The Renovated Aperture Area Measurement Facility at NIST


Moongate Garden, Washington D.C.

Ulf Griesmann, NIST

Council for Optical Radiation Measurement
Virtual Meeting, November 12-14, 2024

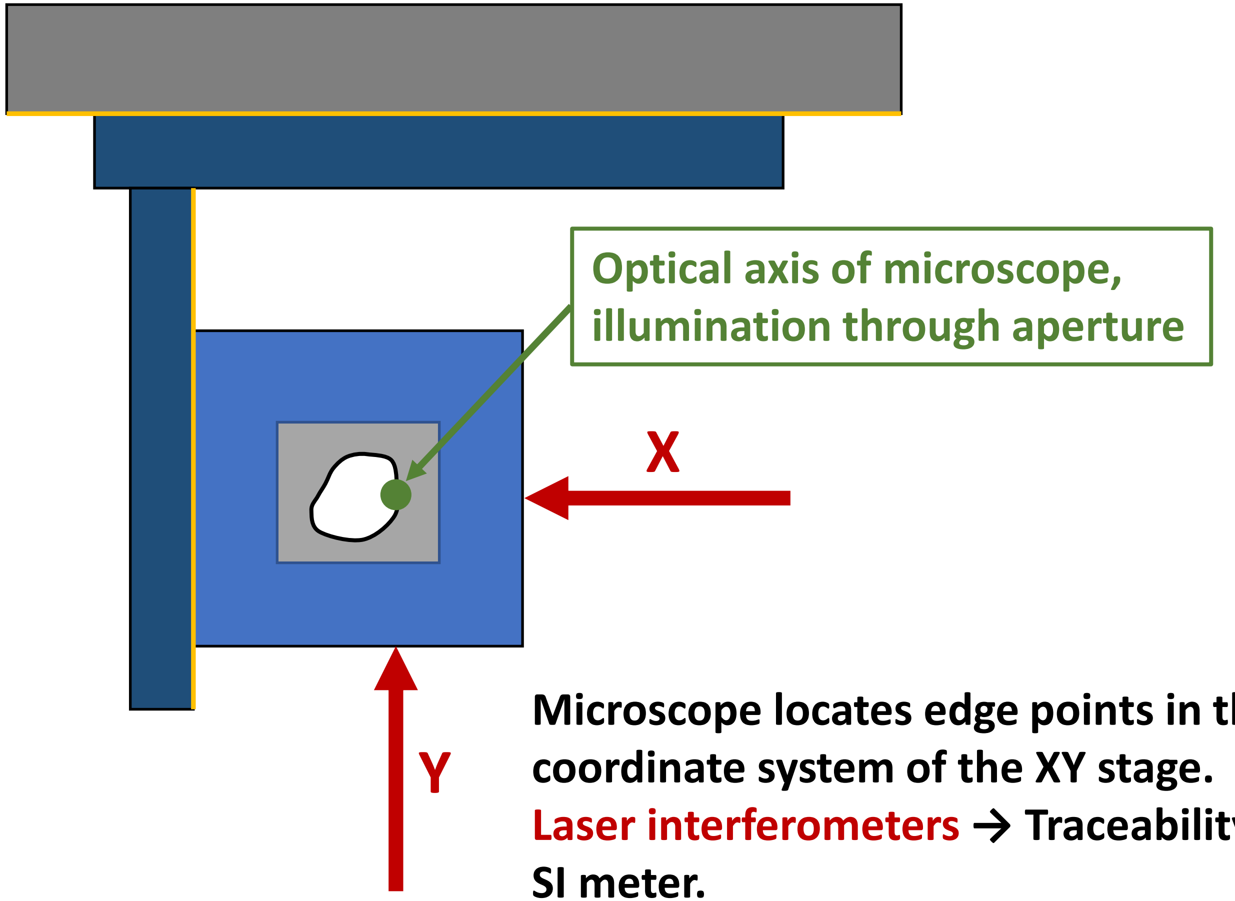
A Look Back to the Beginnings

The original AAM (1999).

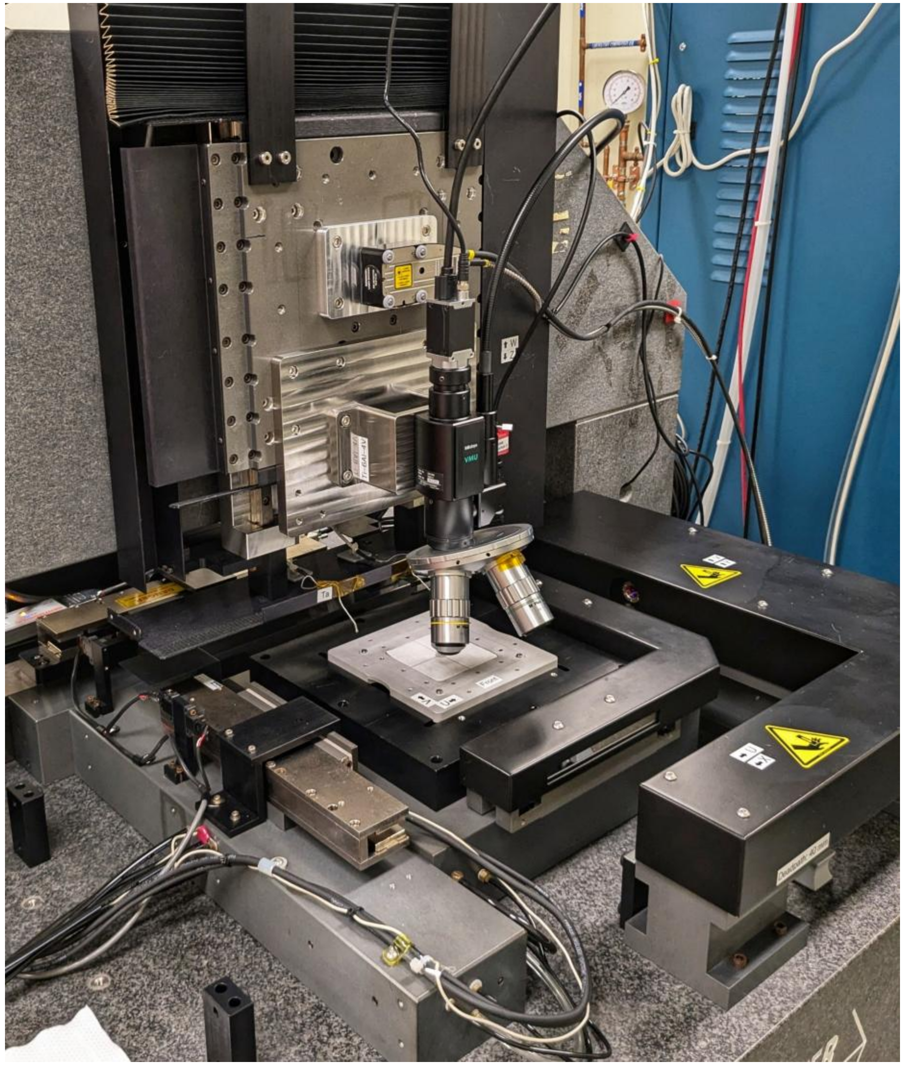
- In mid-1990's: NIST decides to develop an instrument for the measurement of radiometric aperture areas with **direct traceability to the SI length unit** (unlike radiometric flux comparators).
- Aperture Area Measurement (AAM) facility was constructed 1996-1999
  - Ravi Shankar Durvasula, Tufts University
  - Joel B. Fowler, NIST
  - Robert Saunders, NIST
  - Benjamin Tsai, NIST
  - Maritoni Litorja, NIST (after 2000)

Aperture Area Measurement Concept

The AAM is a specialized optical coordinate measuring machine.



Microscope locates edge points in the coordinate system of the XY stage. Laser interferometers → Traceability to SI meter.



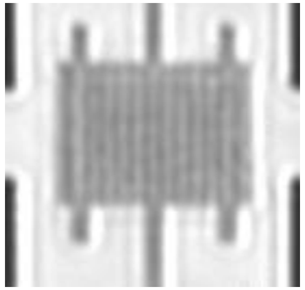
Original AAM Capabilities

- Laser interferometers with resolution close to 1 nm (new interferometers in 2009 with 10 nm resolution).
- Optical brightfield *transmission* microscope.
- Megapixel CCD camera (in 2000 about as much as a PC-type computer could handle).
- Illumination with QTH lamp and green 550 nm (40 nm bandwidth) filter. Not enough light for high-magnification objectives.

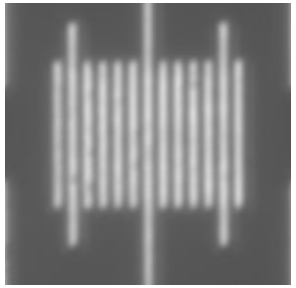
Important Hardware Improvements

LED illuminators (525 nm and white)

NIST SRM2800 Stage Micrometer
1 µm pitch lines



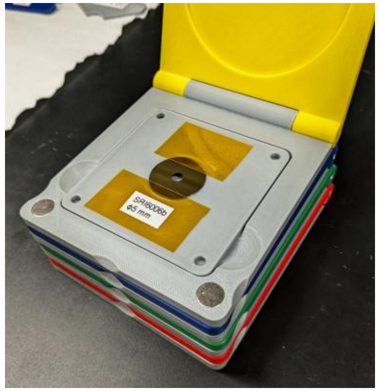
Old



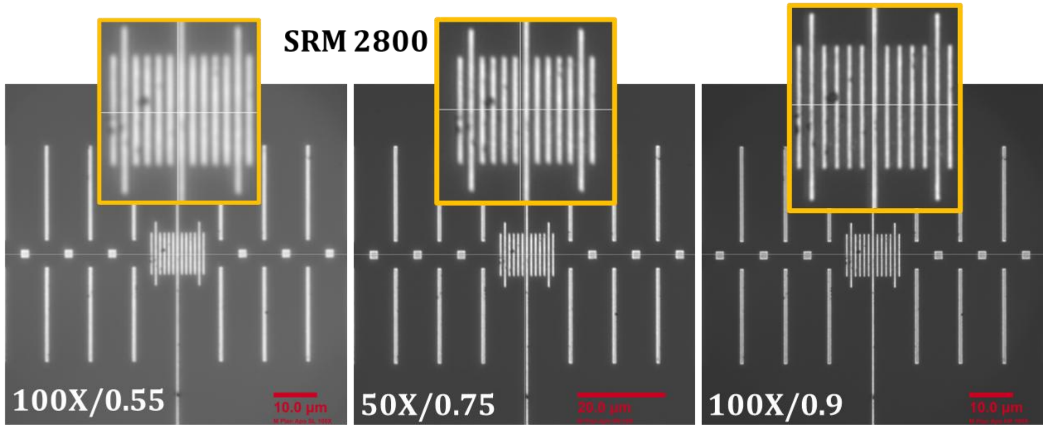
New

100X/NA=0.55 objective

New microscope, new camera, additional high-NA objectives

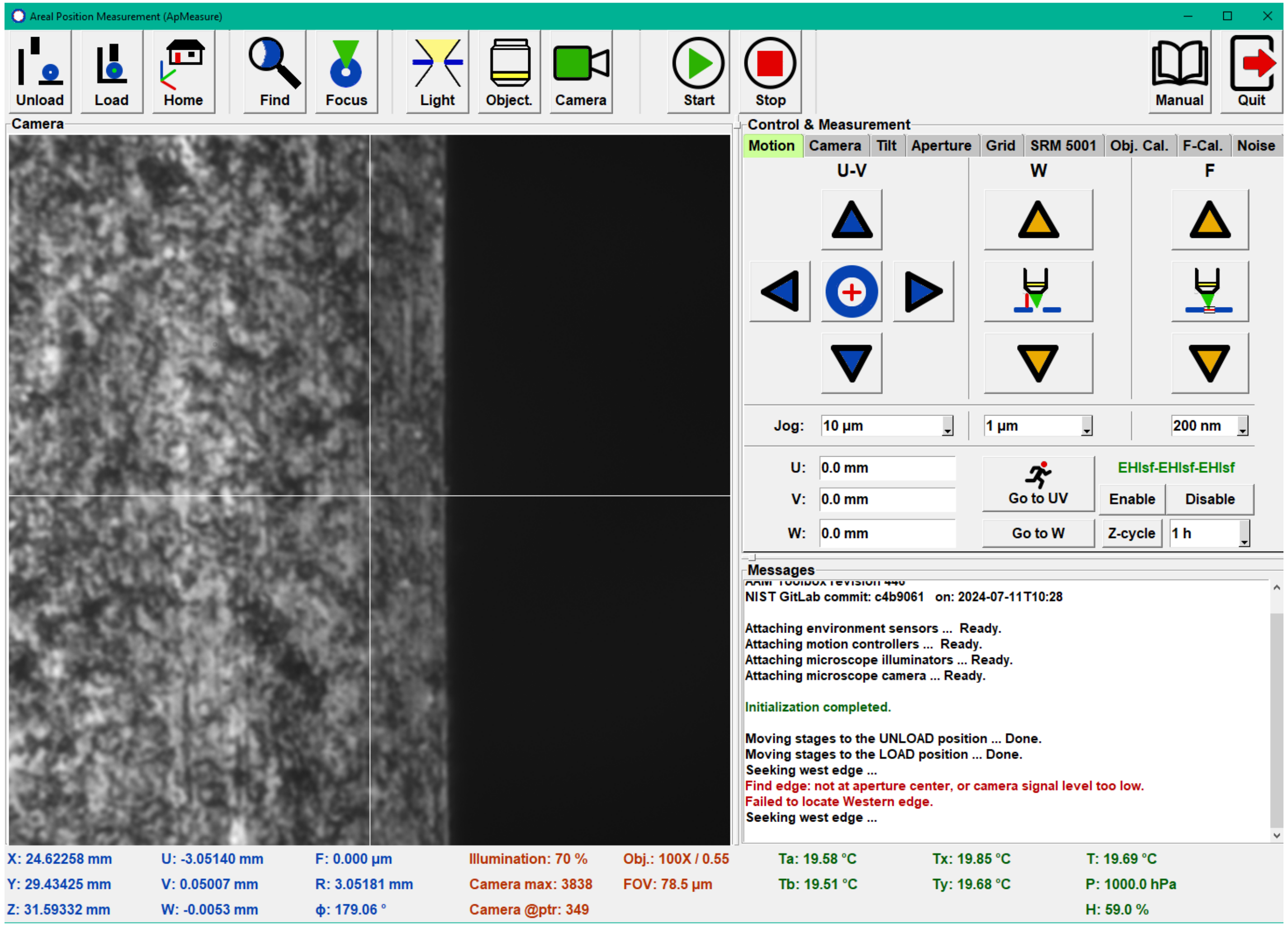


New check standards
NIST SRI6006



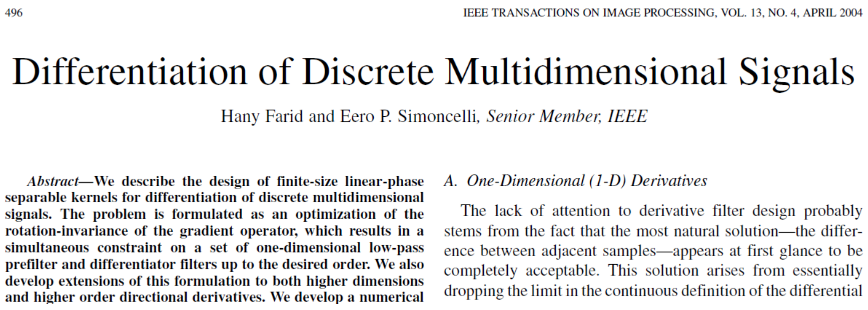
A lot of scattered light!

Software Improvements



Most important innovations:

- From profiles to images: fully image-based data processing (numpy, scipy, ...).
- Instead of one edge point per image, 1000 – 2800 edge points per image.
- New image processing algorithms not available in 2000.



496 IEEE TRANSACTIONS ON IMAGE PROCESSING, VOL. 13, NO. 4, APRIL 2004

Differentiation of Discrete Multidimensional Signals

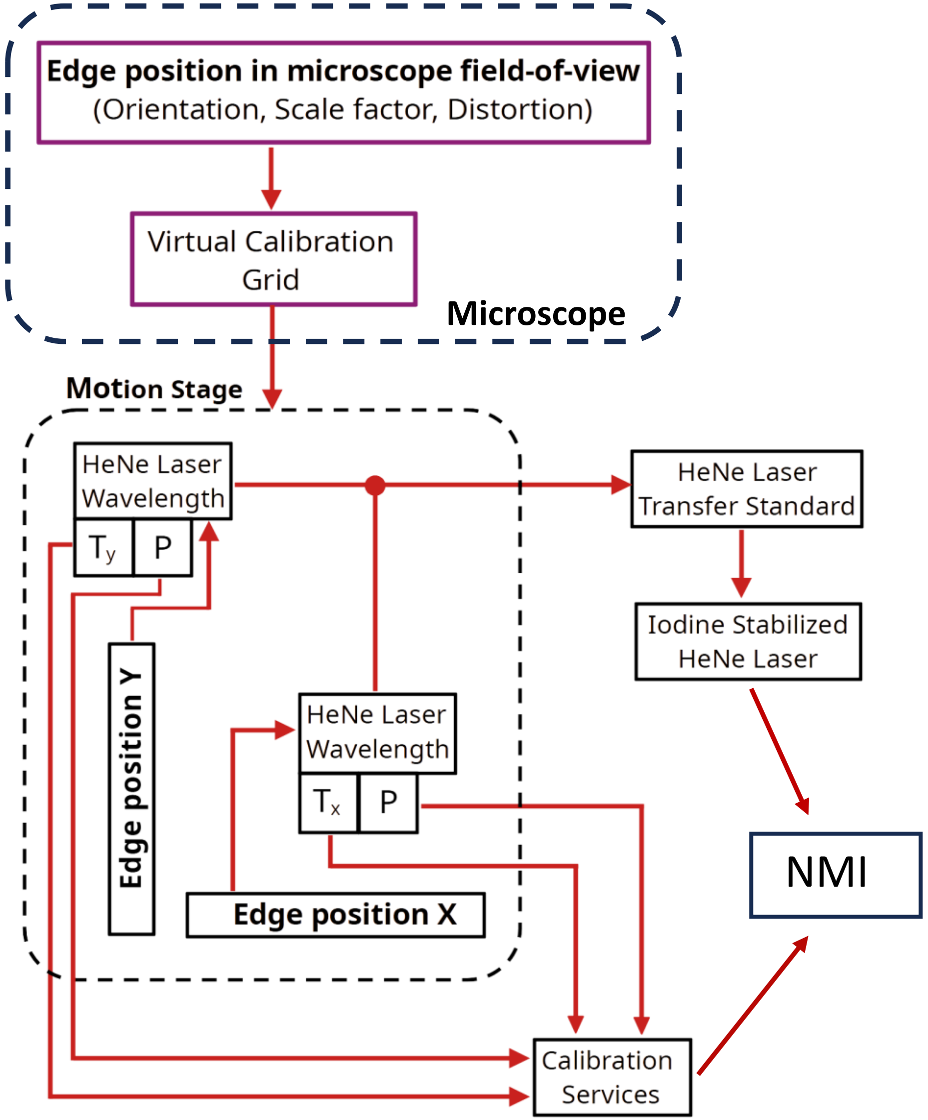
Hany Farid and Eero P. Simoncelli, *Senior Member, IEEE*

Abstract—We describe the design of finite-size linear-phase separable kernels for differentiation of discrete multidimensional signals. The problem is formulated as an optimization of the rotation-invariance of the gradient operator, which results in a simultaneous constraint on a set of one-dimensional low-pass prefilter and differentiator filters up to the desired order. We also develop extensions of this formulation to both higher dimensions and higher order directional derivatives. We develop a numerical

A. One-Dimensional (1-D) Derivatives

The lack of attention to derivative filter design probably stems from the fact that the most natural solution—the difference between adjacent samples—appears at first glance to be completely acceptable. This solution arises from essentially dropping the limit in the continuous definition of the differential

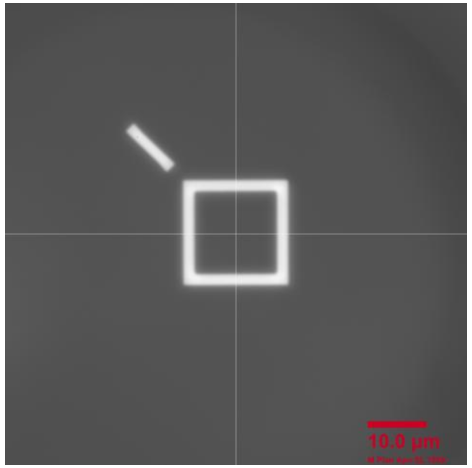
Traceability



Comprehensive New Uncertainty Analysis

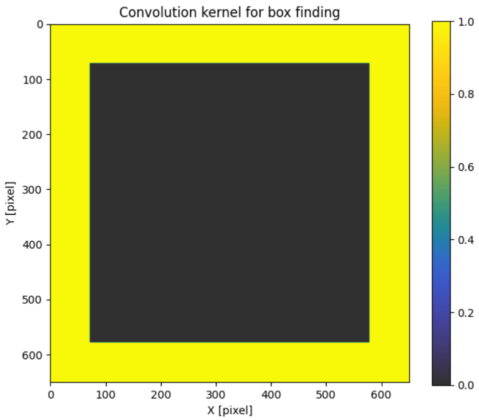
- **Laser interferometers** for X and Y axes
  - Environment sensing and turbulence
  - Deadpath
  - Cosine error
  - Laser system inherent
- Position errors of XY stage (**stage calibration**)
- Image pixel-to-stage coordinate mapping (**objective calibration**)
- Position uncertainty due to **defocus**
  - Z axis limitations
- Edge position uncertainty due to **uneven illumination** (illuminator imperfection, coherent noise, photon noise, camera noise…)
- Position uncertainty due to structural stability (**structural loop**)
- Aperture radius/area uncertainty due to **aperture material CTE** uncertainty

XY Stage Calibration

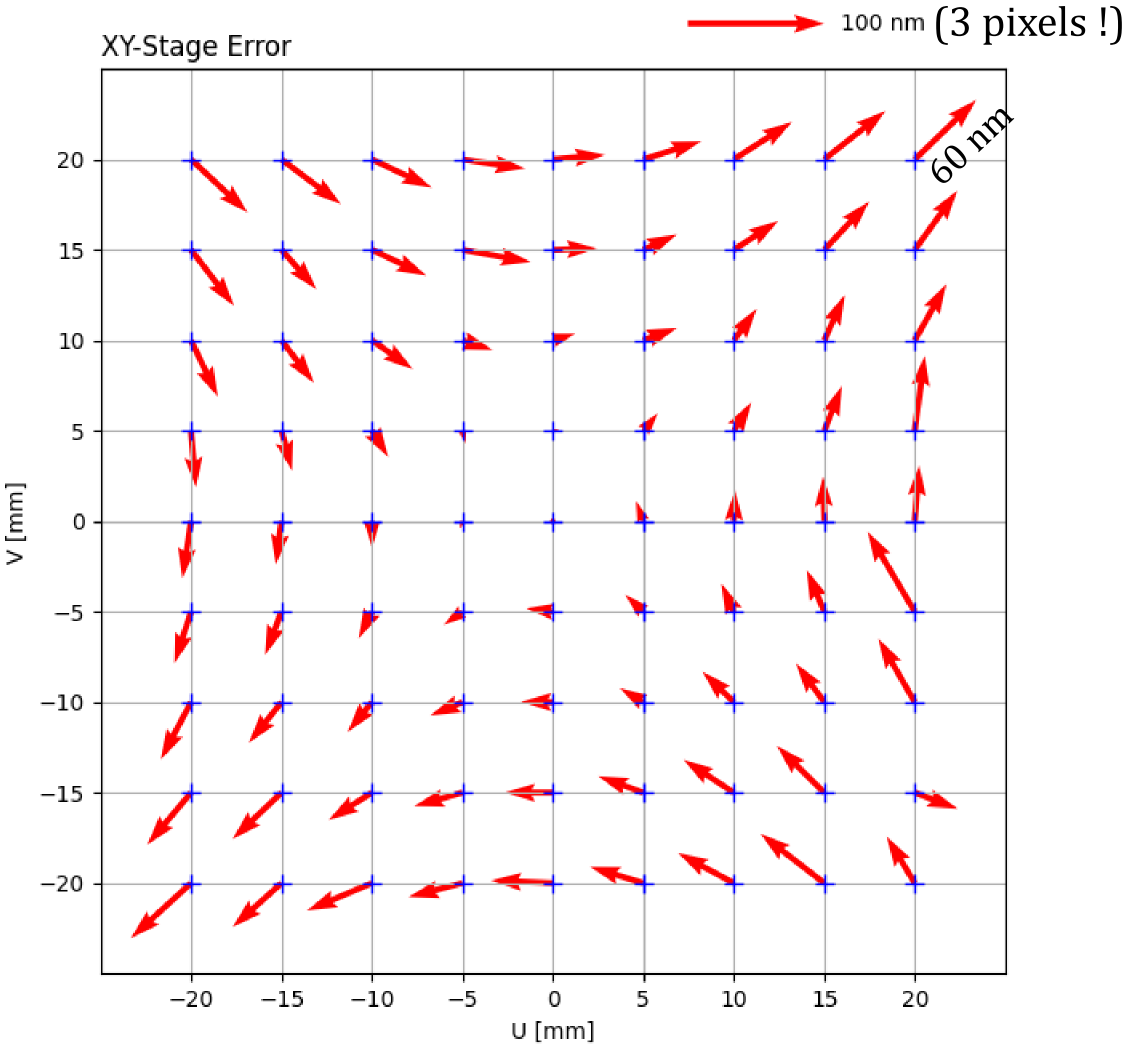


Fiducials on 5 mm X 5 mm grid, position uncertainty ±10 nm (1σ)

1) Convolution with box kernel
2) Find peak of convolution with polynomial fit

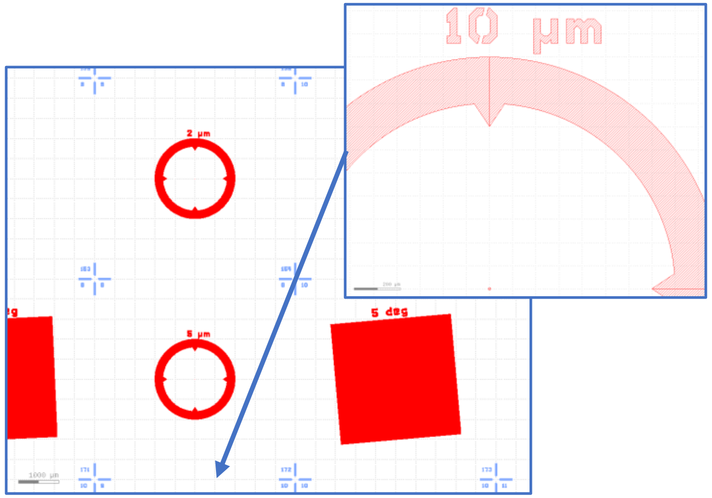


U = r [mm] x 2.14 nm/mm

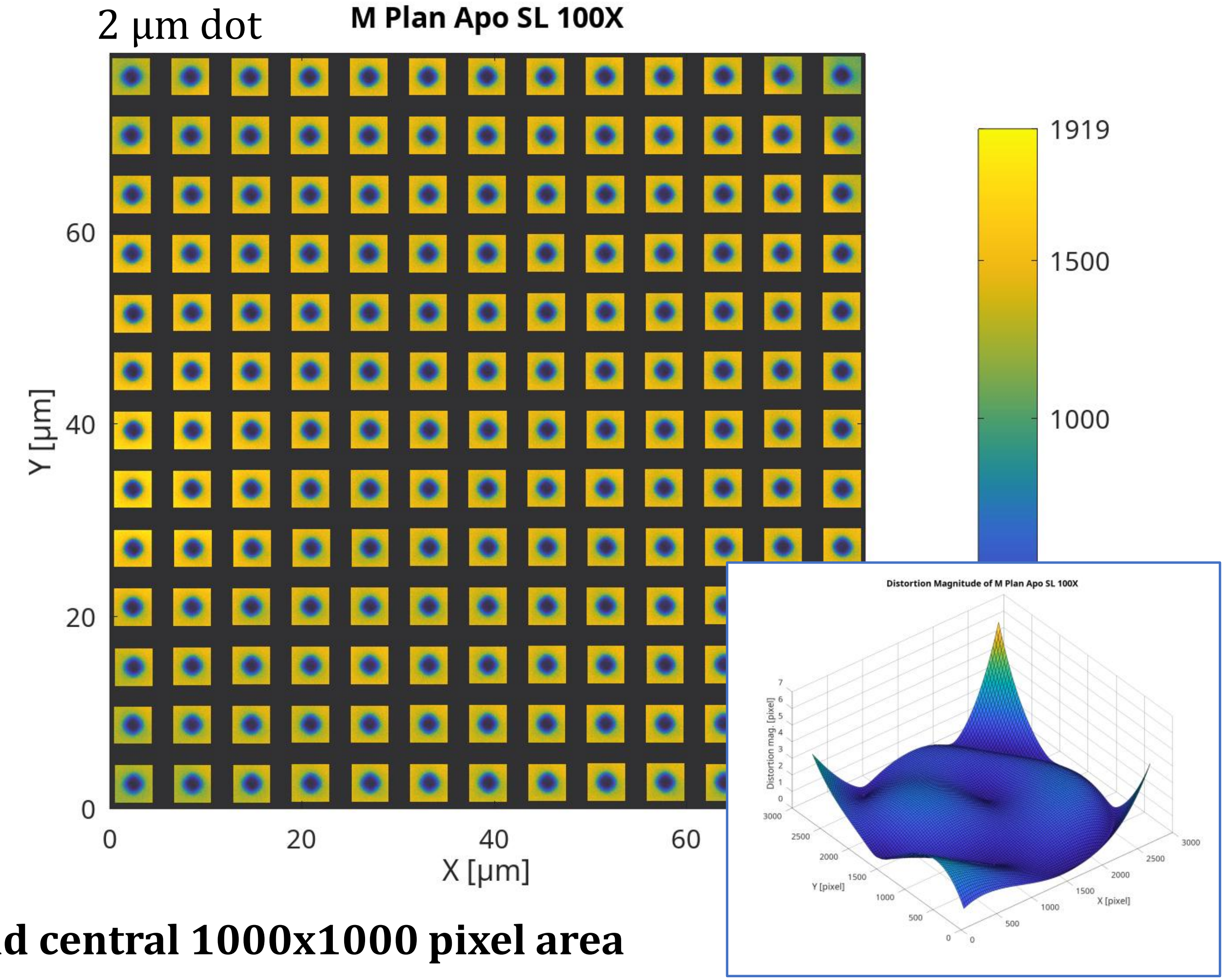


Squareness error: 3.5 µrad (0.2 x 10^{-3} degree)

Objective Calibration with Virtual Calibration Target



AAM calibration mask

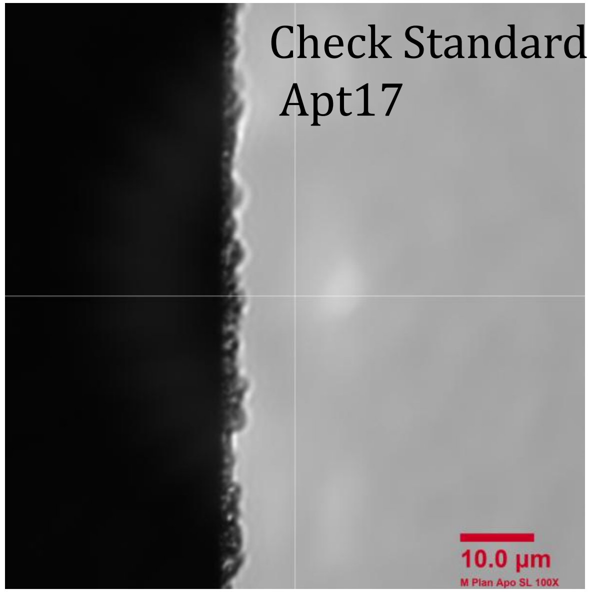


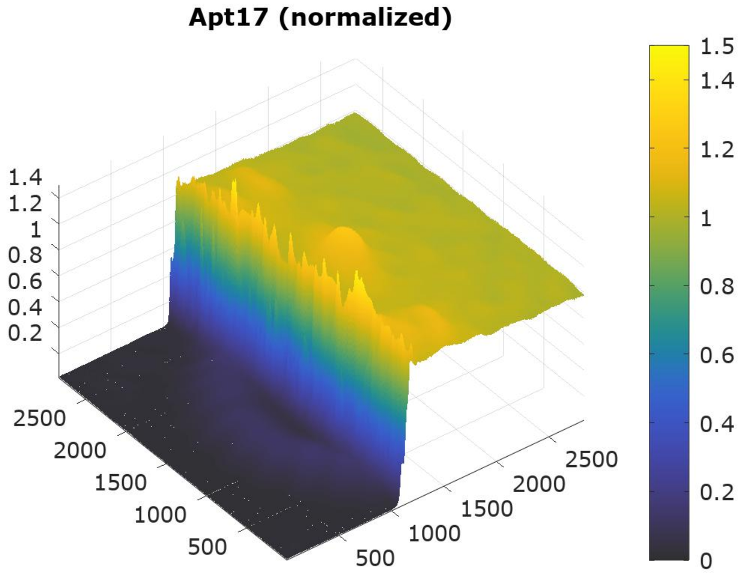
1. **Alignment of image sensor to stage**
2. **Mean sensor scale factor**
3. **Objective distortion map for FOV**

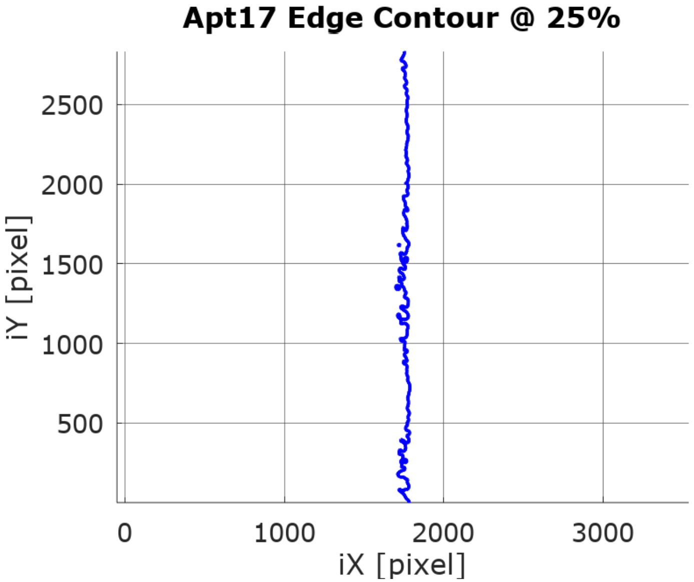
⇒ Pixel-to-stage coordinate mapping (no distortion correction for now)

U = 30 nm (1 pixel) for 100X objective and central 1000x1000 pixel area

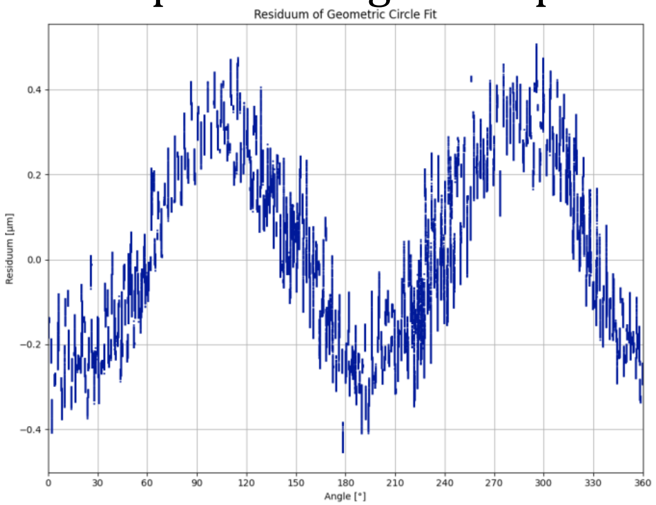
Illumination Non-uniformity





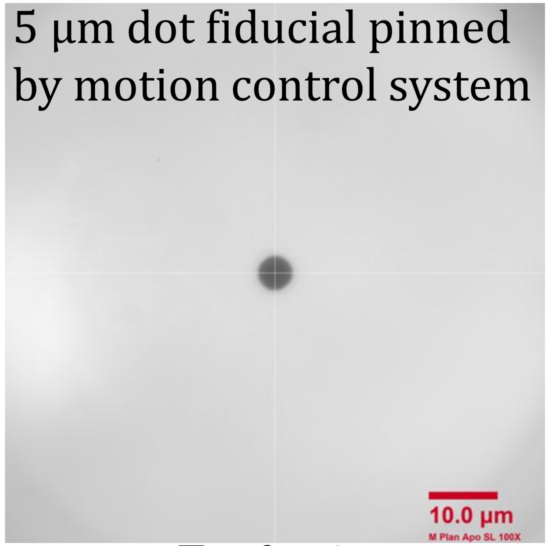


Full aperture edge example

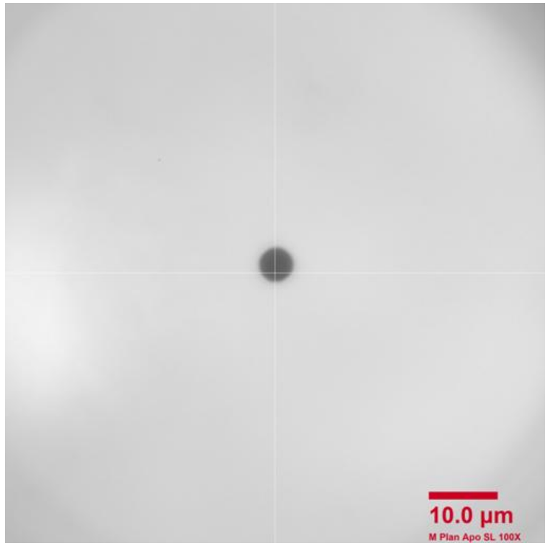


- Illuminator imperfections (possibly in design)
- Stray light in microscope condenser
- Coherent effects
- Photon and image sensor noise
- Use RMS of edge model fit residuum as estimate for edge position uncertainty. Typical **U = 80 nm**
- Note: illumination non-uniformity is indistinguishable from aperture edge roughness; overestimates uncertainty

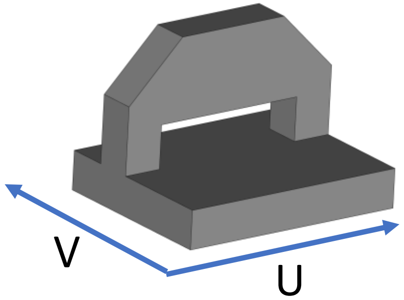
Structural Loop



T = 0 min

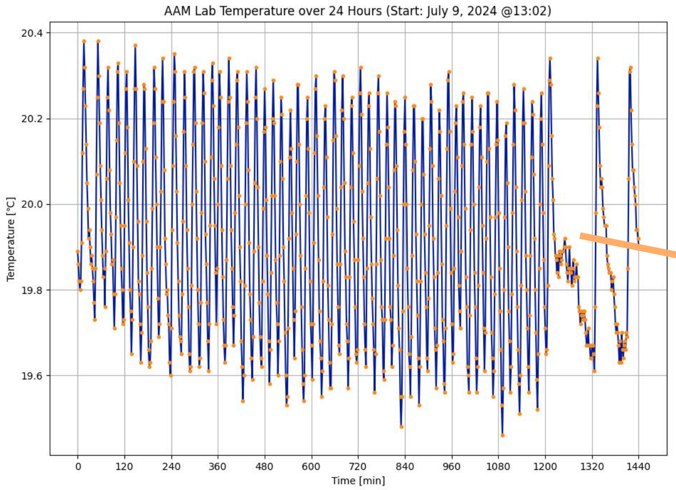


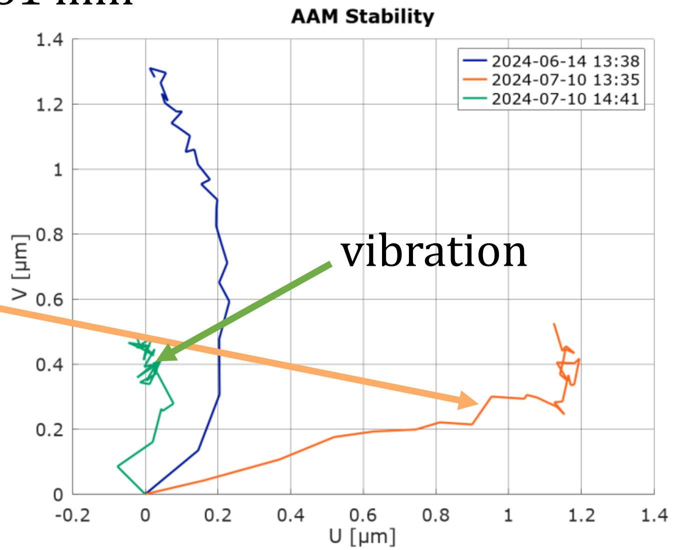
T = 81 min

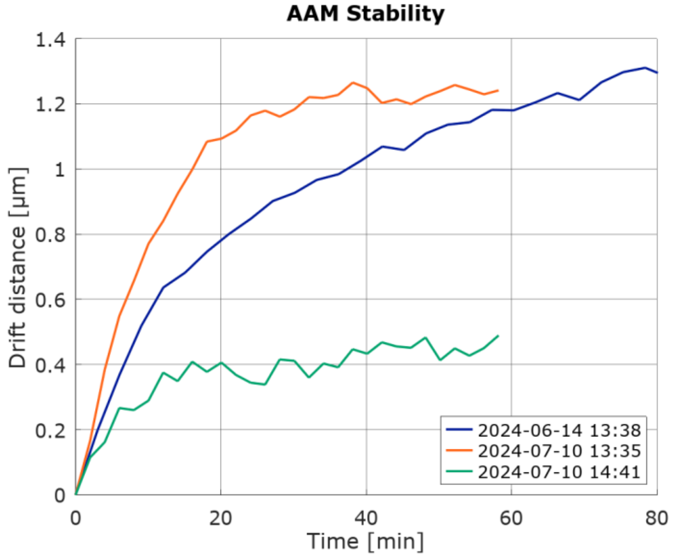


- Creep (friction in Z stage)
- Thermal effects
- Vibration

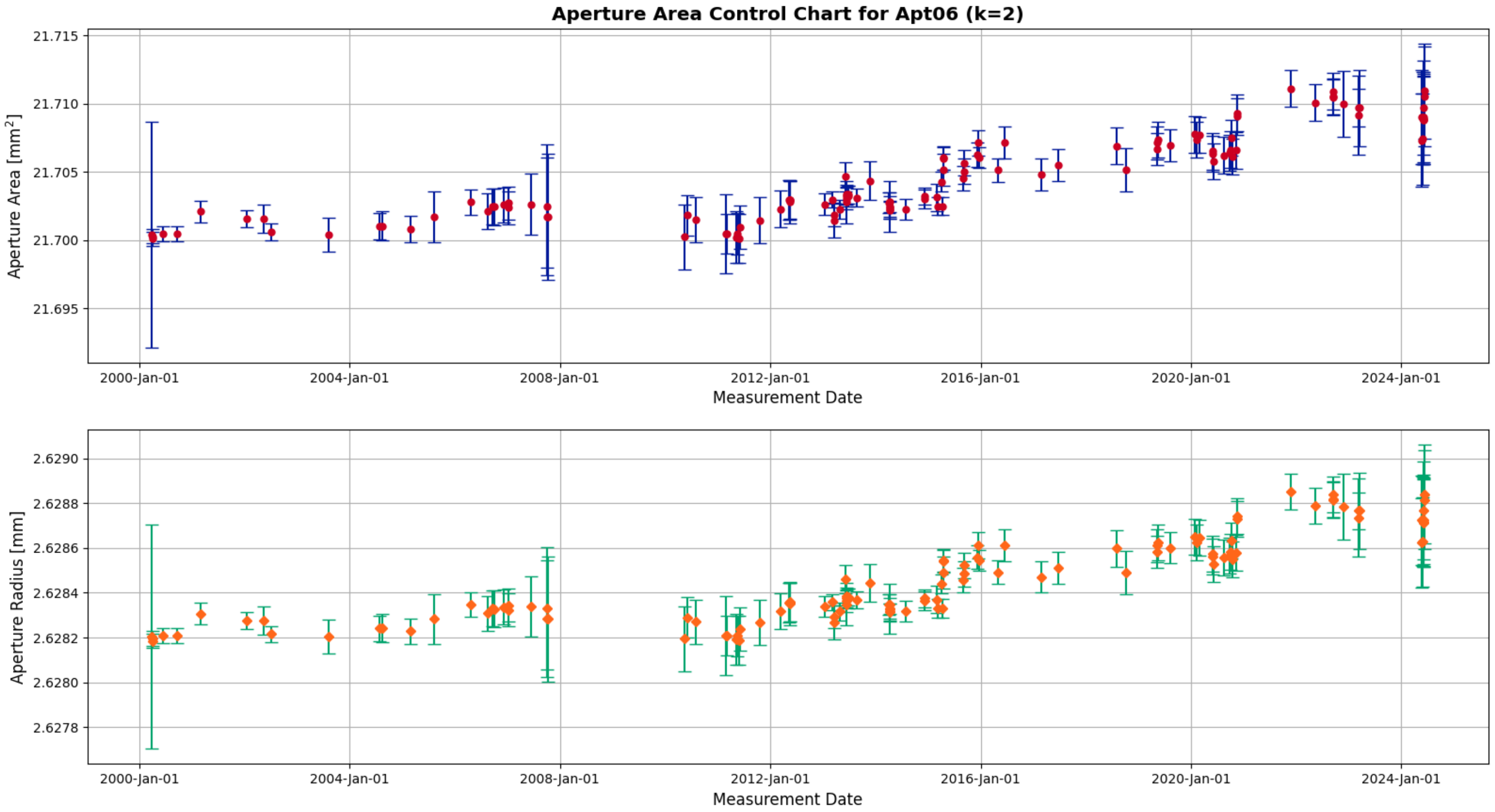
For XY-drift ≅ 50 nm / min, 10 min measurement time: U(R) ≅ 40 nm



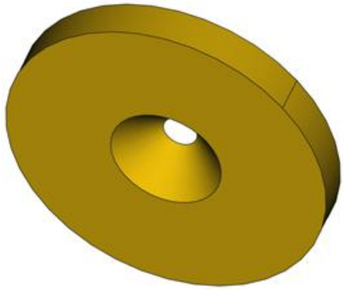




Check Aperture Apt06



Knife-edge aperture made from OFHC Cu and Au coated.



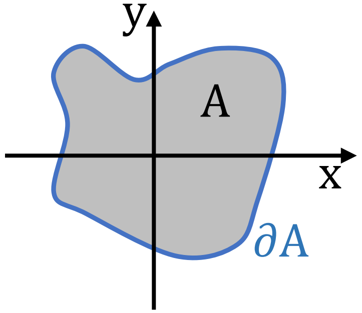
AAM Improvement Continues

1. Green's Theorem in aperture area measurement for arbitrary shape apertures

$$\oint_{\partial A} N\,dx + M\,dy = \iint_A \left(\frac{\partial M}{\partial x} - \frac{\partial N}{\partial y}\right) dxdy$$

Pick $M = x/2$ and $N = -y/2$:

$$A = \frac{1}{2}\oint_{\partial A} x\,dy - y\,dx$$



2. Aperture diffraction modeling

- What is the correct focusing criterium (peak slope, peak intensity, …) ?
- What is the effect of defocus on edge image shape ?

The End