range and (few 10 microrads) and non linearity for steep slopped surfaces.
  - Require precise calibration or and sub-aperture/segmented measurement stitching.
  - Highly sensitive to external temperature fluctuations.
- New sensors must be developed to overcome these limitations
- Collaborative efforts with other synchrotron labs, with active participation of industrial vendors of x-ray optics and metrology instrumentation is necessary to advance metrology capabilities.

Roughness and Micro-stitching Interferometer







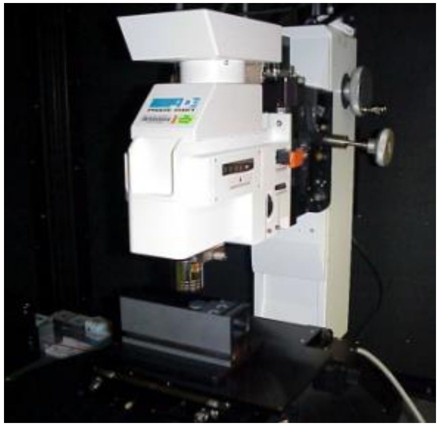


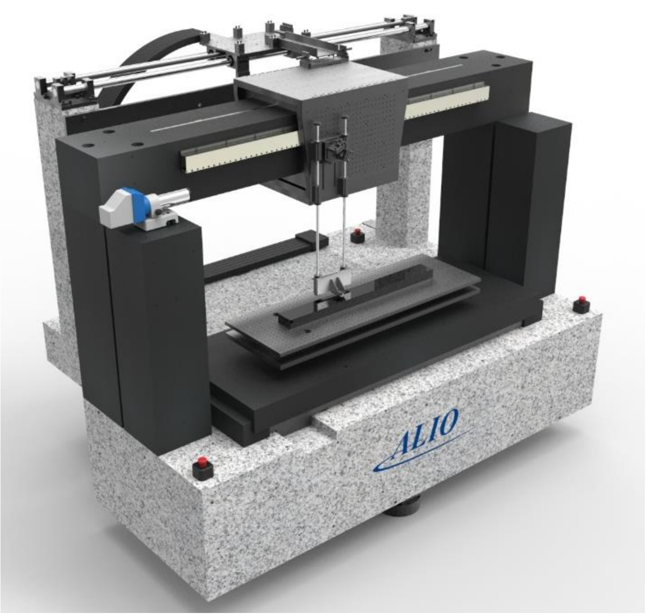
Photo of the APS MicroXam RTS roughness & microstitching interferometer

- 2-D surface profile measurements is essential for profile coating
- Fine resolution of height and lateral dimensions
- Limited to ~100 nm focus mirror with length <100 mm

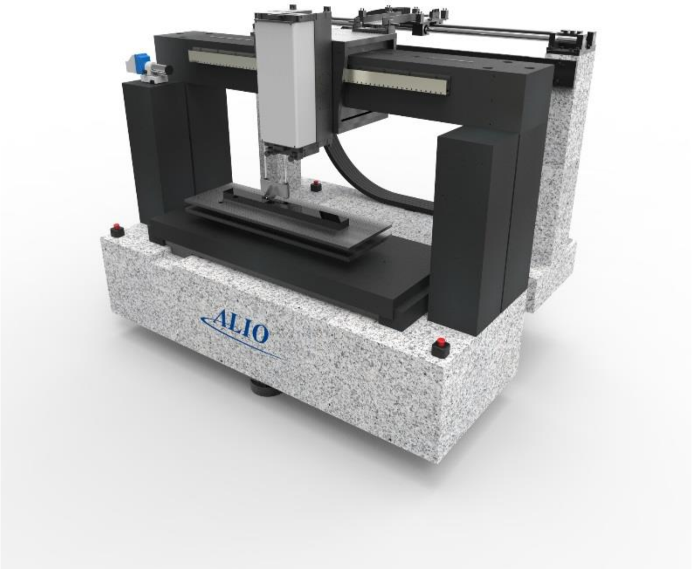
Achieving K-B mirrors with 50-nm focus requires an improved microstitching system to subnanometer figure error

L. Assoufid, J. Qian, C. M. Kewish, C. Liu, R. Conley, A. T. Macrander, D. Lindley, and C. Saxer, SPIE Proc. (2007) 6704.

Future development: 2-D dimensional surface profile measurement of large mirrors



Current sensor: Autocollimator



Future sensor: 2-D stitching

Summary

- The 4th generation light sources require advanced optics:
  - Mirror with unprecedented quality with slope error in the nrad range
  - Wavefront preserving optics for imaging
- Developing a new generation metrology tools is thus essential for both quality control and to support in-house optics fabrication and development.
- New metrology upgrades to support APS beamlines and APS-U include:
  - A new slope measuring profiler with <50 nrad rms resolution on flat mirrors up 1.5 m long.
- Future development:
  - Develop sensor/procedures for measuring curved optics
  - Implement a 2-D sensor with stitching for mirror up 1.5 m

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Thank you!