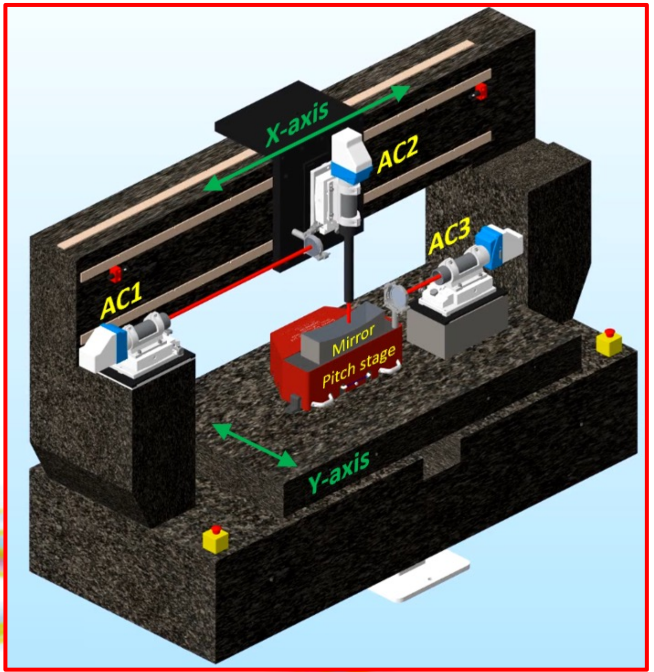
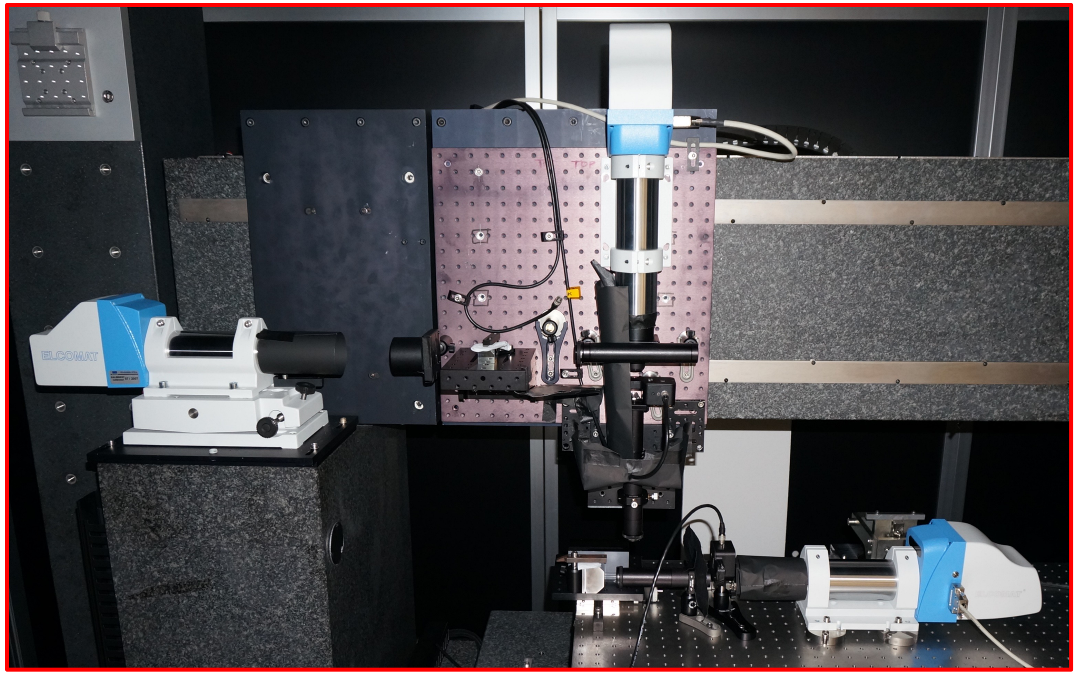
Diamond-VeNOM: a high-speed slope profiler for characterising X-ray mirrors





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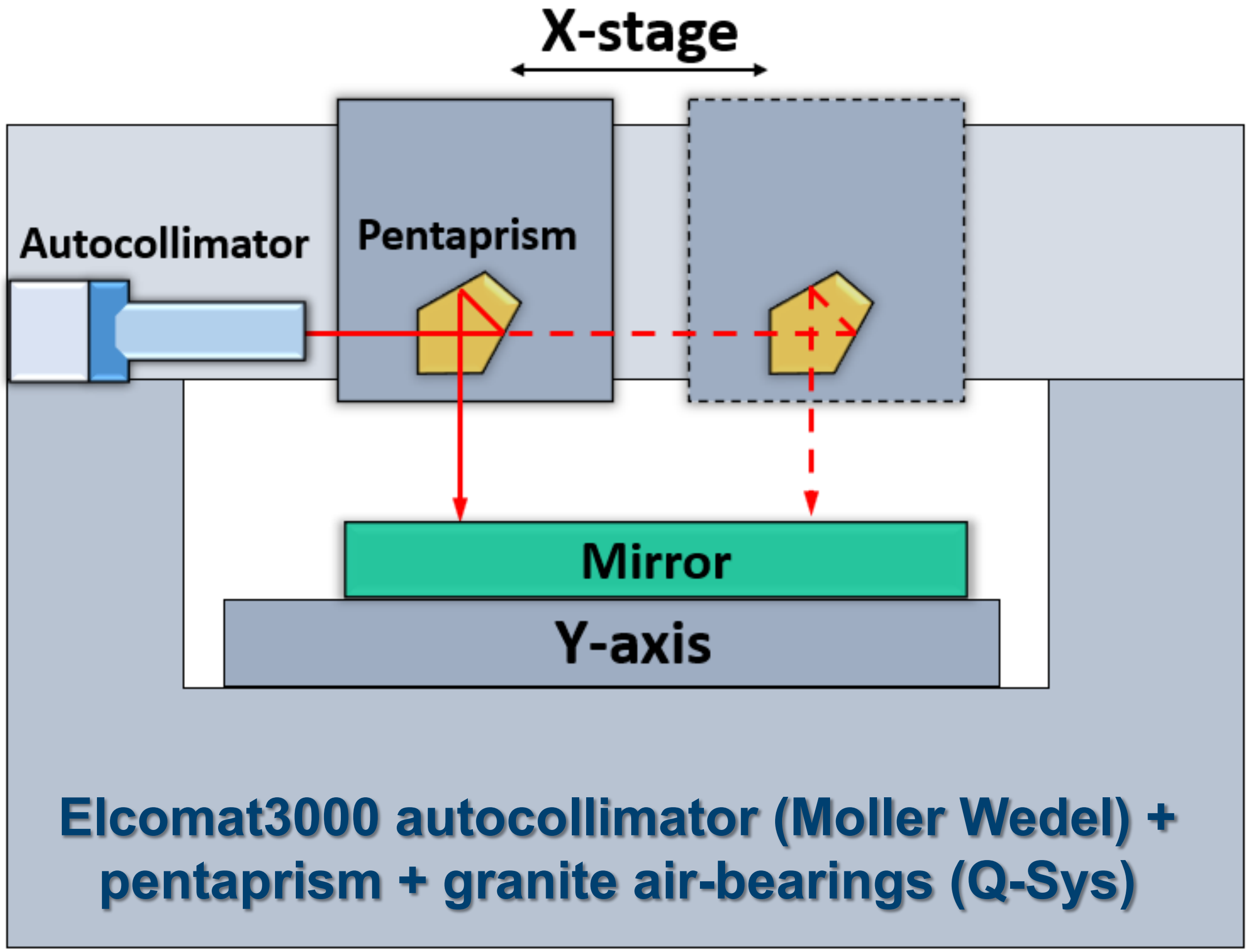
Need for high-quality optical metrology

- Many scientific communities, including synchrotron & XFEL light sources, require curved or flat optics beyond current state-of-the-art (slope errors < 50 nrad & height errors < 1 nm).
- Deterministic correction of X-ray mirrors, such as EEM or IBF, requires accurate metrology data to guide polishing tool.
- Extensive work at many labs has created highly repeatable metrology instruments, including slope measuring profilers (LTP & NOM) & Fizeau- and micro-stitching interferometers.
- As demands for optical quality increases, measurement errors becoming increasingly problematic.
- How can we convert repeatability to accuracy? Calibration & minimisation of systematic errors

- **New instrument: Diamond-VeNOM, an accurate, high-speed, slope profiler of X-ray mirrors**

“Classical” NOM: scanning pentaprism



- Diamond-NOM [1], operational since 2007, has measured 100’s of X-ray substrates & mirror systems
- Step-scan or fly-scan with Elcomat3000 autocollimator (AC) acquisition @ 25 Hz
- Highly repeatable (<< 20 nrad)
- Inspired by BESSY-NOM [2]
- Concept by von Bieren, Qian, Takacs, Lammert, Siewert, et al, since 1980’s
- Successfully replicated at many labs, with extensive developments

[1] S.G Alcock et al, "Diamond-NOM: A non-contact profiler capable of characterizing optical figure error with sub-nanometre repeatability“ https://doi.org/10.1016/j.nima.2009.10.137 (2010).
[2] F. Siewert et al, "Nanometer Optical Component Measuring Machine," in Modern Developments in X-Ray and Neutron Optics (Springer Berlin Heidelberg, 2008).

Instrument measurement errors

- Random errors
  - Reduced by acquiring multiple values (guided by statistical analysis).

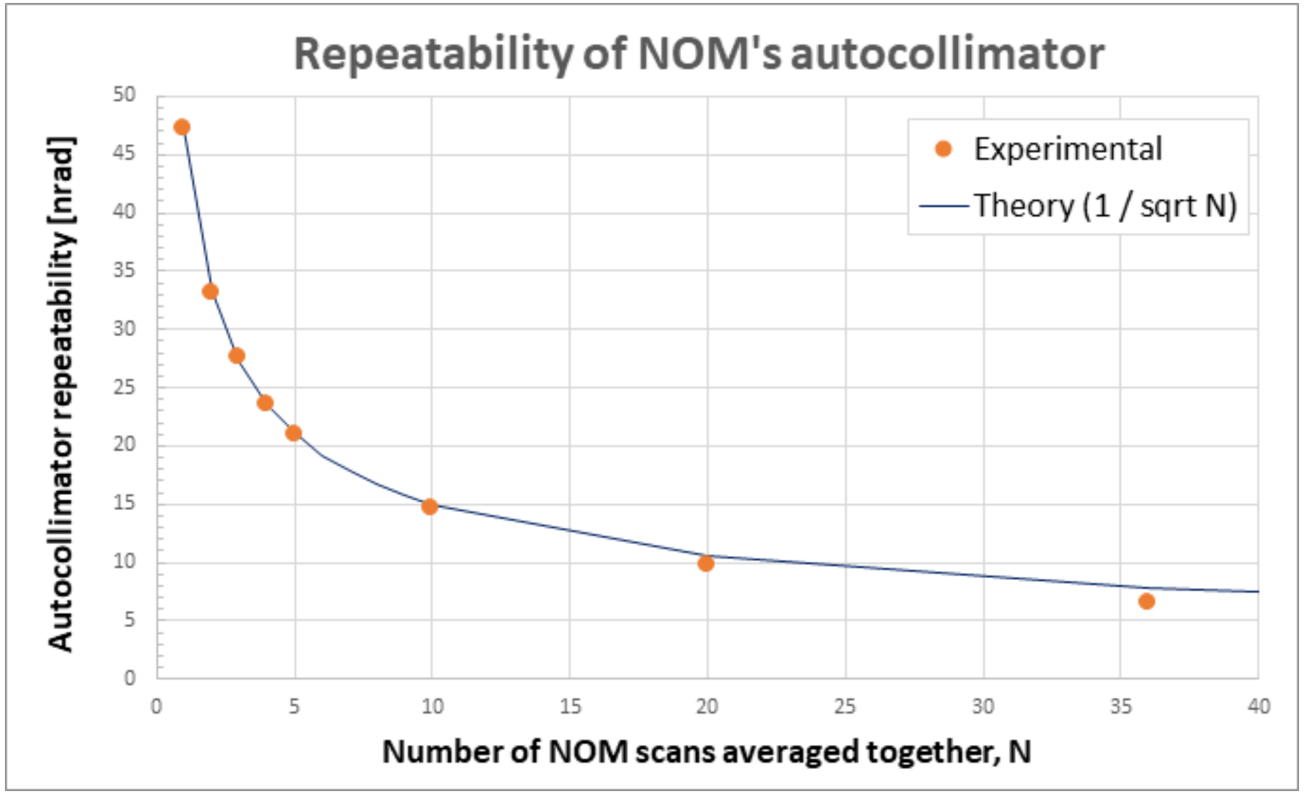
- Systematic errors
  - Environment (temperature, humidity, pressure): varying over hours and days
  - Path length (distance of mirror from AC)
  - Autocollimator's linearity errors: pixel-effect (~11 μrad) + other periods (~280 μrad)
  - Reflectivity & curvature of mirror under test
  - Location & size (& shape) of autocollimator beam-defining apertures
  - Parasitic angular errors of X-axis scan carriage
  - Pentaprism's polishing errors and/or misalignment
  - Vibrations (< 1 sec)
  - Air flow (seconds)
  - Mechanical drifts

- Error minimisation includes:
  - Thermal enclosure around instrument
  - Humidity control
  - Reduce stray light
  - Acoustic damping
  - High-quality optical components
  - NMI calibration
  - Cross-comparison between instruments
  - Round-robin measurements between labs

Ralf Geckeler et al "Environmental influences on autocollimator-based angle and form metrology", Rev. Sci. Instrum. 90, 021705 (2019) https://doi.org/10.1063/1.5057402

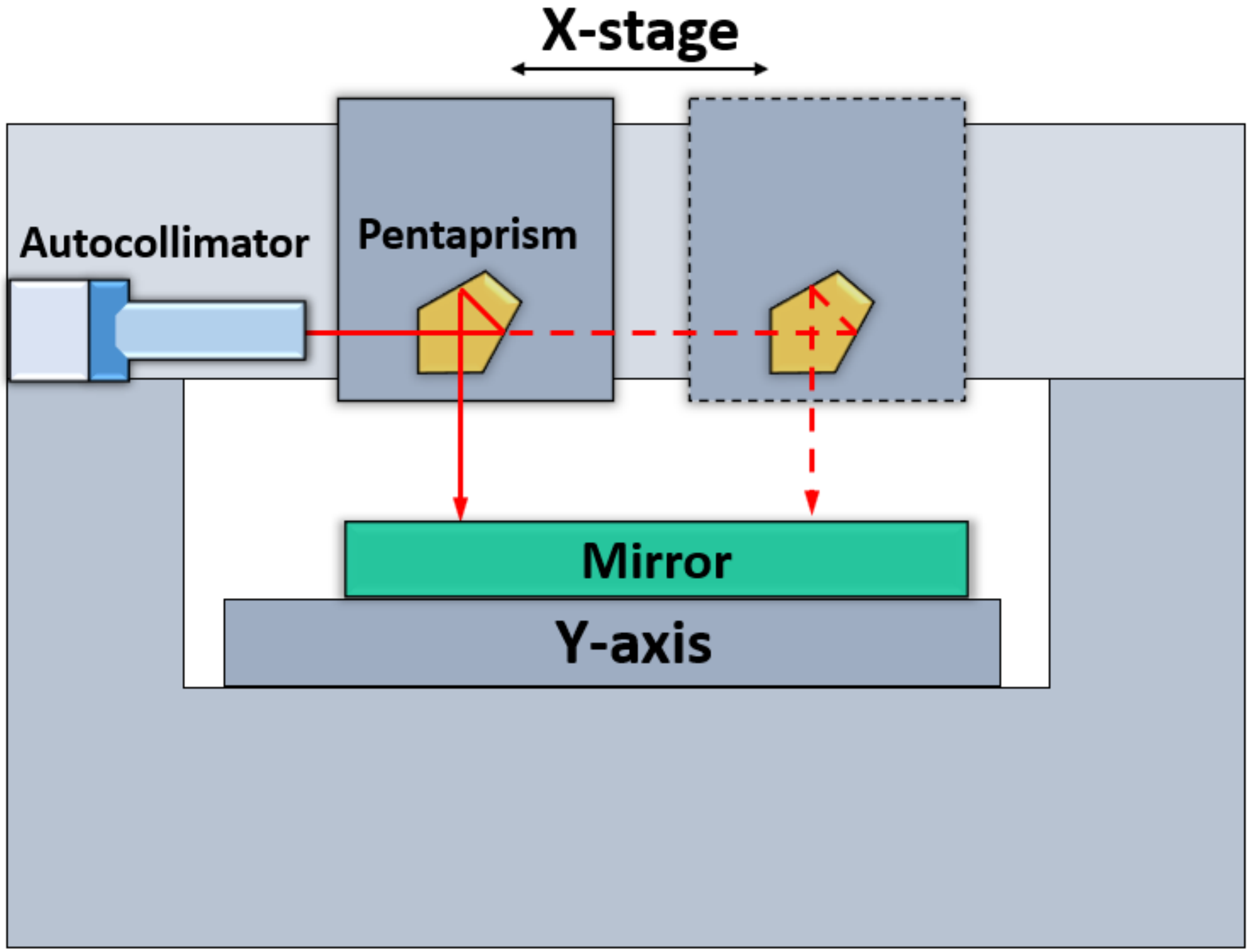
Random errors

- Statistical studies show noise of Elcomat3000 autocollimator is random with a Gaussian (Normal) distribution
- Repeatability = difference between N scans averaged together and average of ensemble
- Circles = AC measured data
- Line = 1/sqrt(N) relationship



Predicts number of scans to be averaged to reduce repeatability to given level (e.g. 20 scans averaged < 10 nrad)

Problems with "Classical" NOM



Problems

- Long, optical path length (> 1m) of AC beam is sensitive to environmental fluctuations
- Variable path length of AC beam

Solutions

- Small-angle generators for self-calibration
- NMI calibration of AC (but only for limited number of parameters)

Ralf D. Geckeler et al, "Distance-dependent influences on angle metrology with autocollimators in deflectometry," Proc. SPIE 7077, 70770B (2008) https://doi:10.1117/12.793742

Strategies to reduce systematic errors

- Measure mirror in multiple configurations to change systematic errors
  - Vary path length of AC beam
  - Flip mirror by 180 degrees (AB vs. BA), or use combinations AB & BA (Yashchuk *et al*)
  - Pitch mirror: use different regions of AC's measurement range (pixel effect etc)
  - Change environmental conditions: add variable wait times between scans, or measure at different times of day, to vary influence of environmental periodicities (Yashchuk *et al*)
  - Monitor everything & compensate using NMI calibration of AC (e.g. PTB, Germany)

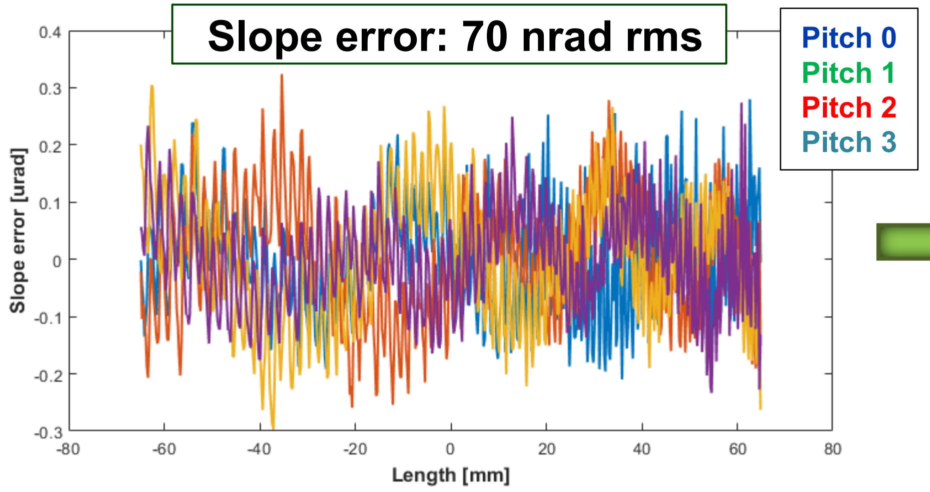
- Error reduction algorithms:
  - Average: Sum different types of scans together to "average away" systematic errors
  - Separate systematic errors from mirror's polishing marks:
    - L.E.E.P algorithm (Nicolas, Polack, Thomasset)
    - Angle shearing (Geckeler *et al*)

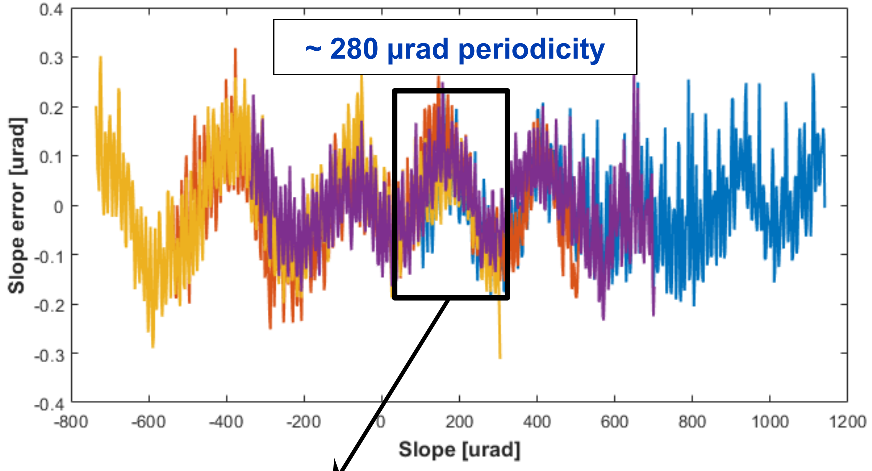
Works very well! But lots of scanning = lots of time

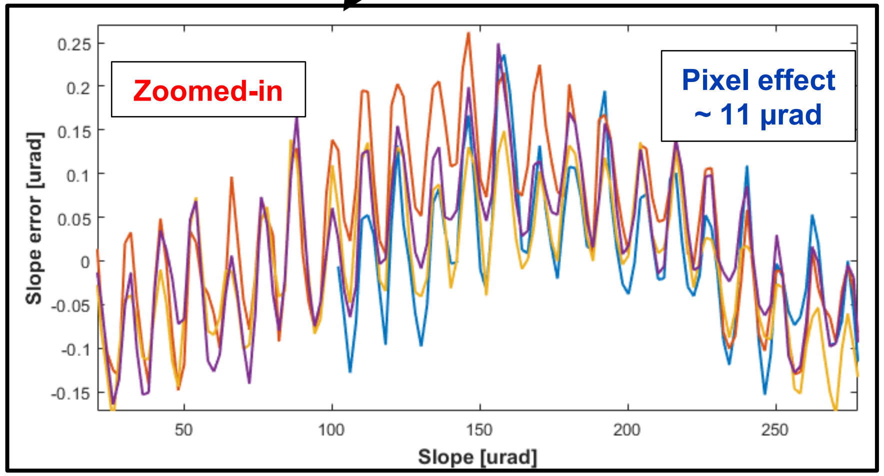
Measuring curved mirrors with slope errors < 50 nrad

- Super-polished, strong ellipticity mirror from JTEC (160 mm long, R ~ 50 m) for I14 nano-probe beamline

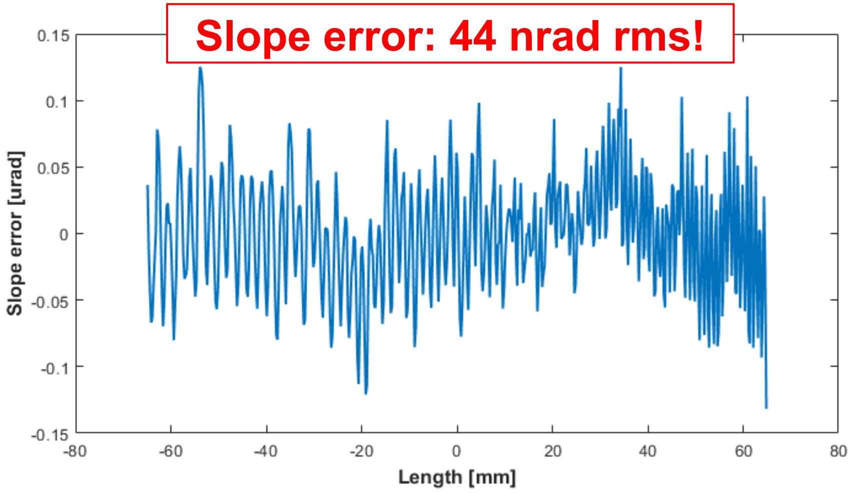
Measuring at multiple pitch angles reveals NOM autocollimator's errors → remove from data to reveal mirror's surface!







Subtract AC systematic errors



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Systematic errors: nearly 20 years later…

The Nanometer Optical Component Measuring Machine: a new Sub-nm Topography Measuring Device for X-ray Optics at BESSY

Frank Siewert, Tino Noll, Thomas Schlegel, Thomas Zeschke, and Heiner Lammert

Citation: AIP Conference Proceedings **705**, 847 (2004); doi: 10.1063/1.1757928

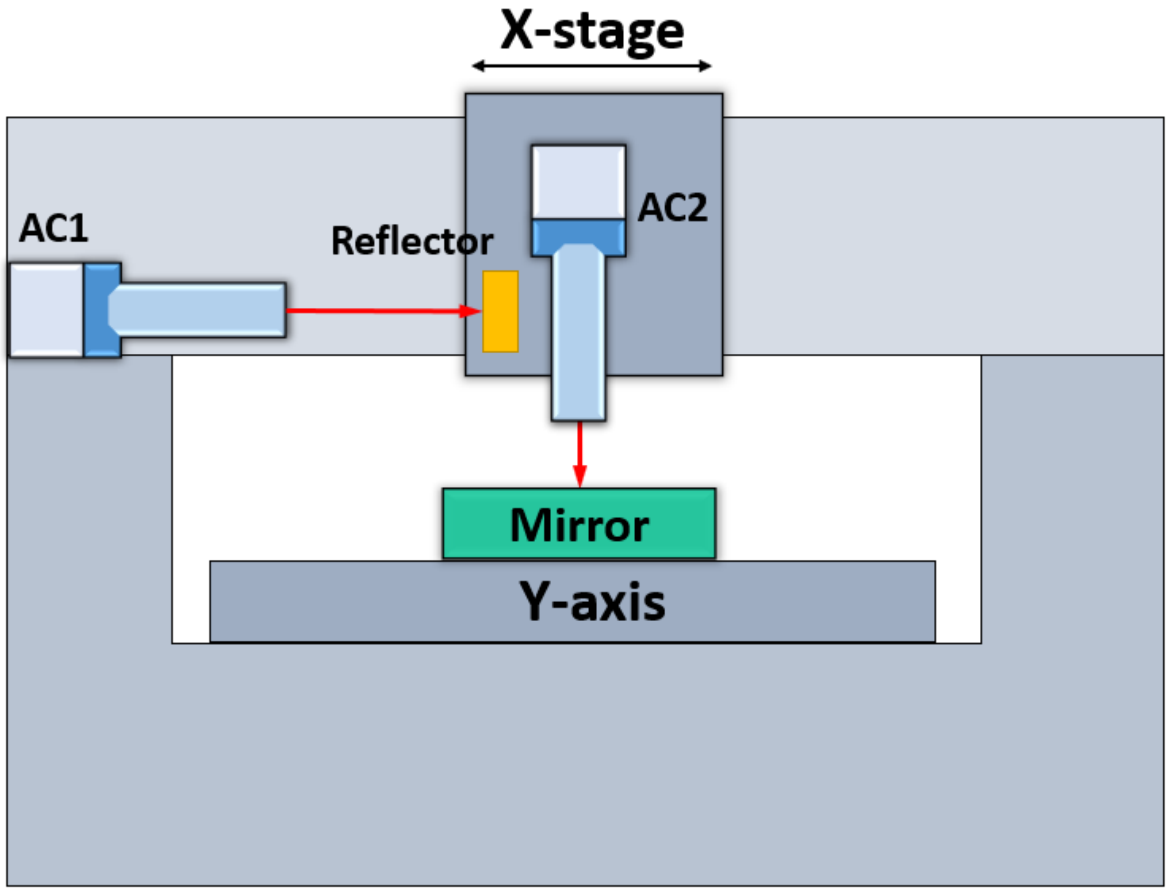
View online: http://dx.doi.org/10.1063/1.1757928

ENGINEERING CONCEPTION AND DESIGN OF THE NOM

The measurement uncertainty of the best surface measuring devices to day, like the Long Trace Profiler (LTP) [2] is limited to about 0.1 arcsec rms [3]. Only in special cases, could this 0.1 arcsec rms limit be improved [4]. The main problem is a multitude of systematic errors, which are not easily detected in the measurement result. To acquire a

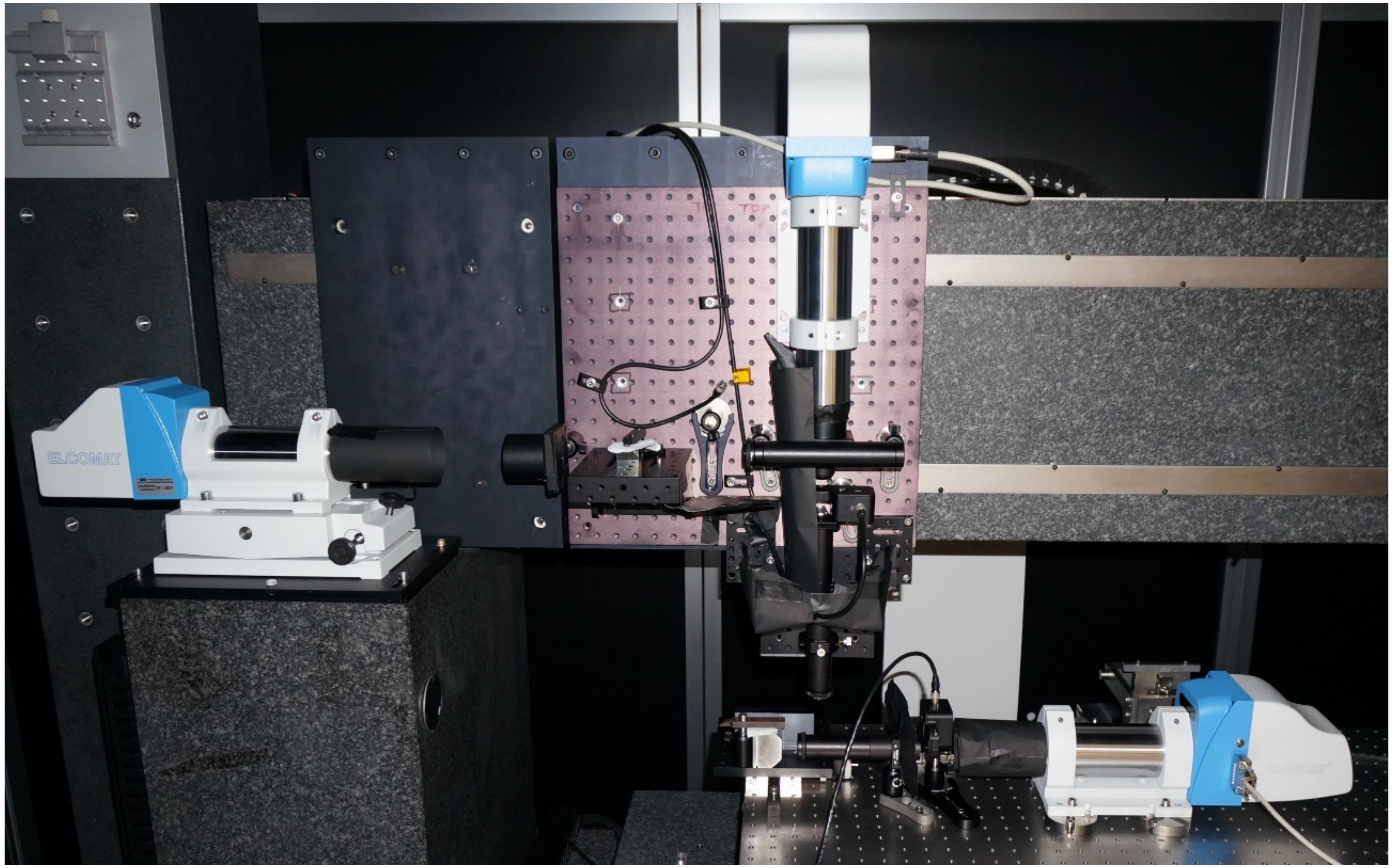
Double AC setup

- To reduce path-length errors, & improve accuracy, double AC NOM's developed at Brookhaven & Lawrence Berkeley National Labs [3,4] + ?
- AC1 only sees small parasitic angles of X-axis variations: less sensitive to path length changes ☑
- Fixed path length for AC2 measuring optical surface ☑
- Reduces systematic errors, but doesn't address several systematic errors, including differences in reflectivity or curvature of mirror under test ☒



[3] Qian and Idir, "Innovative nano-accuracy surface profiler for sub-50 nrad rms mirror test," https://doi.org/10.1117/12.2247575 (2016).
[4] Lacey et al, "Development of a high performance surface slope measuring system for two-dimensional mapping of x-ray optics," https://doi.org/10.1117/12.2273029 (2017).

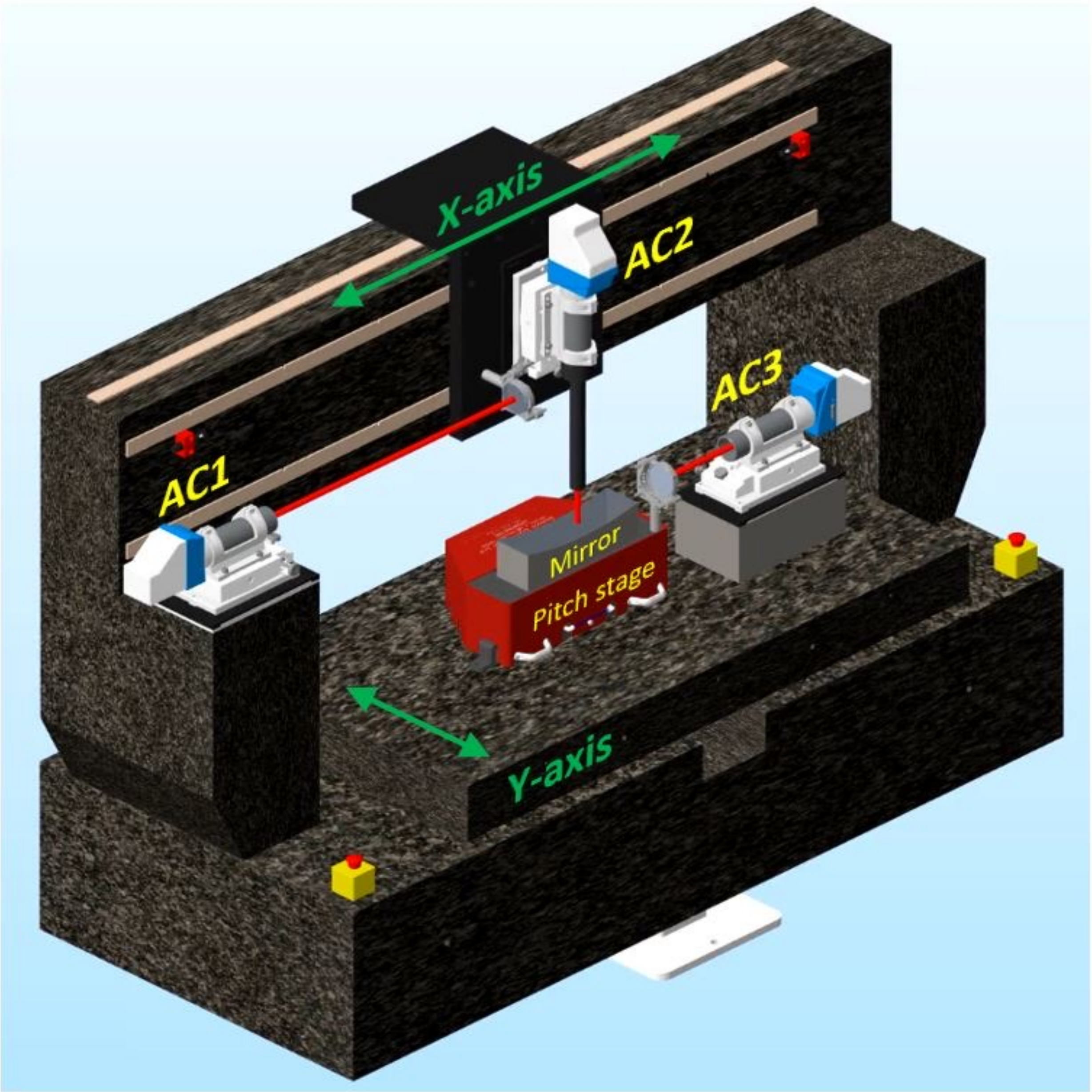
Diamond-VeNOM (velocity-NOM)



New VeNOM concept

- Freeform motion of translation stage, synchronized with dynamic pitch changes of test optic **DURING** scanning
- All motion synchronised with autocollimator data via triggered shutters
- Combines metrology benefits of previous schemes & provides many new possibilities!

Diamond-VeNOM (velocity-NOM)



- Mirror under test placed on a motorized pitch stage which moves **DURING** scan
- AC1: mounted on side pillar, monitors parasitic angles during freeform motion of X-stage
- AC2 (Elcomat 5000): mounted on X-stage, directly measures optical surface
- AC3: monitors angle of a reflector located on motorized pitch stage

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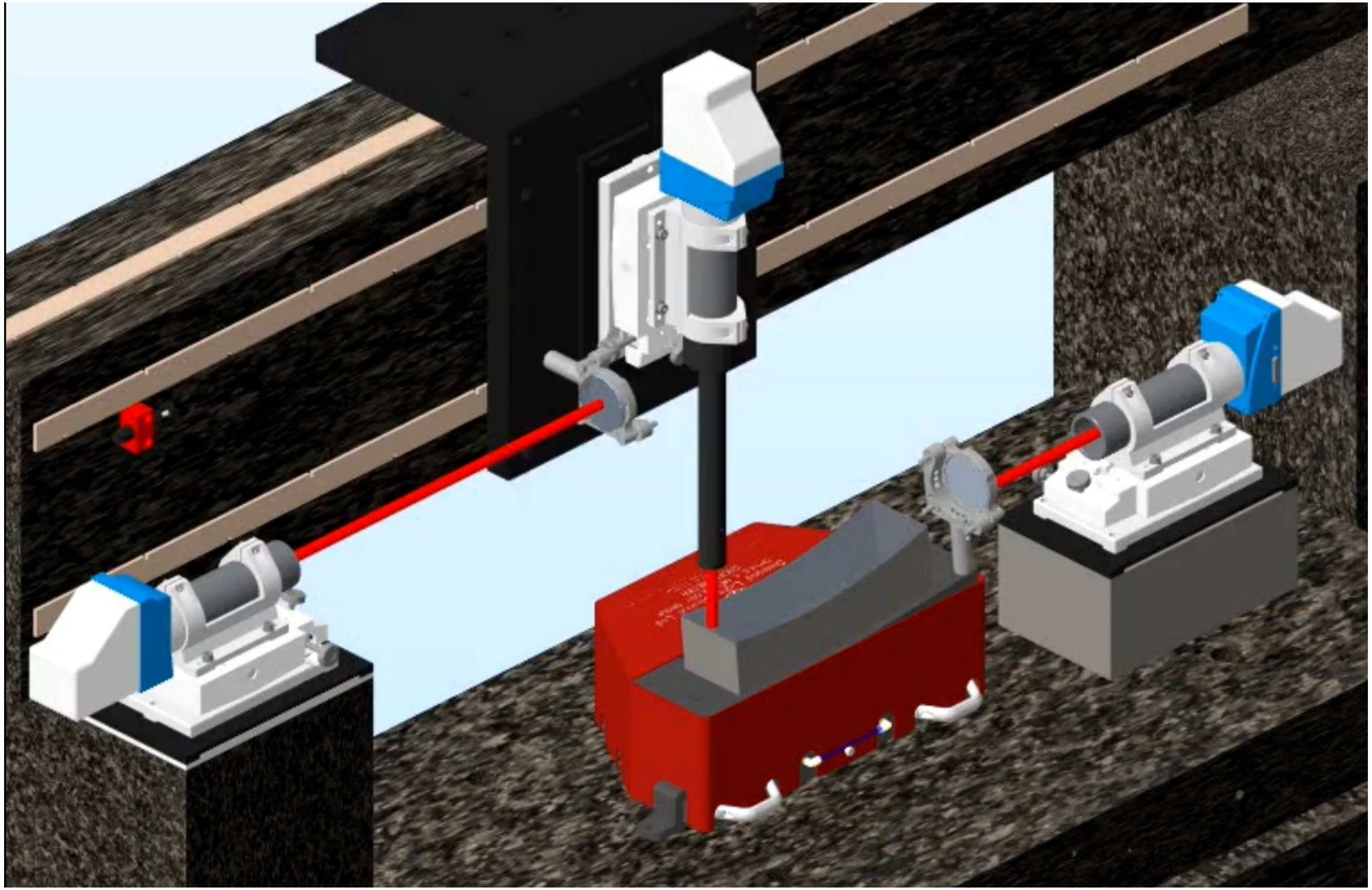
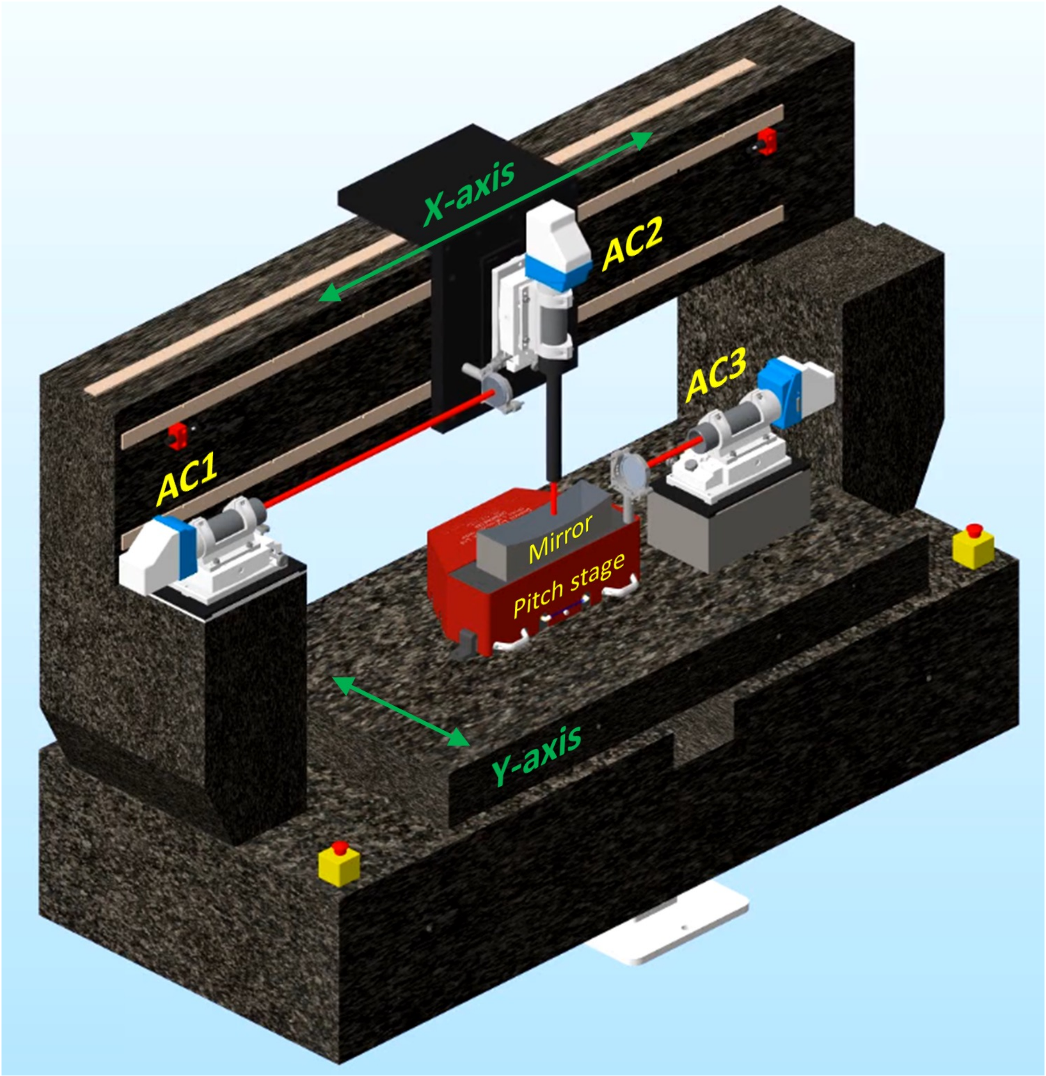
Diamond-VeNOM (velocity-NOM)



Improved accuracy

- AC1 = flat mirror on X-axis stage. Angles ~ few microrad, so length-dependent issues (affects single AC + pentaprism) are minimized
- AC2 = mirror under test & calibrated for fixed distance. Optical surface is continuously nulled for each measurement point. Systematic errors from curvature or reflectivity are negligible for small angles measured
- AC3 = flat mirror on pitch stage. Observes large angles, but always measures same flat mirror under fixed conditions (distance, curvature, reflectivity & larger aperture). Can be calibrated for this specific case at NMI



New hardware for VeNOM

- Synchronization rates required for VeNOM cannot be supported by NOM's old instrumentation hardware

New PMAC Power Clipper controller for NOM's motion stages (Q-Sys)

MÖLLER-WEDEL OPTICAL

New Elcomat5000 autocollimator: 10x faster acquisition @ 250Hz

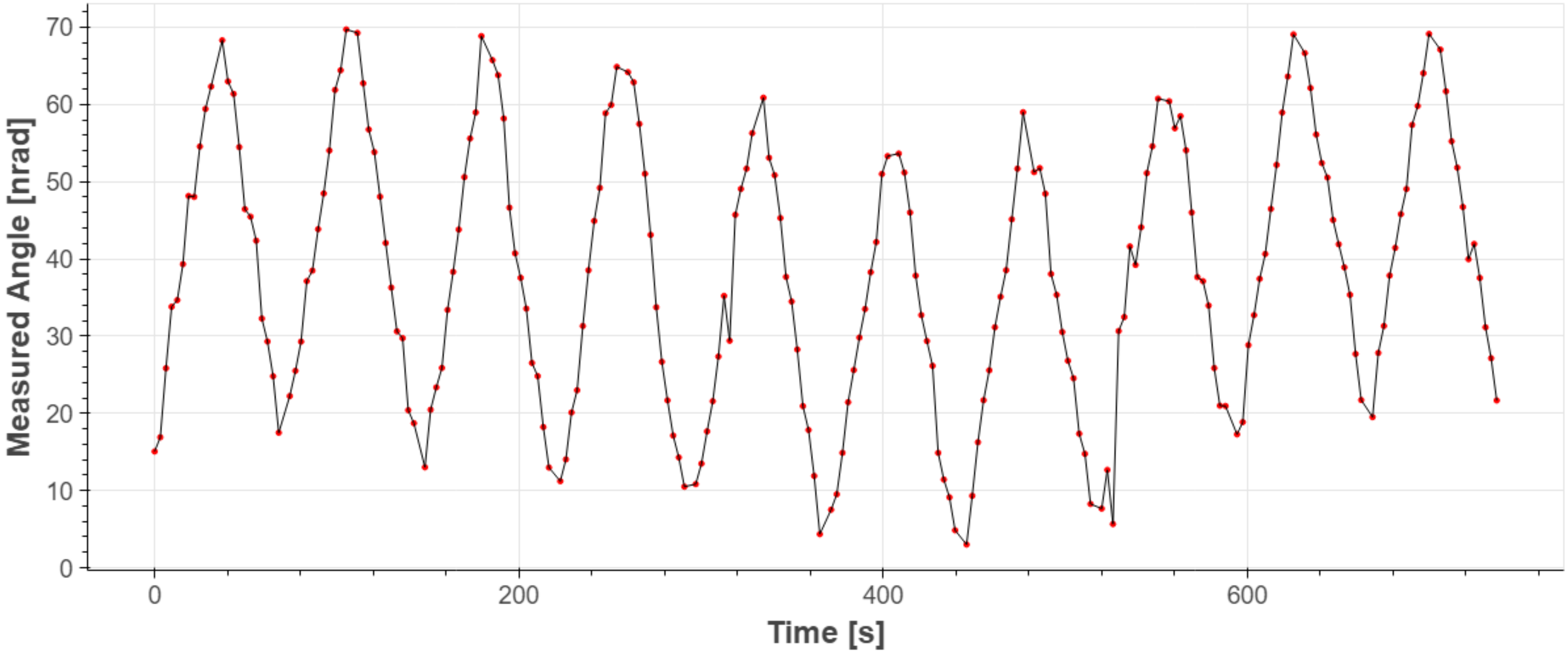
MOXA box serial server

Electro-mechanical rotary shutters (Thorlabs SH-05)

PandA box acquisition & control system (encoder inputs & triggers fast mechanical shutters)

Elcomat5000 performance: 5 nrad steps

- Stair-case of ultra-small angle steps (generated by Diamond-NANGO) as viewed by E5k



S.G Alcock et al. "A novel instrument for generating angular increments of 1 nanoradian", Rev. Sci. Instr. 86, 125108 (2015) https://10.1063/1.4937352

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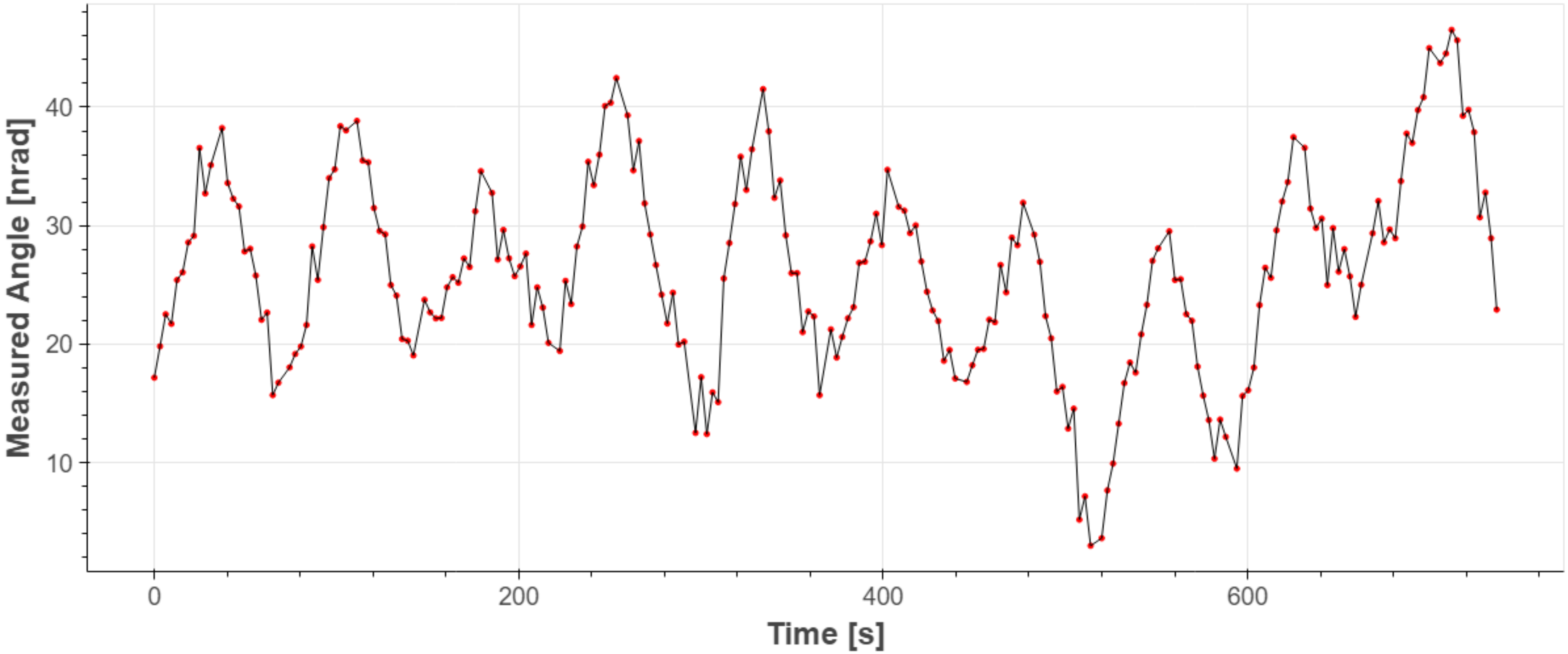
Elcomat5000 performance: 2 nrad steps!!!

- Stair-case of ultra-small angle steps (generated by Diamond-NANGO) as viewed by E5k



S.G Alcock et al. "A novel instrument for generating angular increments of 1 nanoradian", Rev. Sci. Instr. 86, 125108 (2015) [*https://10.1063/1.4937352*](https://10.1063/1.4937352)

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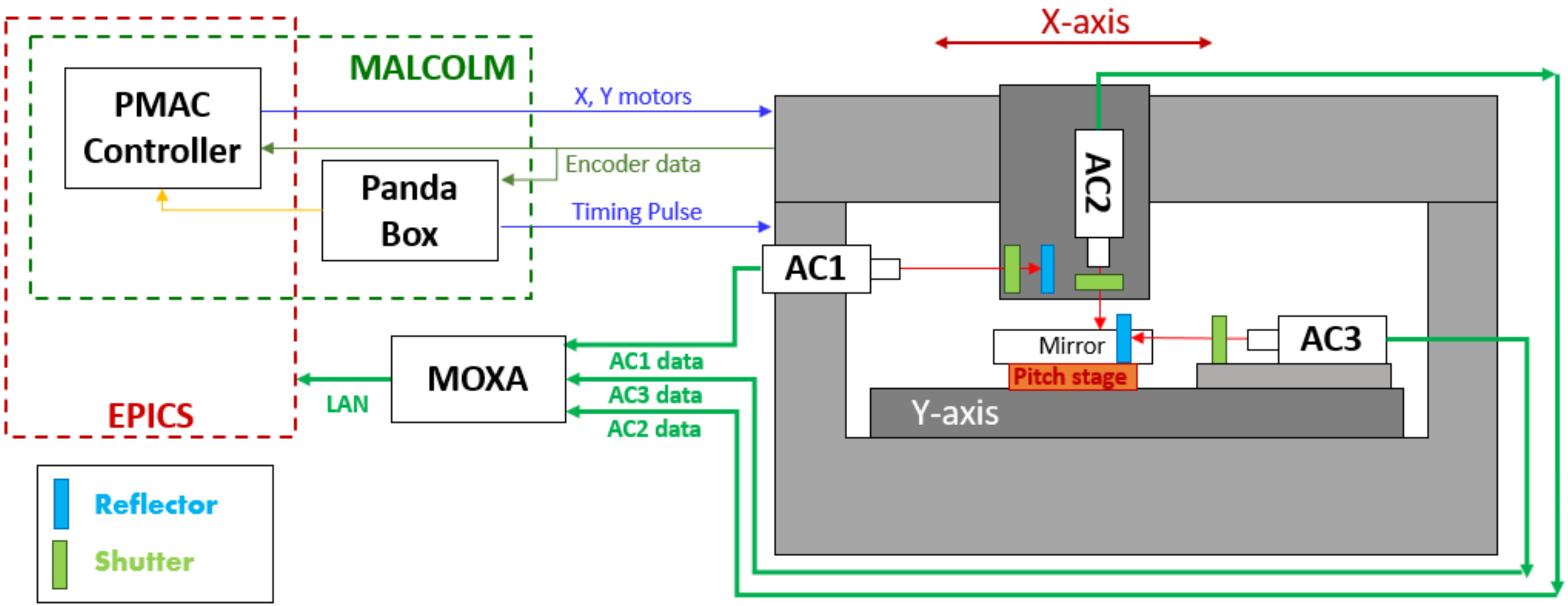
Co-ordination between X-axis, pitch stage & ACs

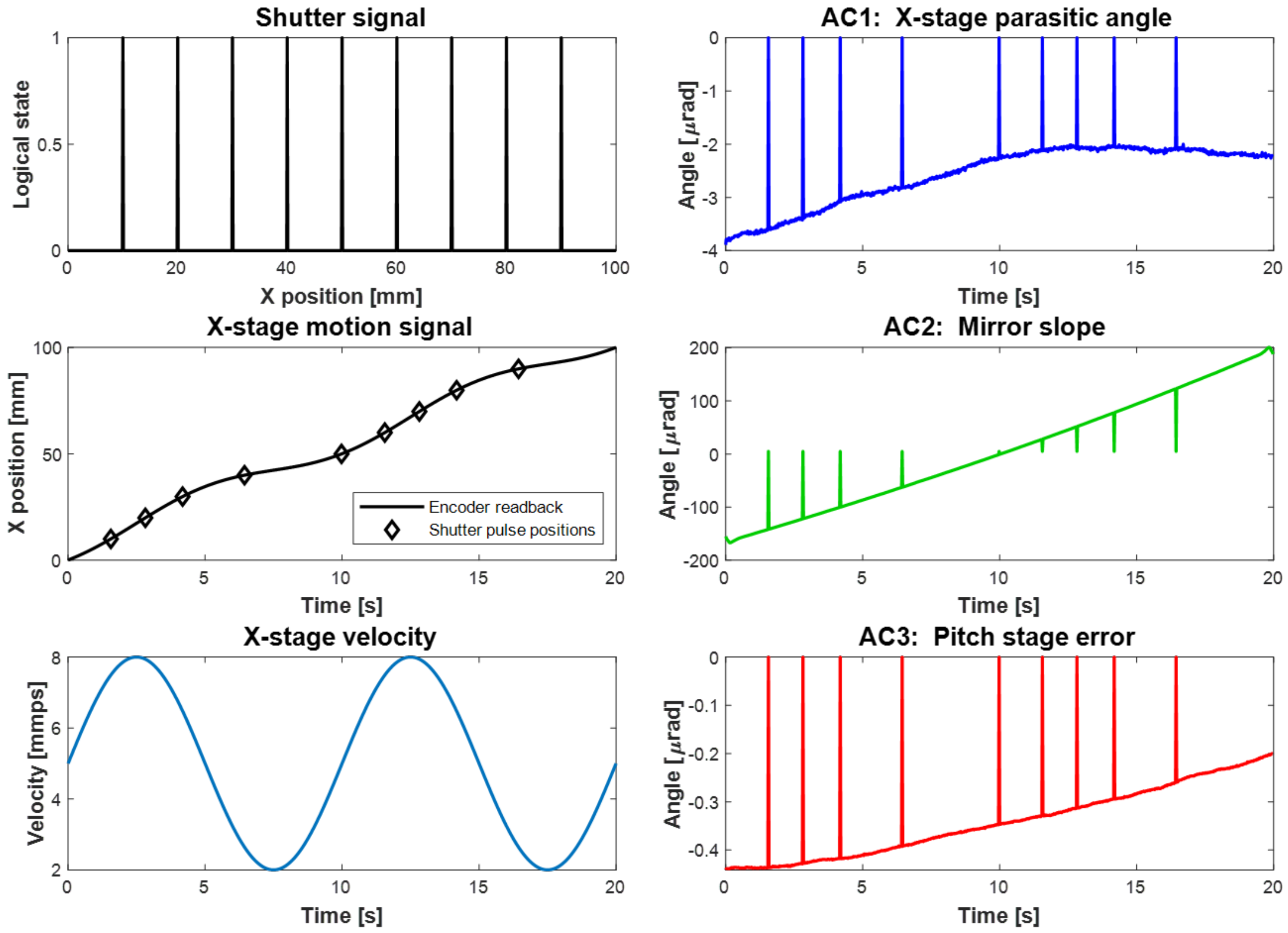


- New power PMAC controller + PandA I/O box → synchronisation of motion stages & shutters, via Malcolm framework & Mapping Project
- Powerful & adaptable UI with python scan & analysis scripts (enhanced automation & metadata logging)

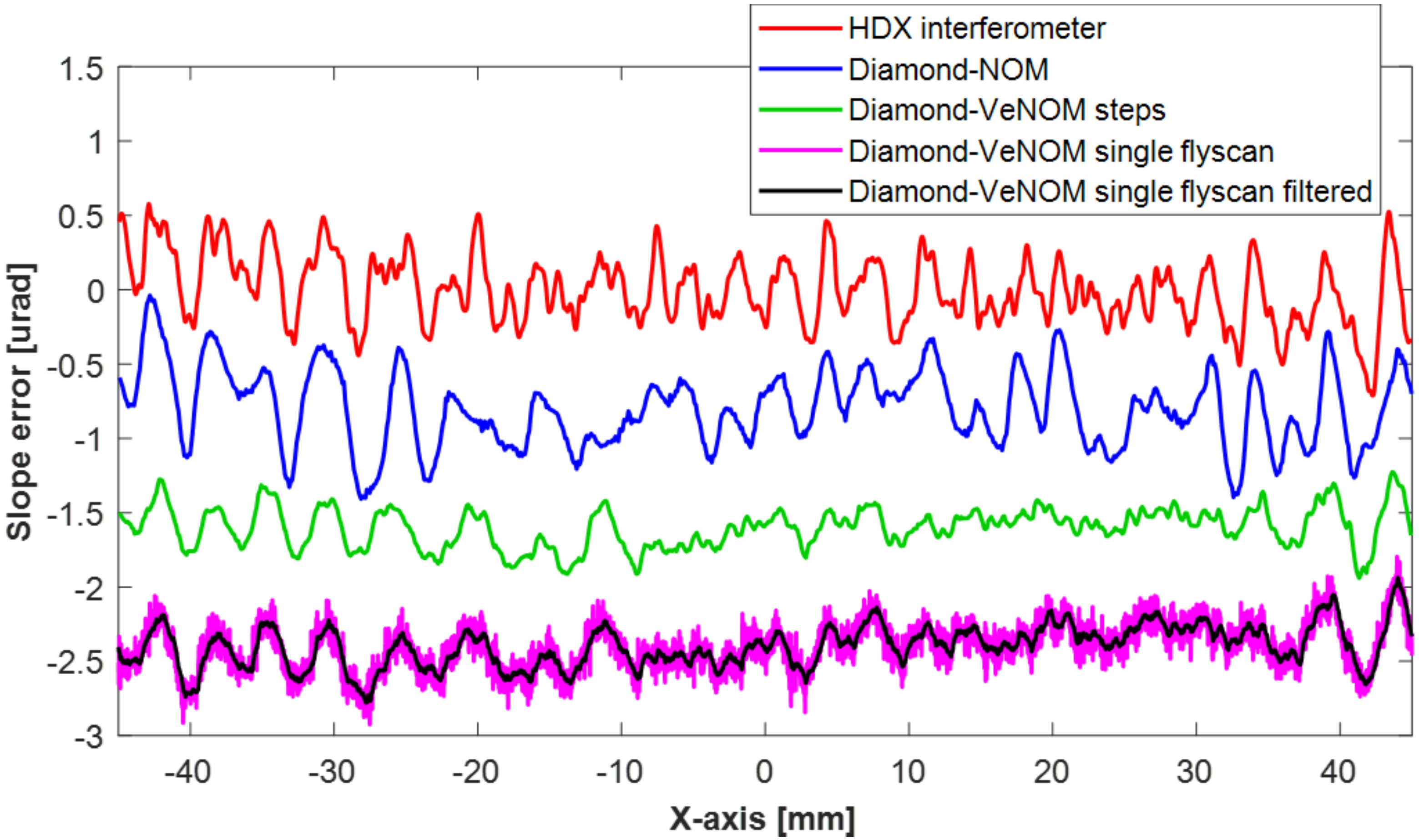
Enables dynamic, freeform trajectories for motion axes: Position, Velocity, Time (PVT)

Data synchronisation

- Shutters triggered once translation and/or pitch stage reach user-defined positions and/or angles
- Null values embedded within autocollimator data stream align with motion trajectories & location on optical surface



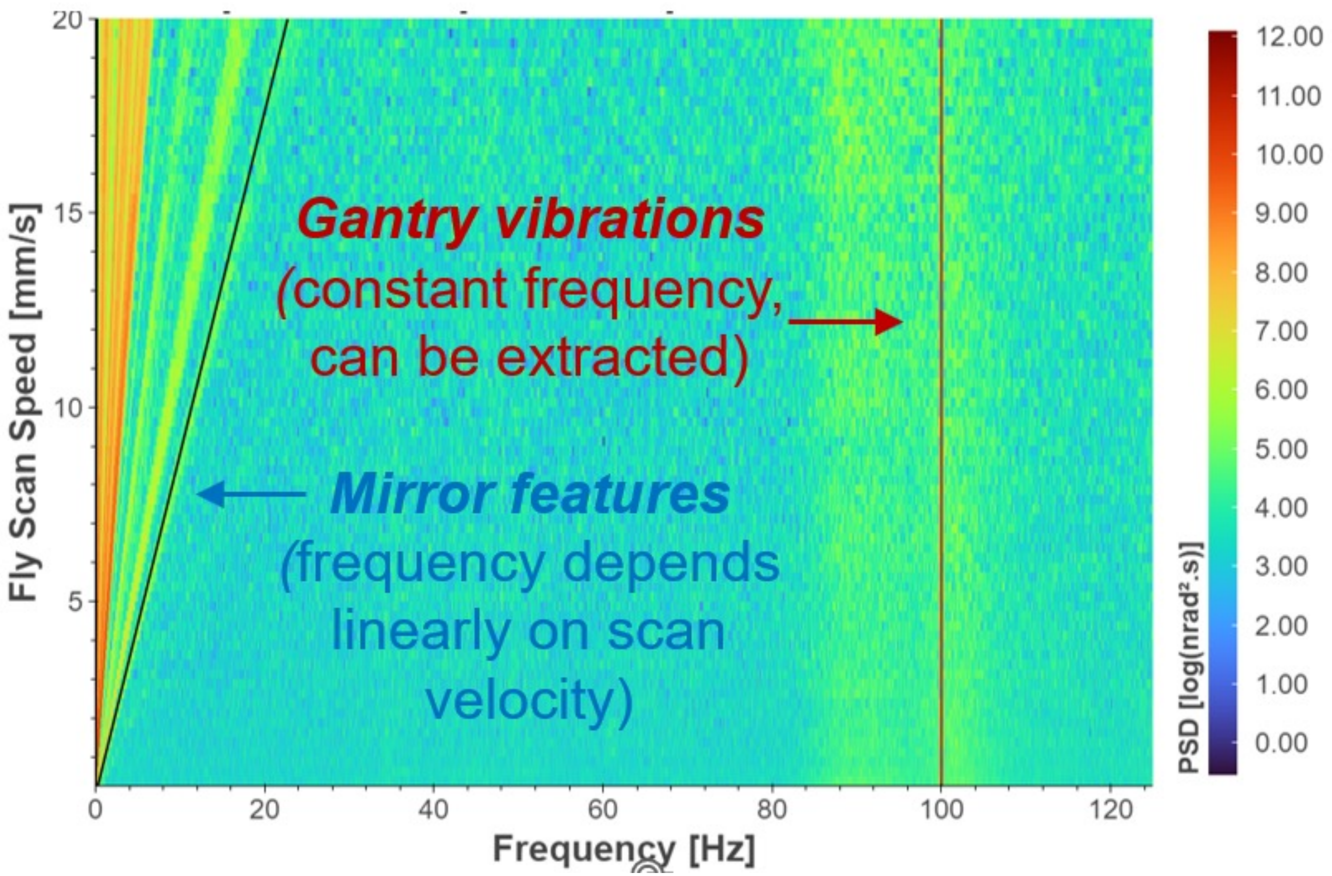
Cross-comparison



- Good agreement between instruments for 100 nrad X-ray mirror with elliptical profile
- Spatial filtering of single fly-scan in close agreement with average of multiple fly-scans

10x faster AC & fly-scan operation → 30 seconds / measurement!

Separating polishing marks from vibrations / noise



Concept

- Fly scan @ 80 different speeds
- Calculate PSD of measured AC angle as function of time (1/f)
- Plot Power Spectral Density (PSD) versus frequency & scan speed

- **Mirror's surface information: spreads linearly as speed increases**
- **Vibrations of NOM's gantry: constant frequency**

Dynamic nulling of optical surface

- Angle measured by AC2 is function of position (X-axis) & time:

θ_{AC2} *(x, t)* = *Mirror's slope profile (x)*

+ Mirror's slope errors (x)

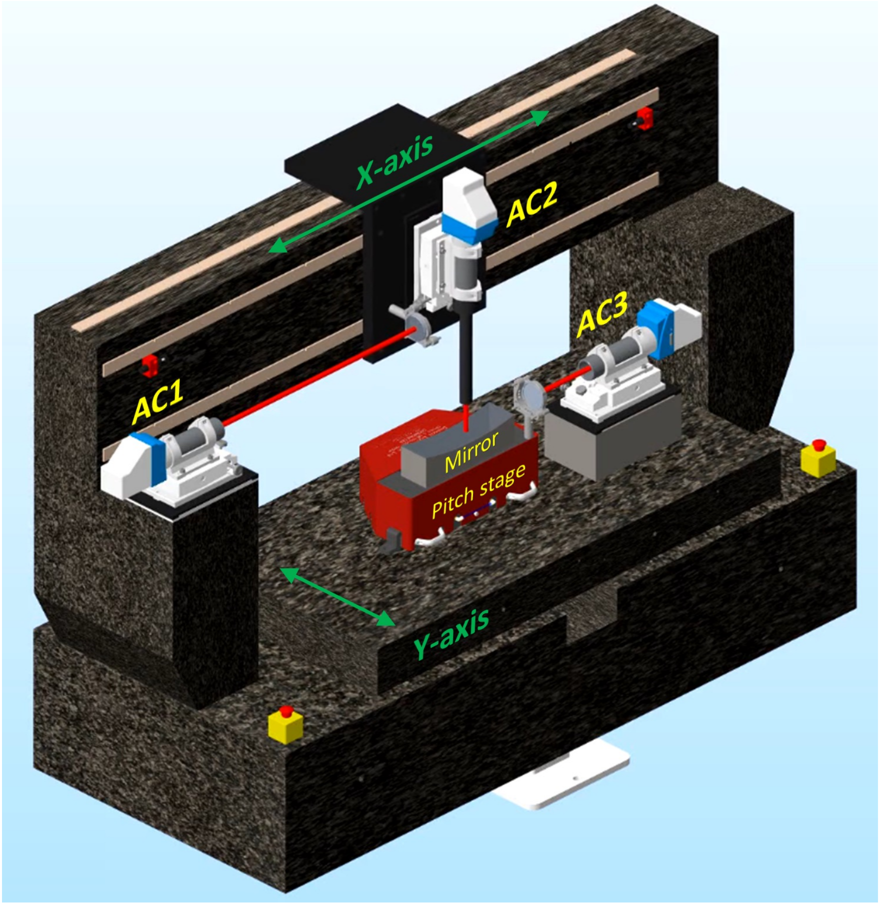
+ Parasitic angle of X-stage (x)

+ Pitch angle of goniometer (t)

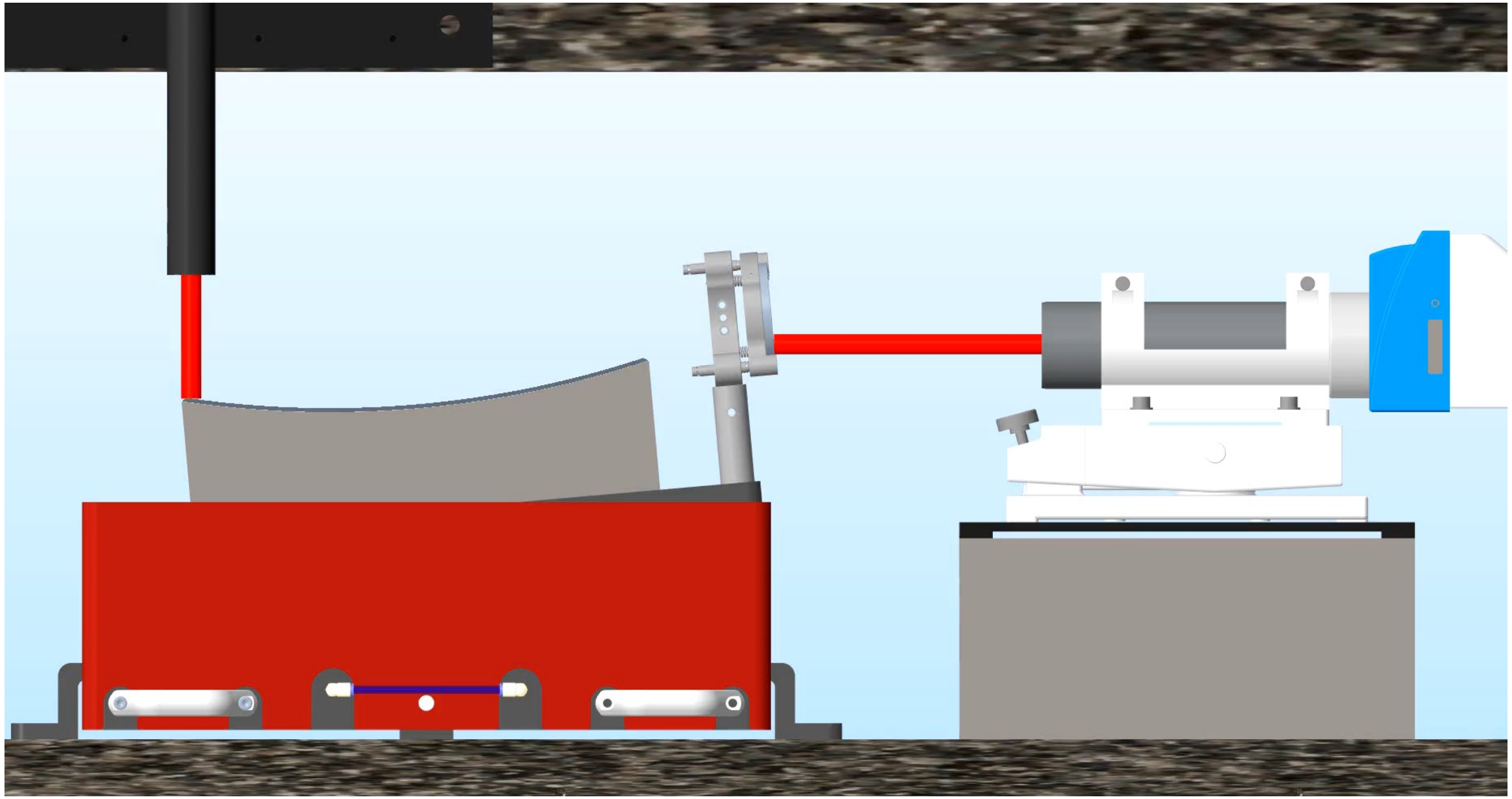
+ AC's linearity errors (θ_{AC2})

+ Vibrations (t)

+ Mechanical & environmental drifts (t)



Dynamic nulling of optical surface



- Principle: minimise angle seen by AC2 (to reduce systematic errors due to curvature, reflectivity, etc)
- Velocity of X-stage & pitch rate chosen to match mirror's slope profile

Dynamic nulling of optical surface

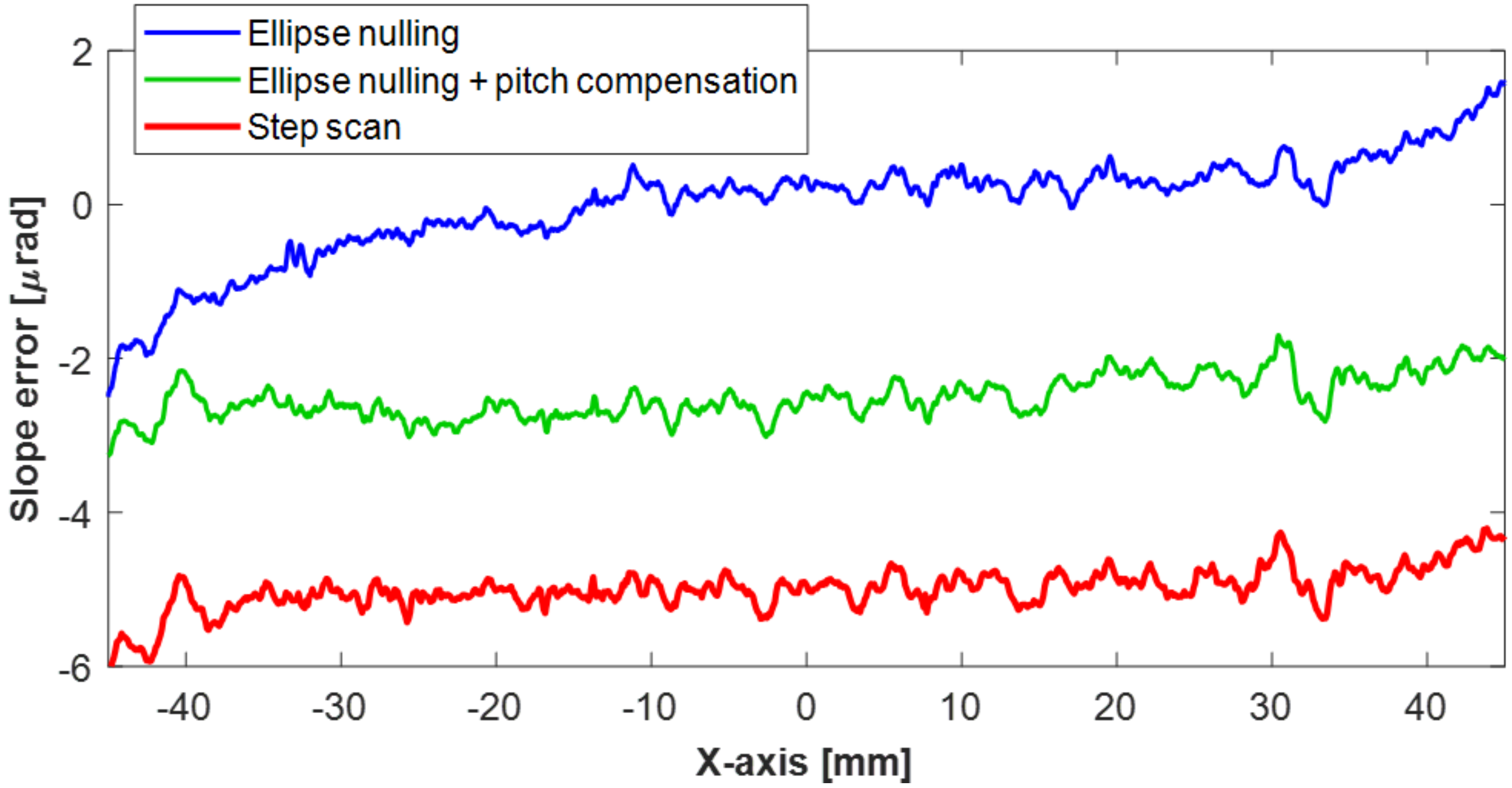
- Can set θ_{AC2} (x, t) ~ 0 throughout scan by careful choice of X-axis speed + pitch stage angle rate
  - Cylinder null = constant velocity for X axis + constant rate of angle change for pitch stage
  - Ellipse null = variable velocity for X axis (elliptical profile) + constant rate of angle change for pitch stage
  - [Ellipse null + correction of pitch stage's linearity errors = add perturbation to variable velocity for X-axis]
- Can choose X-axis speed to match to ANY slope profile (freeform)

ADVANCED: beyond nulling of optical surface!

- Deterministically add angles to nulled measurement to purposefully change experiment during or between each scan:
  - Null the effects of slow-variations in environment (logged by weather station)
  - Apply LEEP algorithm (offset pitch angle) DURING scan
  - Move through specific sections of AC2's measurement range (and/or AC3) to apply an "anti-pixel effect" (or cancel other pseudo-periodicities such as ~ 280 μrad)
  - Apply analytical functions to slope profile (sine wave or chirp) which can be more efficiently extracted ("lock-in" principle)
  - Any crazy ideas to break time, spatial, or angle-dependent symmetries! ☺

In the past, with a fixed curvature mirror, you only had a single slope profile to measure.
Now you can now controllably apply any slope profile you want!!!

Experimental: nulling an elliptical profile



Slope measured during nulled fly-scan

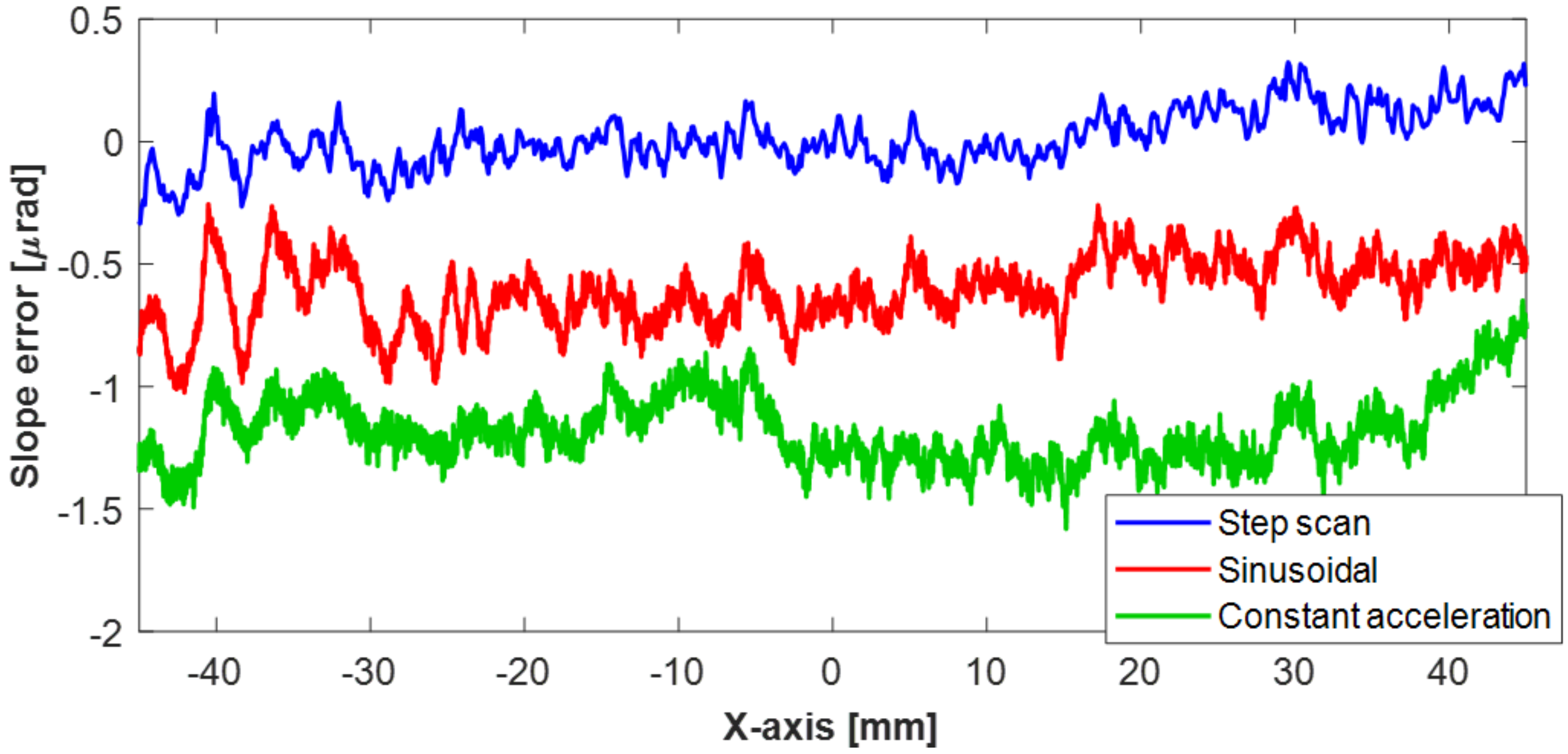
Slope measured during nulled fly-scan after compensating for pitch rate errors of goniometer

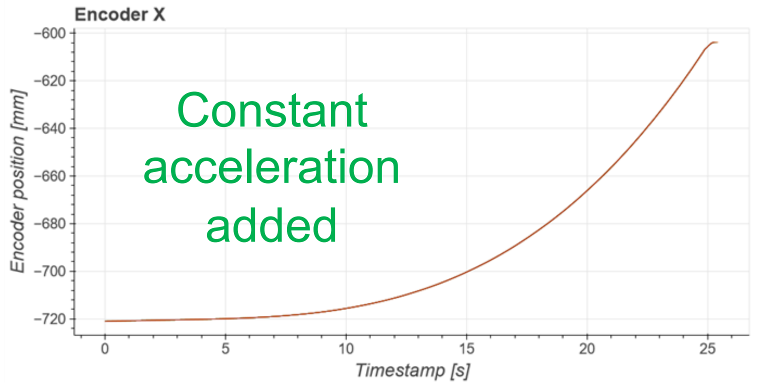
Slope error measured by step scan with no nulling

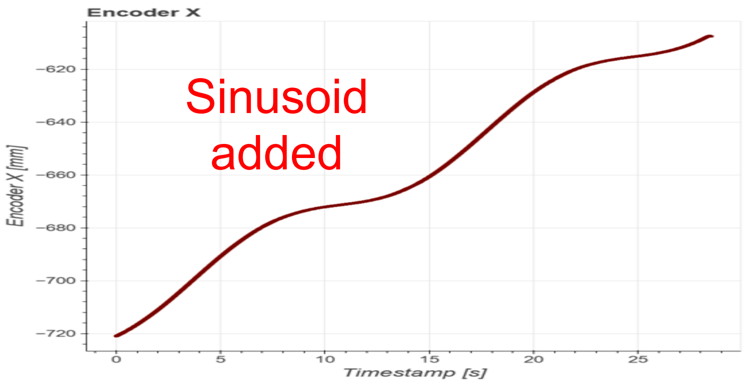
- To ensure that AC2 sees zero angle (to minimise systematic errors), linear velocity of X-axis & angular velocity of pitch stage were co-ordinated to null elliptical slope profile of 100 nrad X-ray mirror

Experimental: Deterministic trajectories

- Deterministically add sinusoid or constant acceleration to nulled measurement of 50 nrad X-ray mirror
- Principle proven ☑
- Further commissioning & development ☺







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Summary

- Diamond-VeNOM: fast & versatile slope profilometer utilising multiple ACs with 250 Hz acquisition
- Combines advantages of several previous schemes
- **Adds a new concept: freeform, dynamic scanning of the mirror, including pitching the mirror DURING scan!**
- **All motions synchronised with autocollimator data via triggered shutters**
- Reduced systematic errors to improve accuracy
- Fly-scanning, combined with speed enhancement of new autocollimators, leads to a 20X time efficiency of VeNOM compared to Diamond-NOM, without loss of data quality
- VeNOM can accurately measure a 100 nrad mirror in 30 seconds using “Super-fly”!

Acknowledgements

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- **Collaborators within our metrology community for sharing their great ideas!**