Development of the MAGIS-100 primary imaging system

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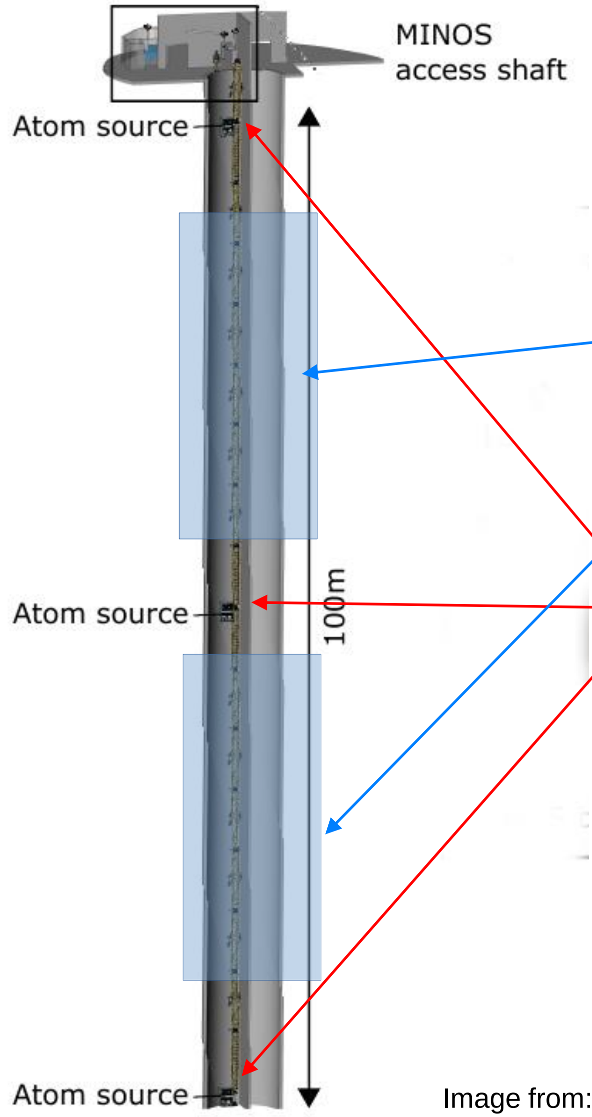
MAGIS-100 imaging



“Diagnostic” imagers located throughout interferometer region.

“Primary” imagers located at connection nodes.

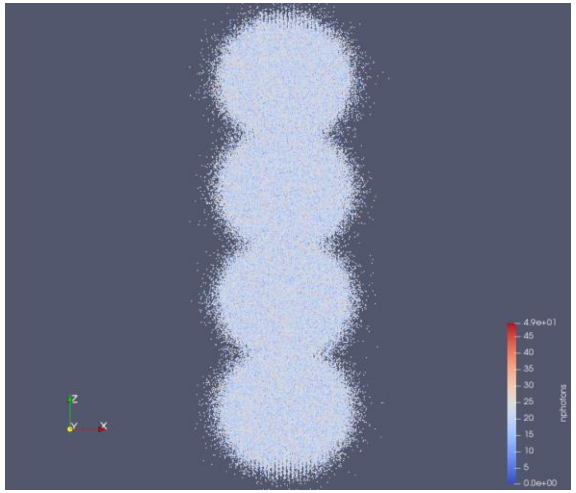
Image from: Abe et al (2021) 10.1088/2058-9565/abf719

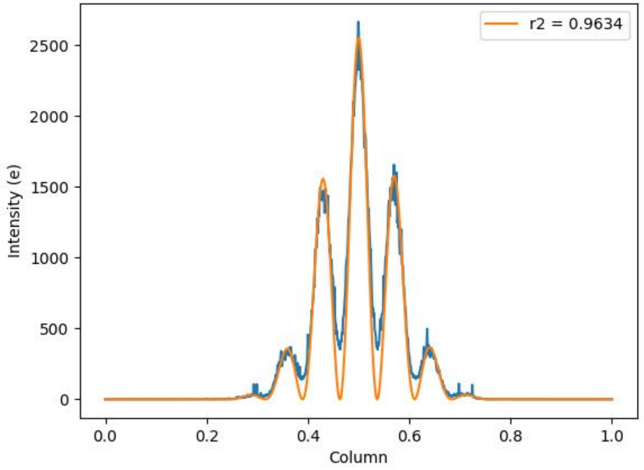
There are two imaging systems in the MAGIS-100 design.

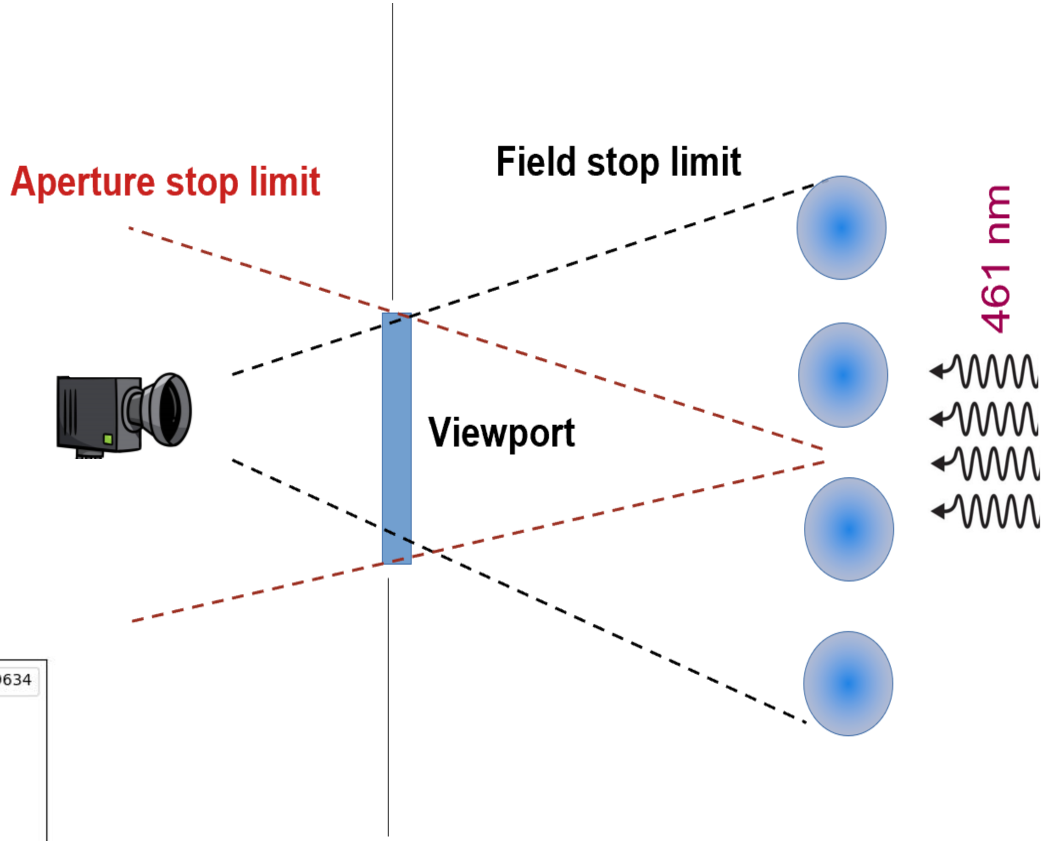
- **Diagnostic Imaging System** – many cameras situated along interferometry region. Fast optics enable accurate localisation of cloud position throughout transit. Designed and built by SLAC
- **Primary Imaging System –** High sensitivity & resolution cameras located at each connection node used for imaging and phase fitting of atom clouds. Designed and built by Oxford (OPMD).

MAGIS-100 imaging

- Two science cameras per atom source connection node.
- Atoms fluoresced by **461nm** laser.
- Up to **4 clouds** per image, **~1mm** in diameter.
- Spatial frequency of interest **~100um**.
- Distance to target **~155mm**
- Exposure time ~**200 us** (atom cloud diffusion)
- Goal is **phase measurement**



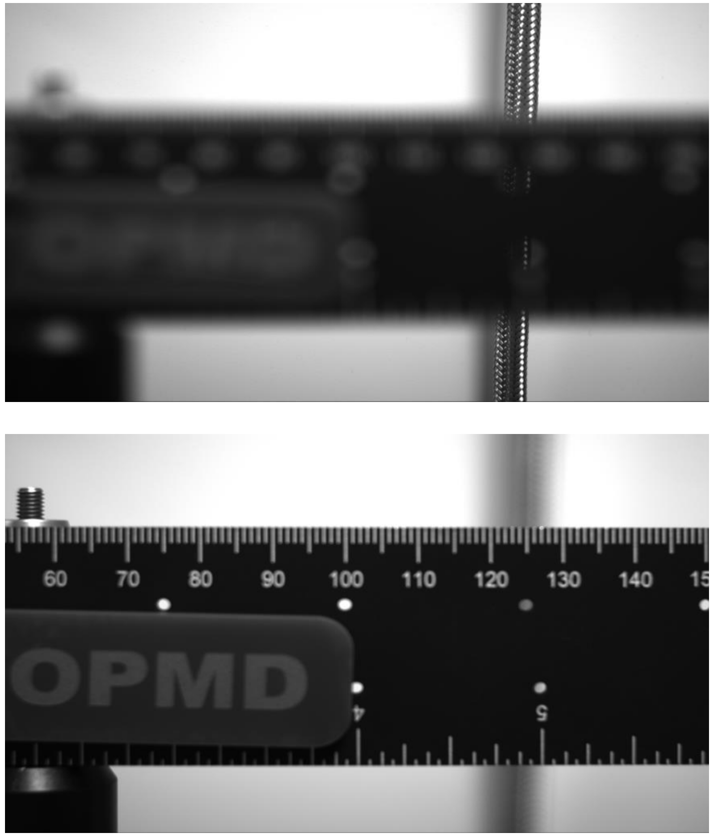




MAGIS-100 science imager

Lucid Vision Triton – **Sony IMX541 sensor**:

- 4.5k x 4.5k pixels, 2.74um square
- 5.5 FPS
- 12-bit ADC
- Global shutter
- Dark current 1.6e/s
- QE ~70% at 450nm
- ~2.1e read noise
- PoE



First light and DoF example.

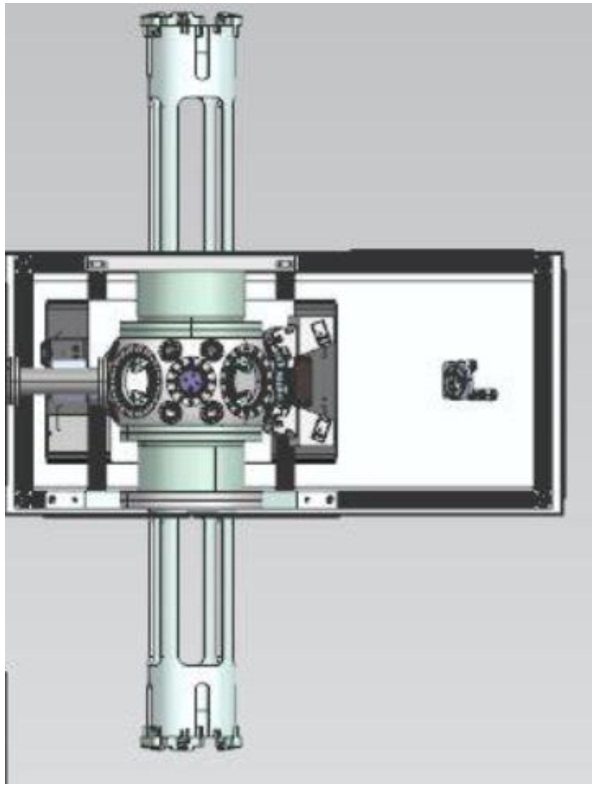
50mm fixed focal length lens:

- f/1.8 to f/16
- Mwd 200mm
- Max diameter ~50mm

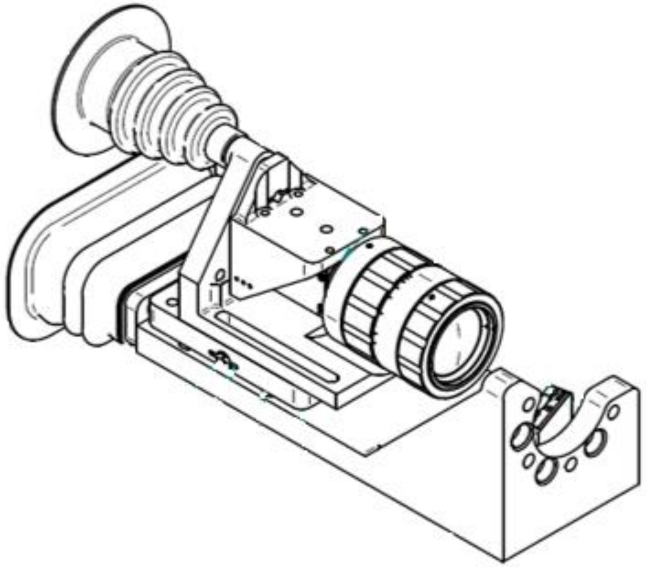
Small physical envelope, total weight <<1kg.

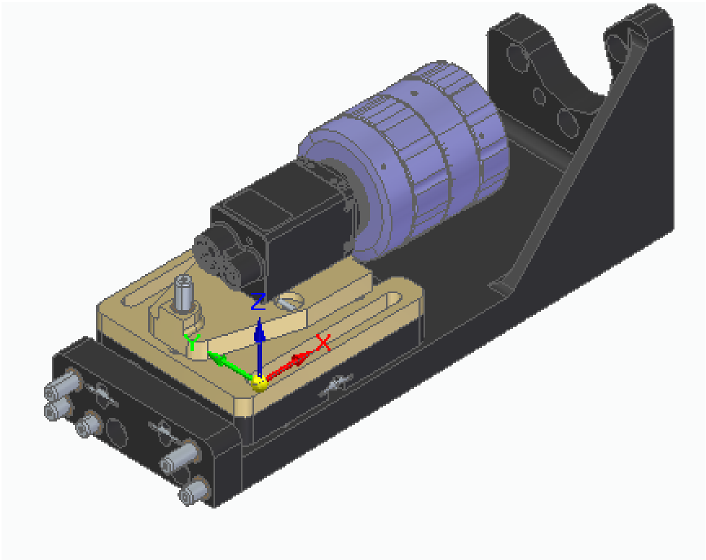
Mechanical mount

- Custom mount and mechanics for attachment to connection node viewports and operation.
- Three-axis fine position adjustment (~a few mm) accessible from outside.
- No active cooling.
- Under design, still a few details to be decided. Will produce a prototype at Oxford for thermal testing etc.



MAGIS 100 atom source connection node





Calibration plan

- MAGIS characterisation testbench at Oxford - accurate **radiometry, flat fielding** and **tuneable light source with monochromator.**

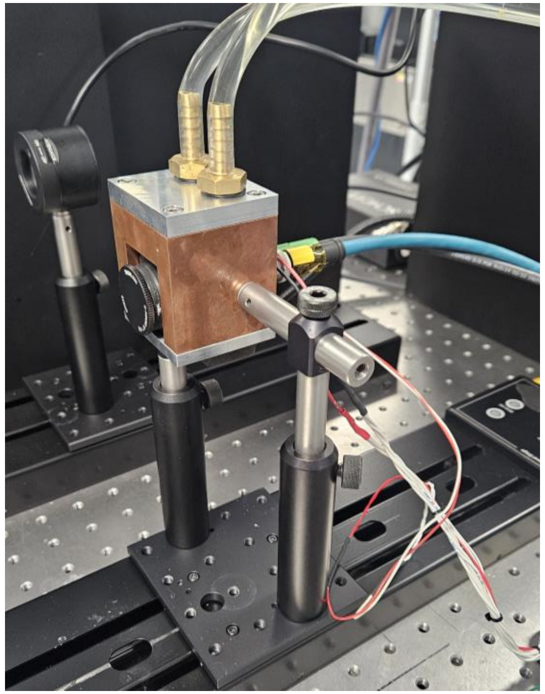
- Each camera and lens will be **characterised individually** and at across a **range of temperatures** - exact plan close to finalisation**.**

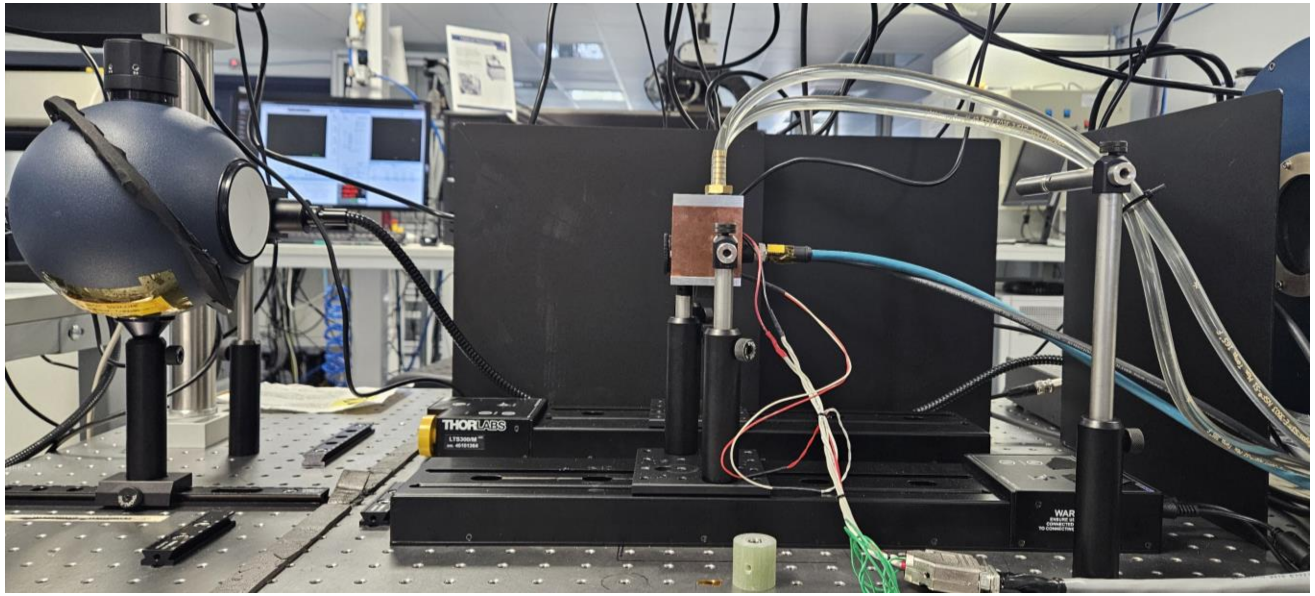
- **Bias frames, Dark frames, Flat-field images, PTC pairs, QE.**

- **MTF** - via both the knife edge method and (using 450nm laser light) via laser speckle.

- **Lens throughput, OTF.**

- Timing jitter tests etc.

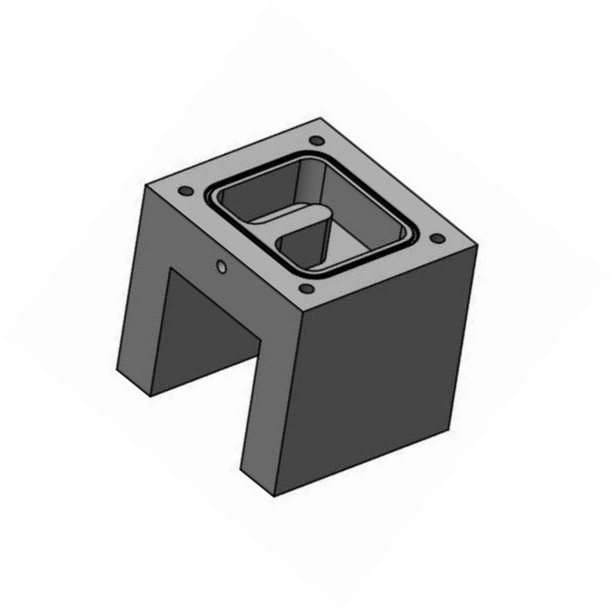


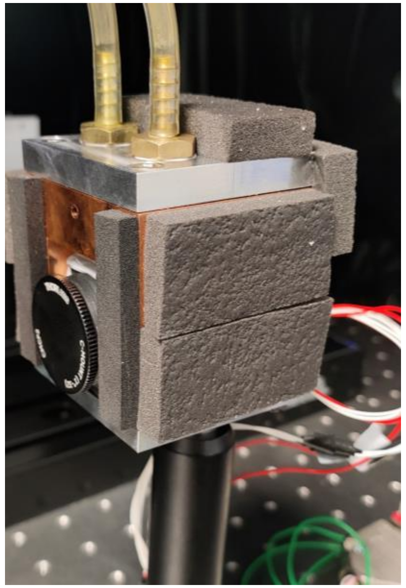


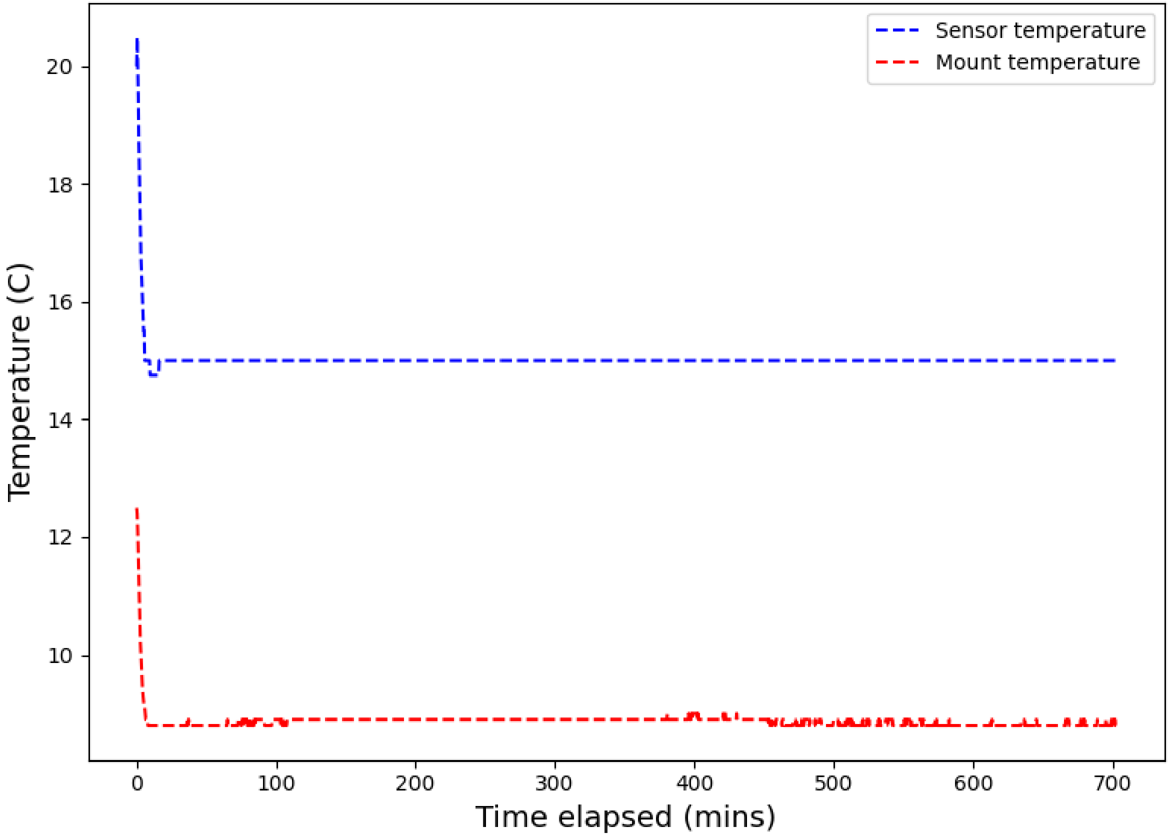
Thermal mount

Custom thermal mount

- Water cooled at 10°C.
- 12V, 3A Peltier.
- Sensor temperature stable across several hours.
- Allows testing at low end of temperature range expected within the shaft.



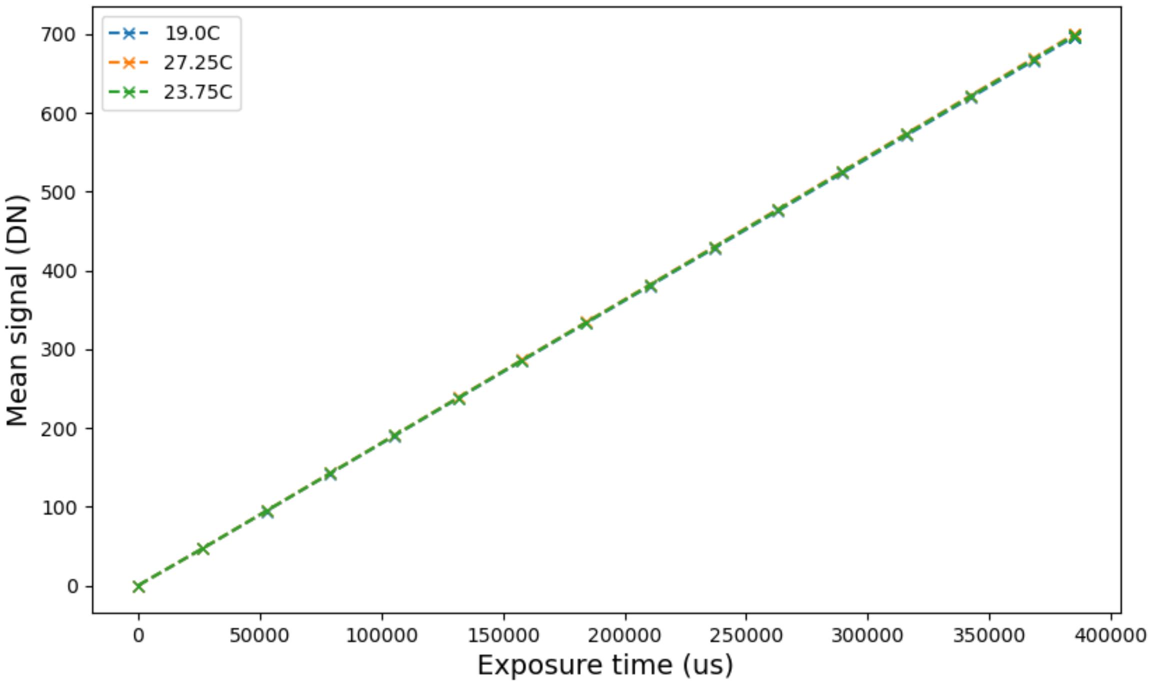




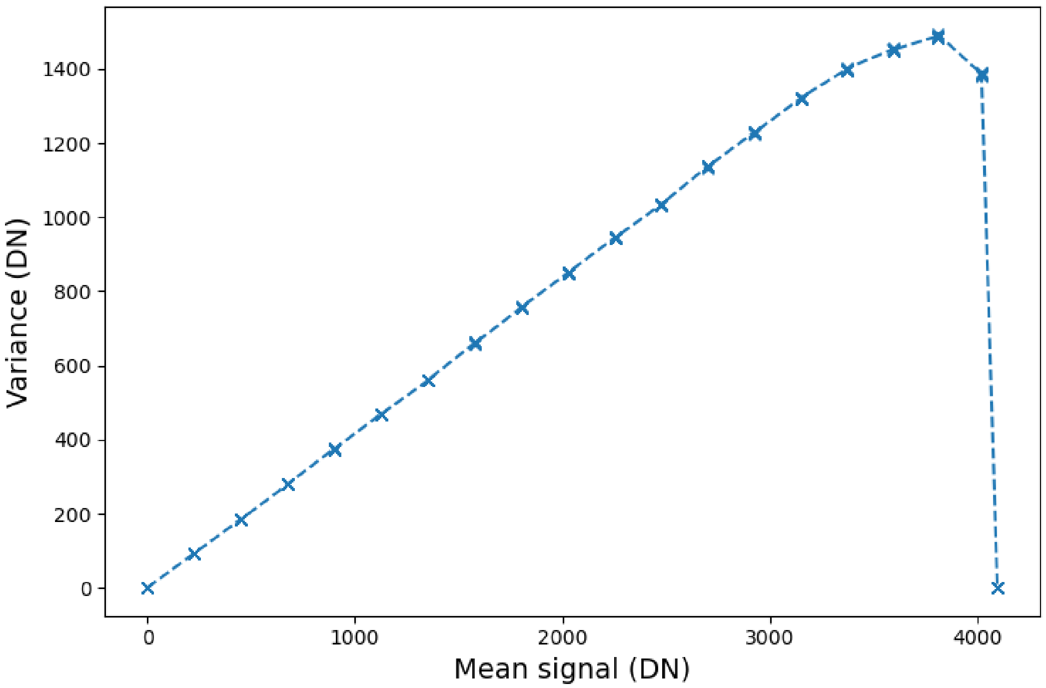
Initial testing

12-bit output, **gain ~10e/DN**

Linearity

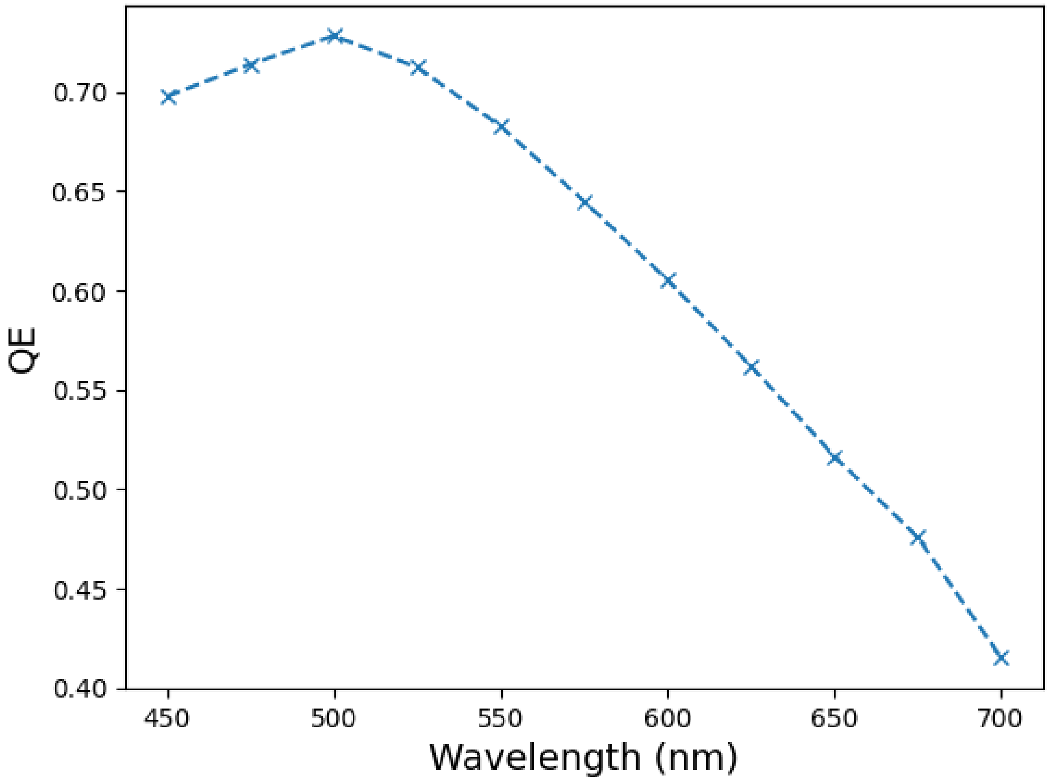


Mean-variance

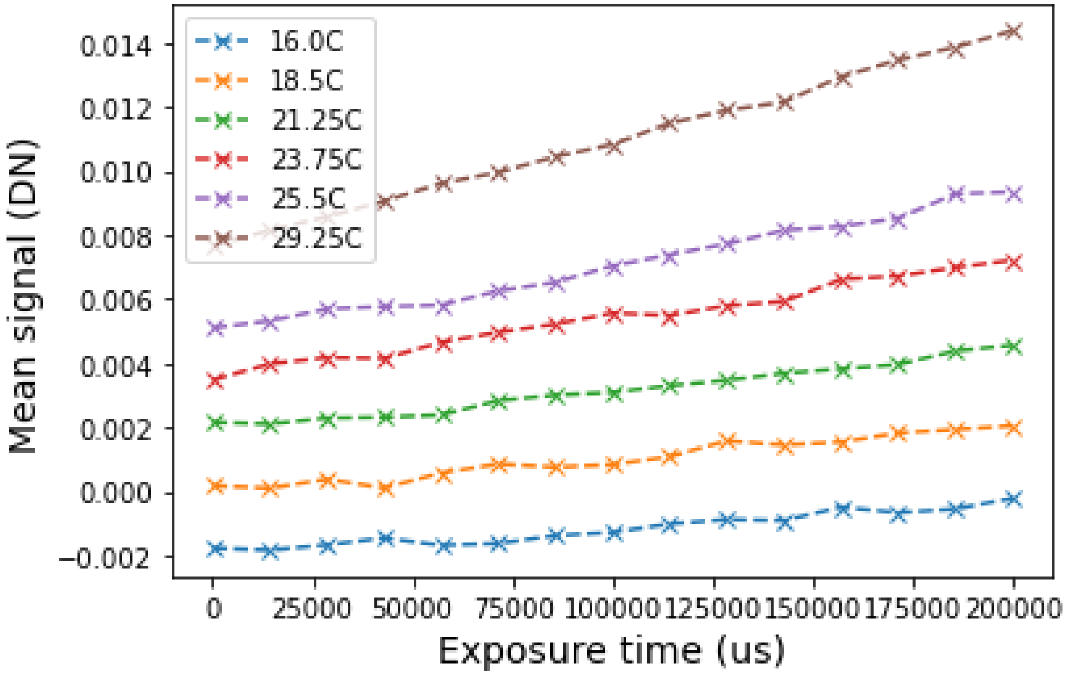


Initial testing

QE ~70% at 450nm

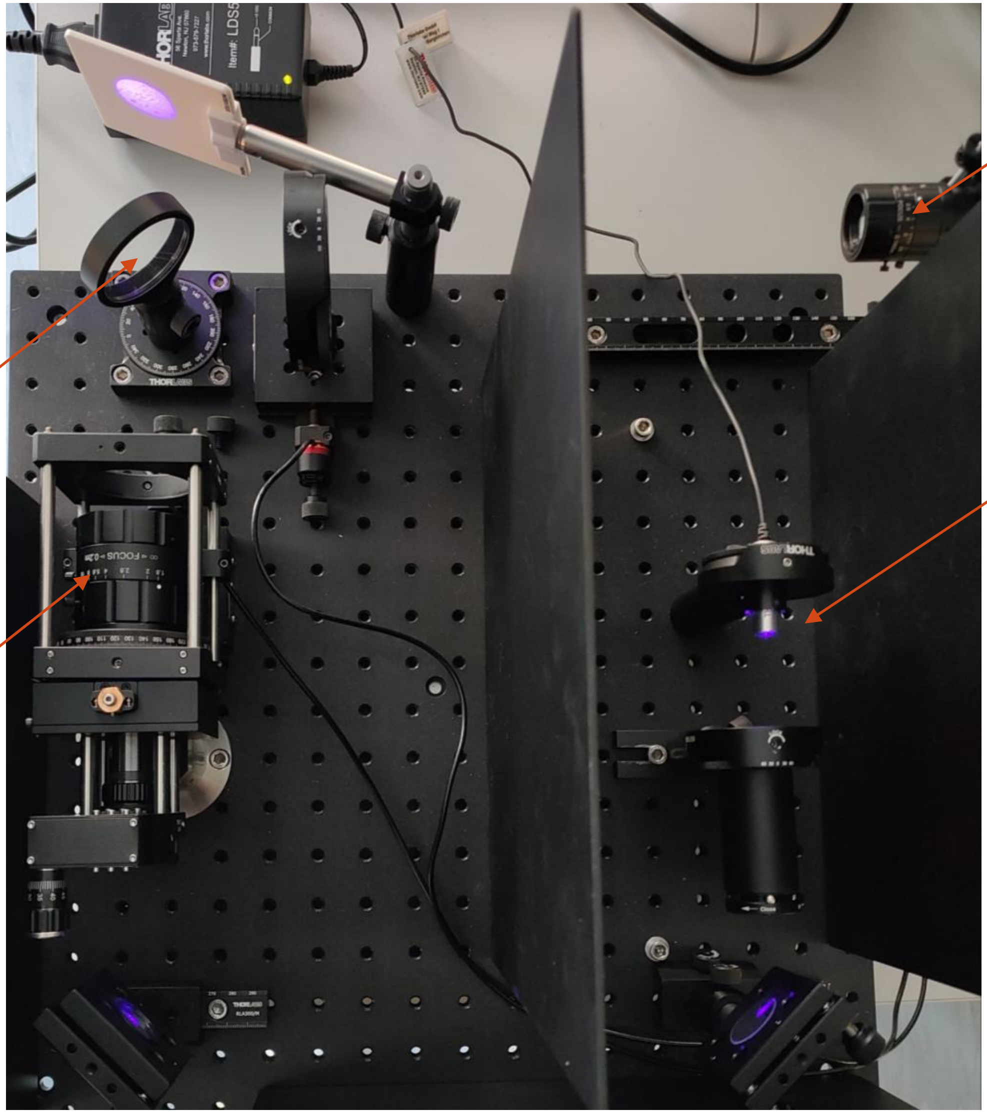


Dark current



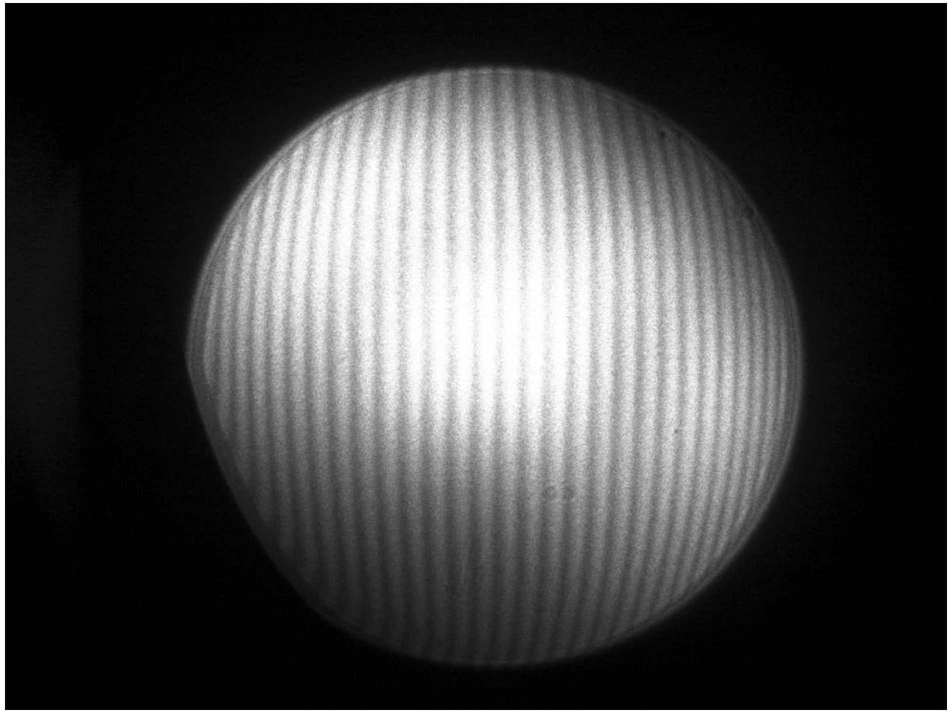
Optical testing

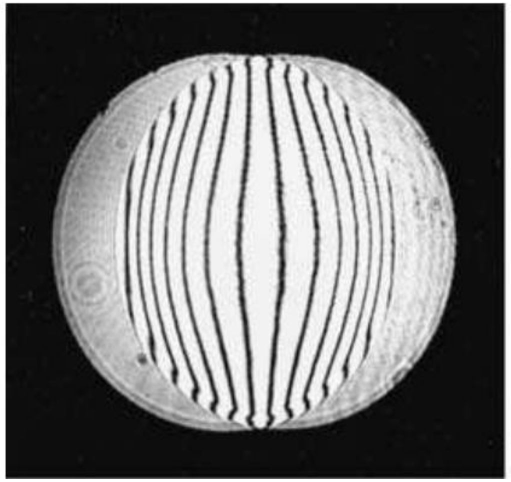
- Lens assemblies undergoing characterisation using **lateral shear interferometry -** allows for partial correction of spherical aberrations & coma.
- Flat-field illumination for vignetting performance.
- Specialist **depth of field target** to verify focussing and aperture performance.



Pupil function

Shear interferograms from optical testing bench.

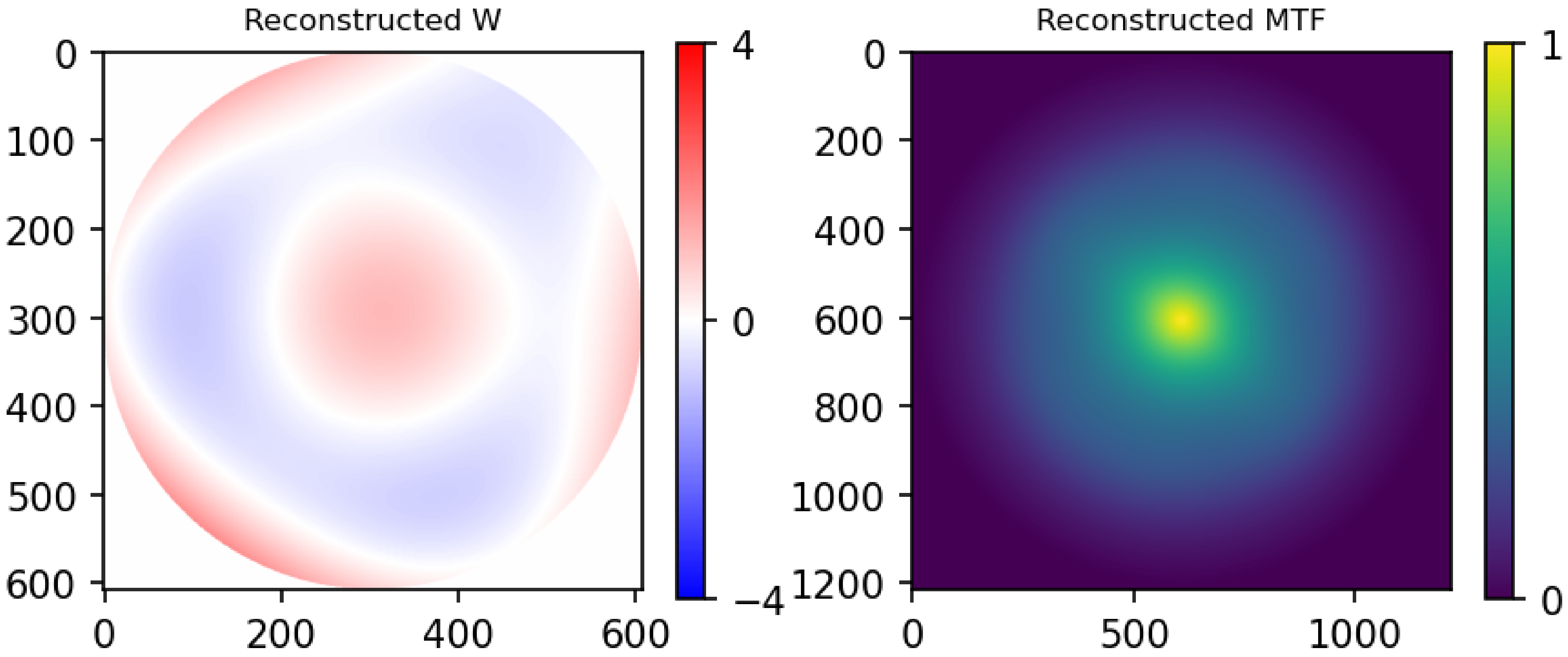




Textbook “spherical aberrated” shear wavefronts - (Malacara “Optical Shop Testing”)

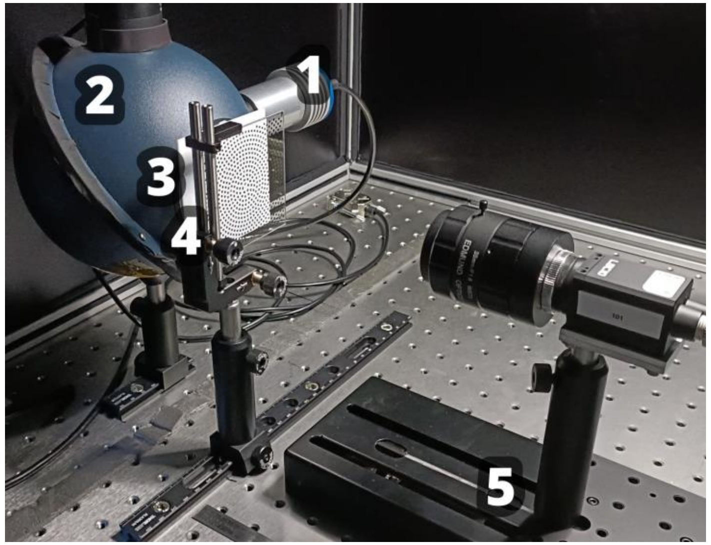
Pupil function

Recovery of pupil function and associated MTF -

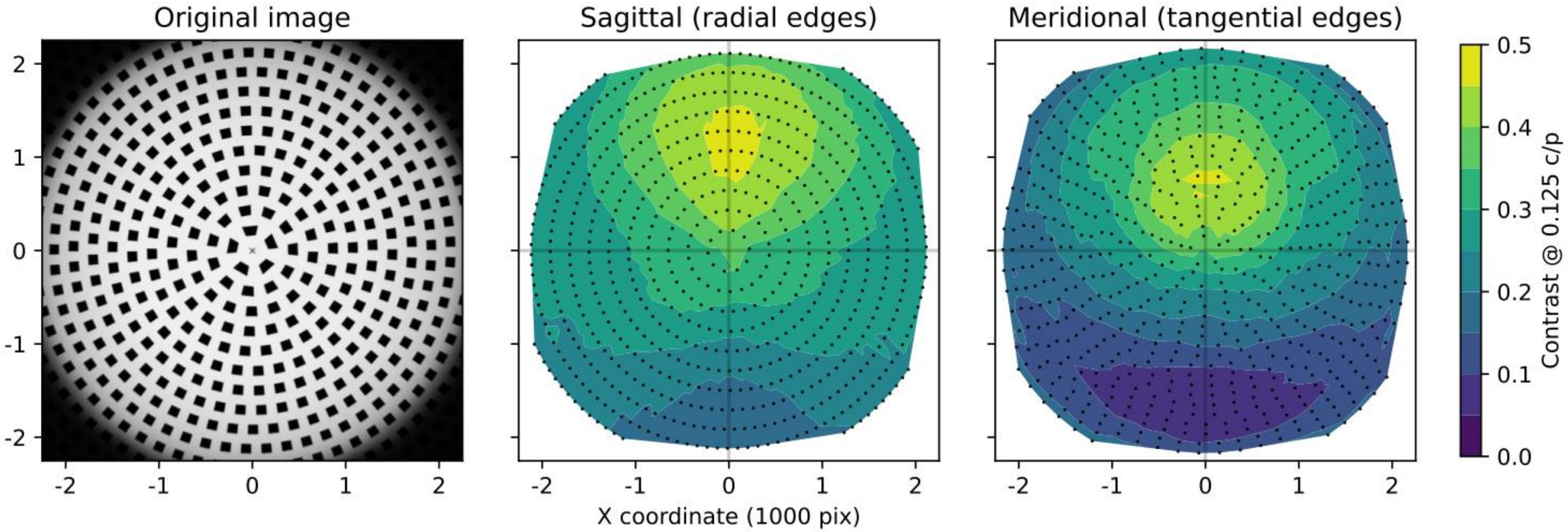


Measuring system MTF

- Measure system MTF using slant-edge method.
- Custom target for spatial frequency coverage.
- Use of mtf_mapper package for data analysis.
- Comparison with Zemax black boxes for candidate lenses.



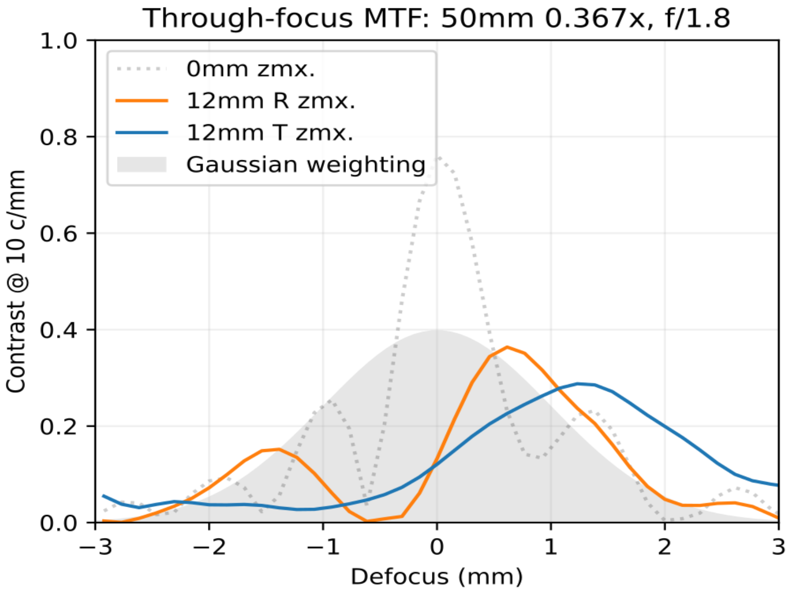
1. Tuneable blue LED source.
2. Integrating sphere.
3. Diffuser.
4. Custom MTF target.

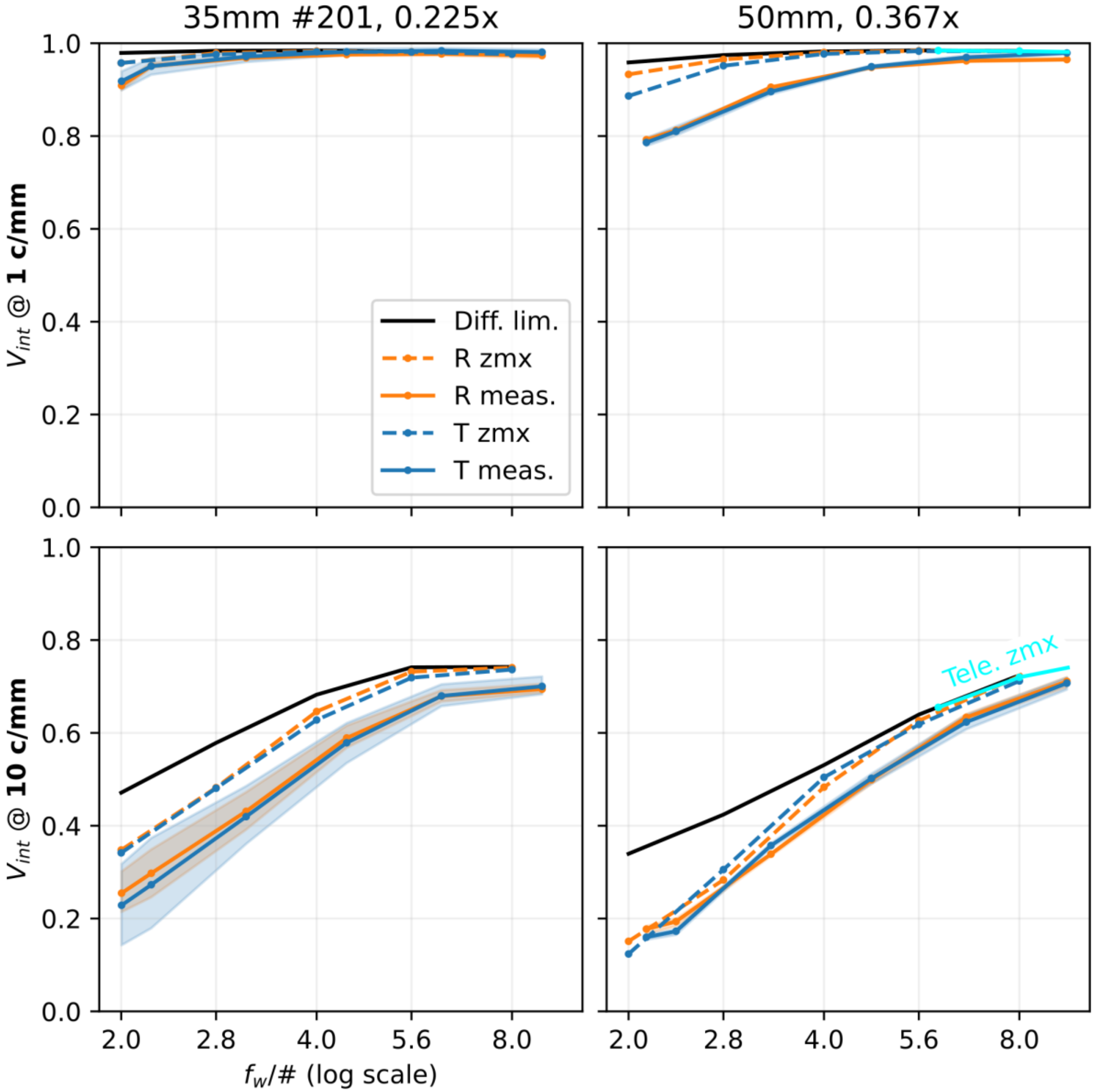


Work by H. King - MPhys student project

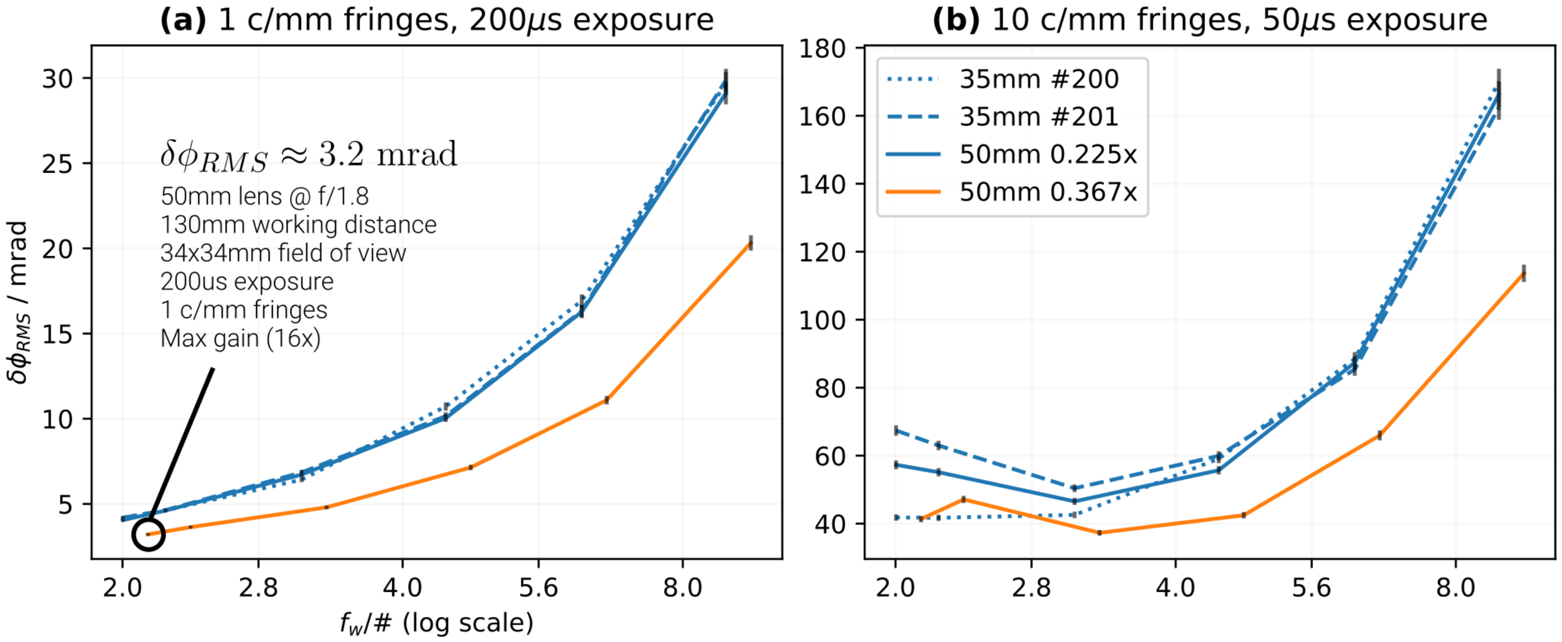
Fringe visibility loss from imaging system

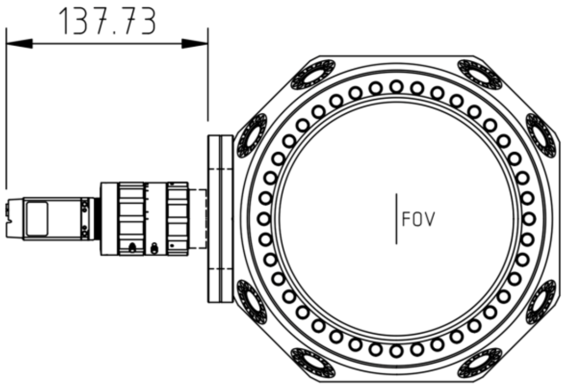
- Resolution affected by depth of field - integrate through-focus MTF across entire cloud to get integrated fringe visibility loss.
- Plotted for MTF from Zeemax, lab measurements, against aperture diameter.



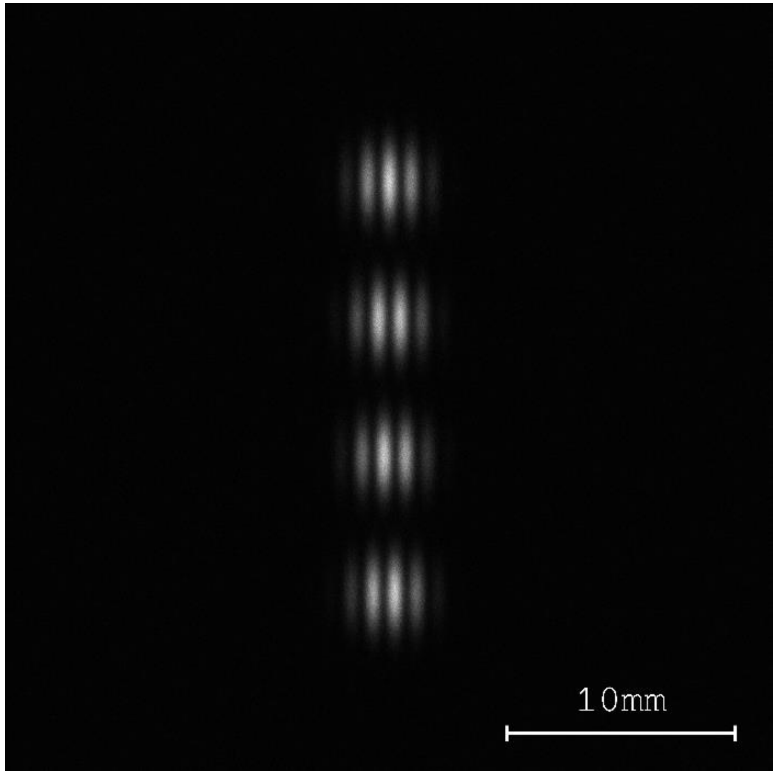


Simulations: focal length and f#





- Input integrated visibility loss into image model to determine optimal parameters for minimising phase error.

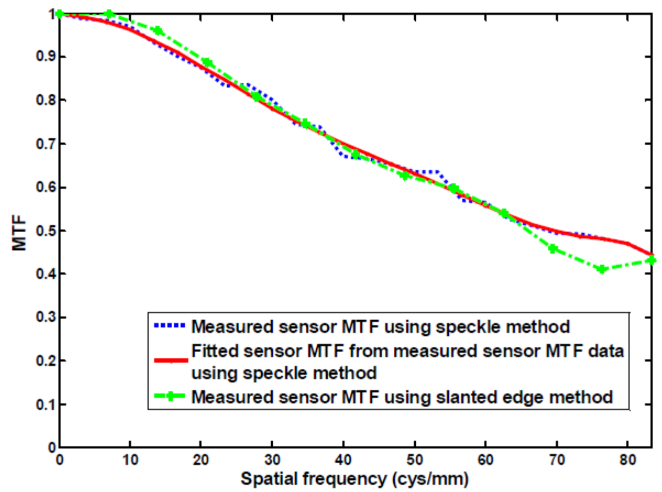


Full simulated image for circled params. Includes: noise, atom diffusion, measured through-focus MTF

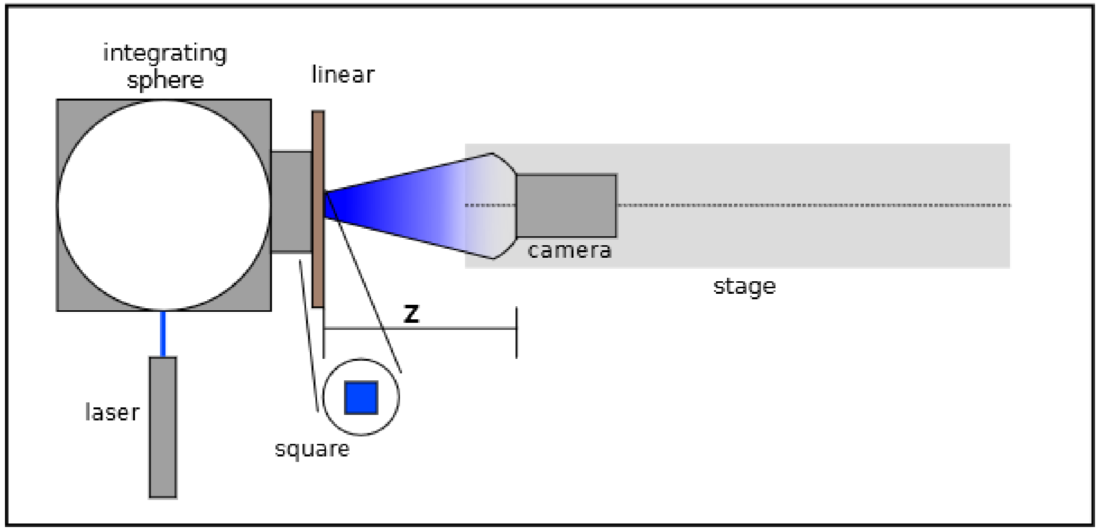
Laser speckle MTF method

- Laser light produces a speckle pattern when shone on a rough surface.
- Can use integrating sphere and diffuser for producing such a pattern (Boreman *et al.* 1990).
- MTF can be obtained if speckle power spectral density is known and image spectral density is measured.

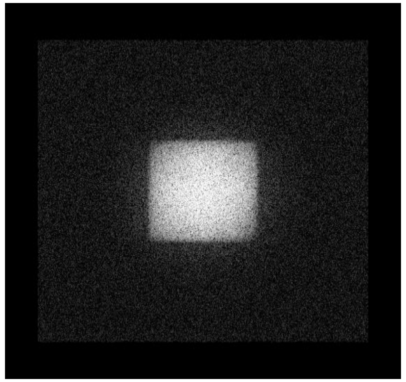
MTF measured with laser speckle (Chen *et al.* 2008)

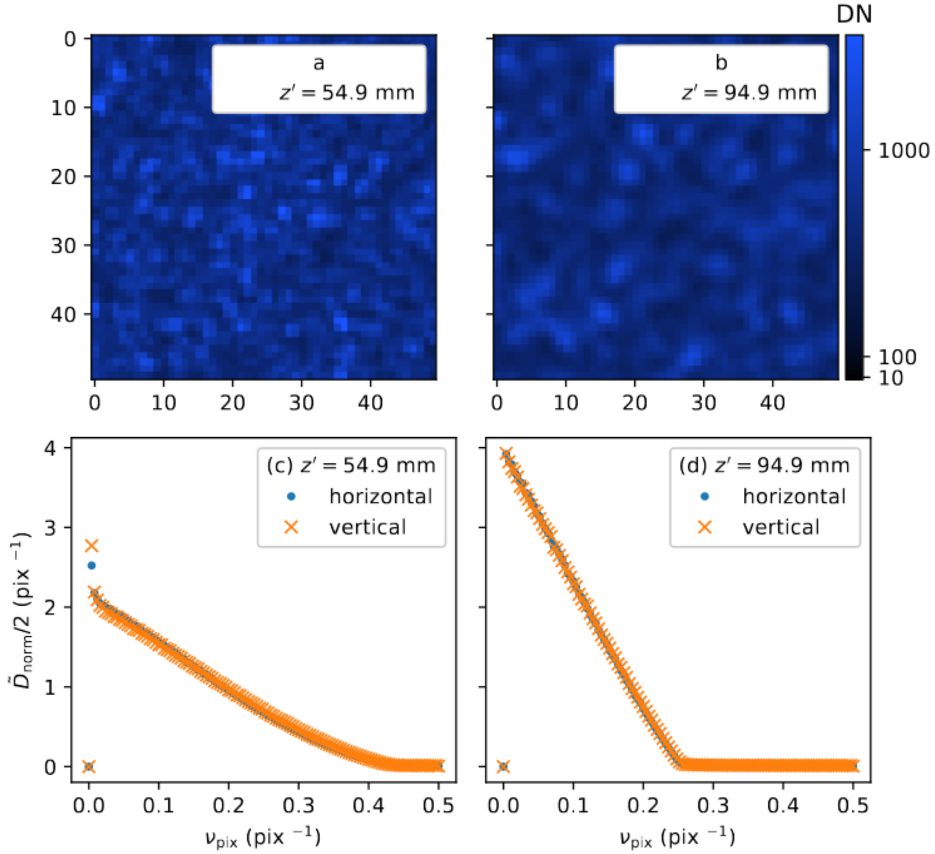


Experimental setup



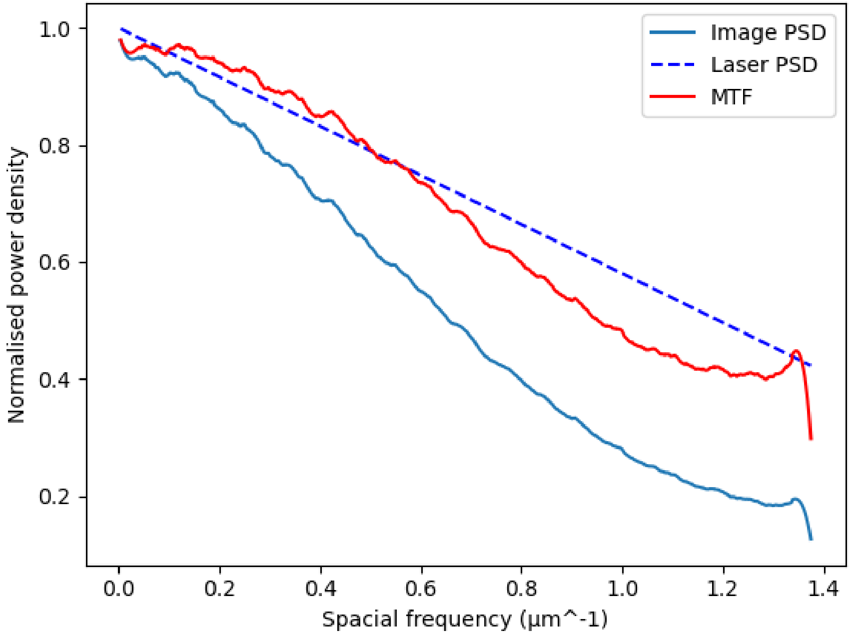
Laser speckle MTF





Two speckle patterns at different projection distances and the resulting PSDs obtained for each.

(early!) MTF for image at 20mm

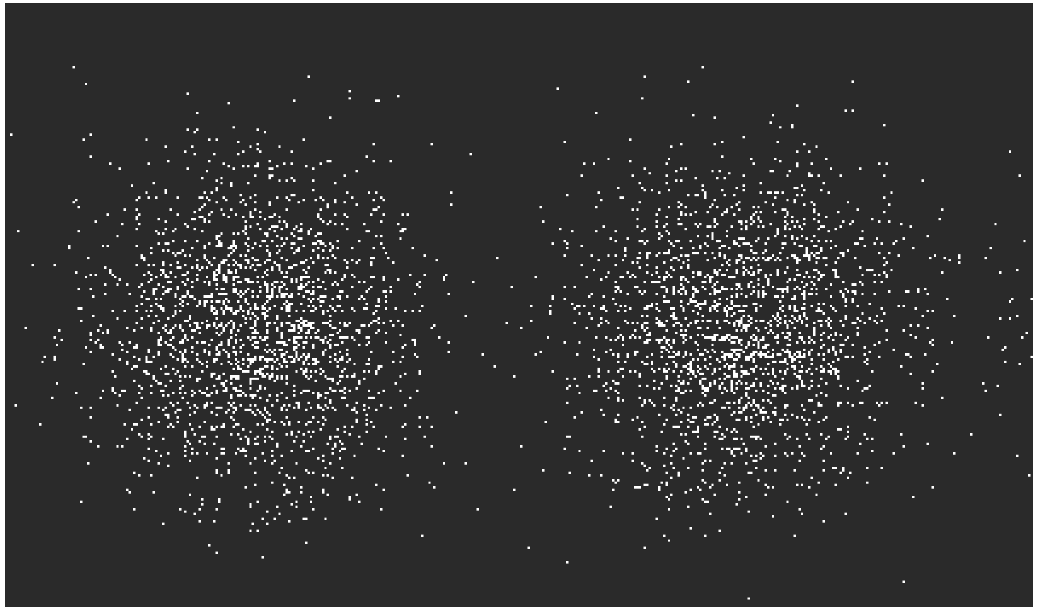


Summary

- Oxford OPMD group tasked with production of **primary imaging system** for MAGIS-100 atom interferometer at Fermilab. Aim to minimise the error on phase recovery introduced by the imaging system.
- Simulations of **realistic photon distributions at sensor plane**, plus associated sensor effects.
- Candidate camera comprising **Sony IMX541** CMOS sensor + **Edmund 50mm** fixed focal length lens.
- Optical characterisation using lateral shear interferometry to correct for lens aberrations.
- System resolution (MTF) for full cloud using slant edge and laser speckle methods. Simulations of final random phase error for various lens options, aperture diameters, exposure times.
- Development of final **test + calibration procedure** for sensor, lens and complete system well underway, with early results for gain, linearity, QE, dark current etc..

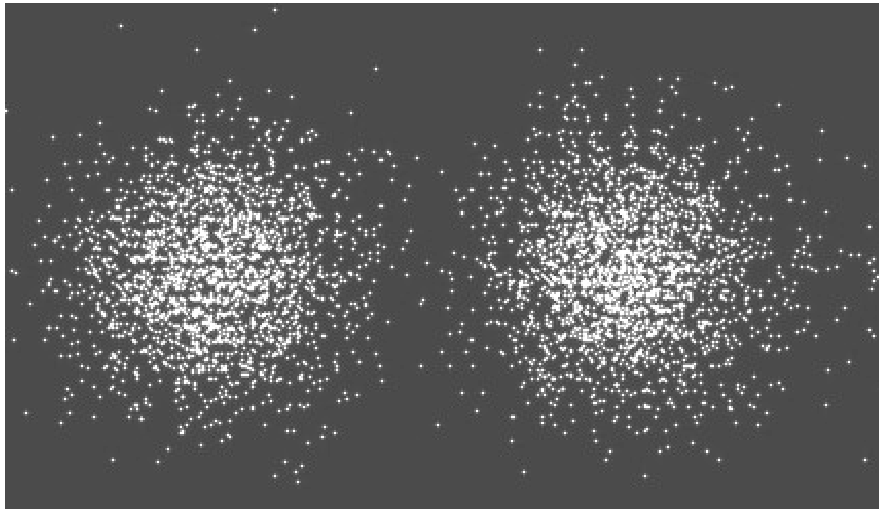
Depth-of-field effects

Atom cloud is a 3D object. Photons at the centre of the cloud (along optical axis) are in focus:

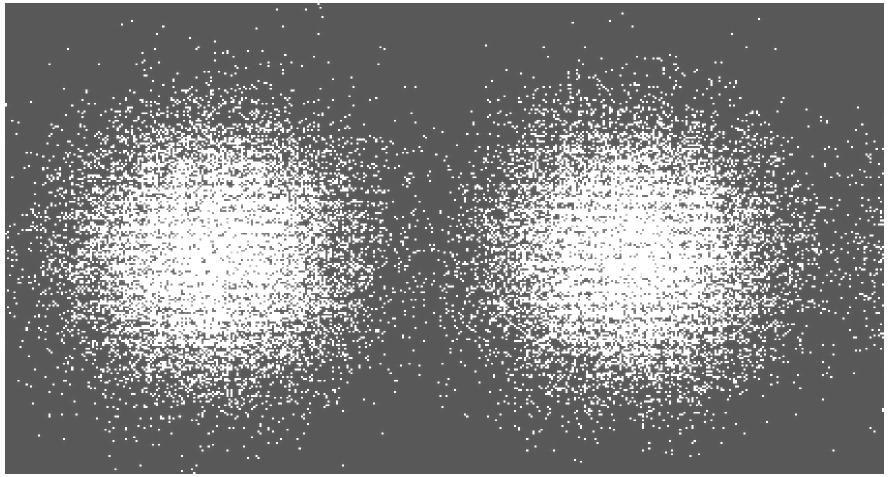


Without DoF effects

DoF with 10mm diameter lens

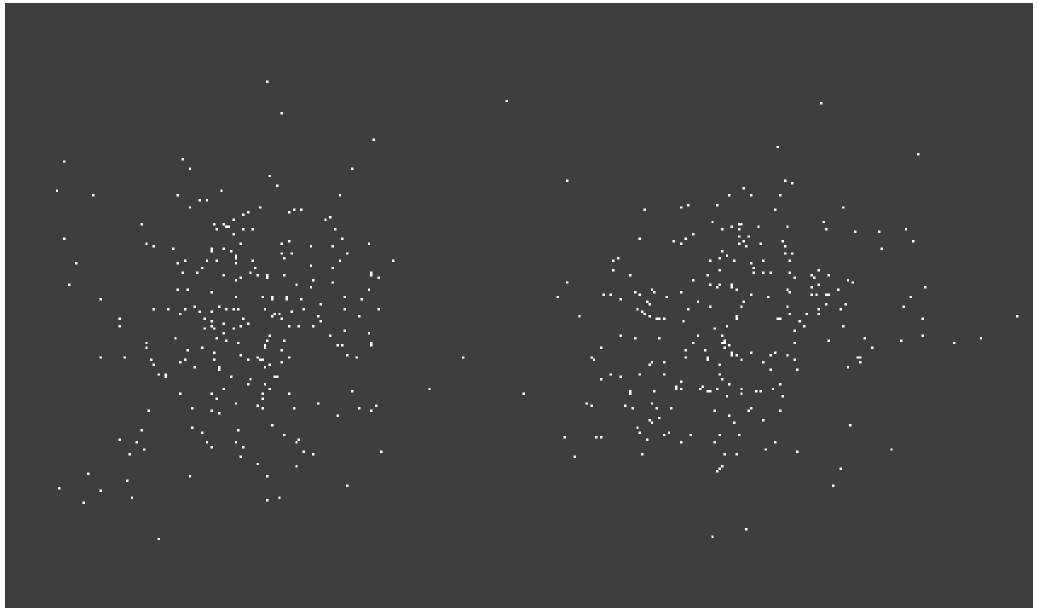


DoF with 30mm diameter lens



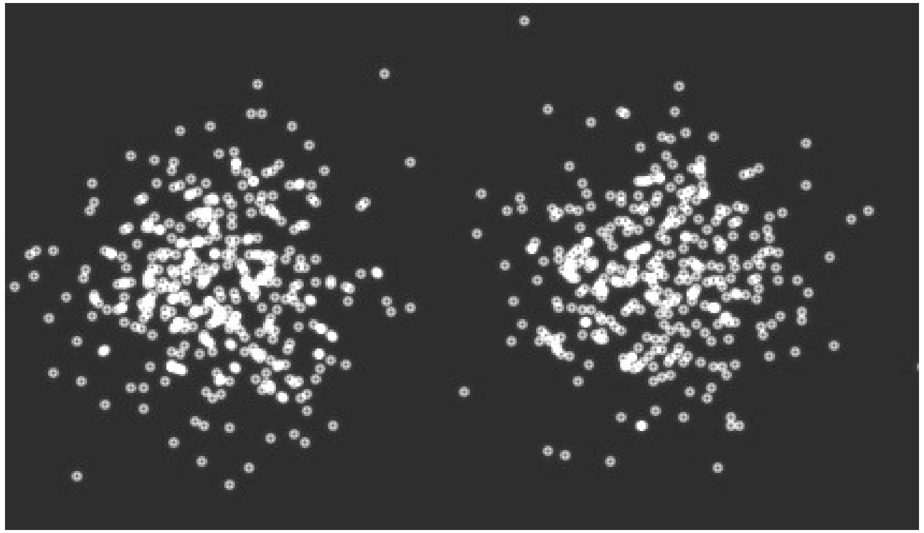
Depth-of-field effects

Atom cloud is a 3D object. Photons at the edges of the cloud (along optical axis) are out of focus:

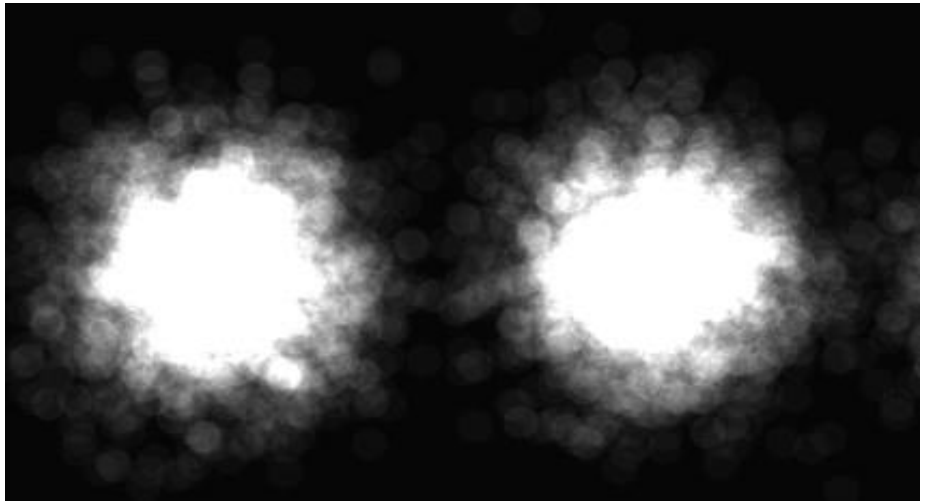


Without DoF effects

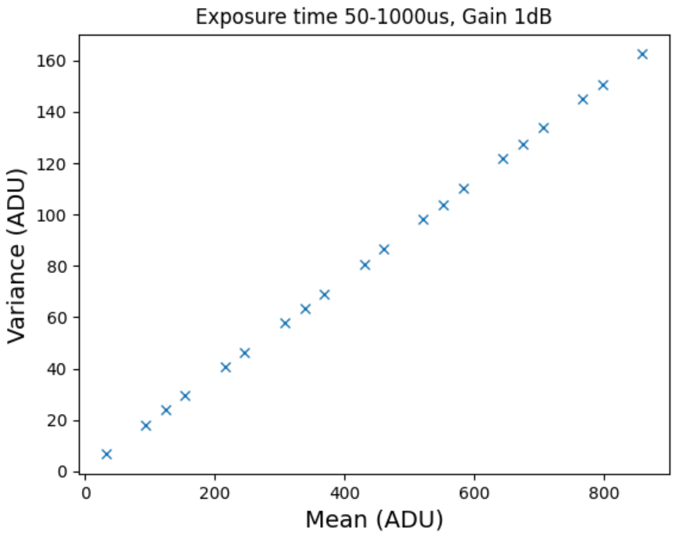
DoF with 10mm diameter lens

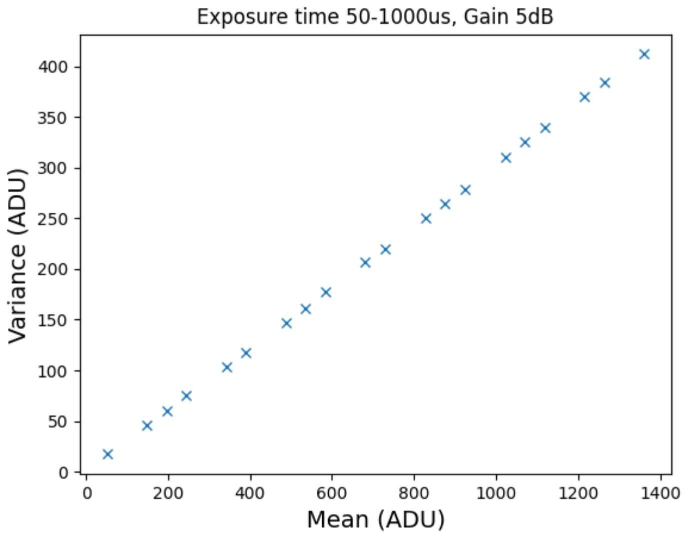


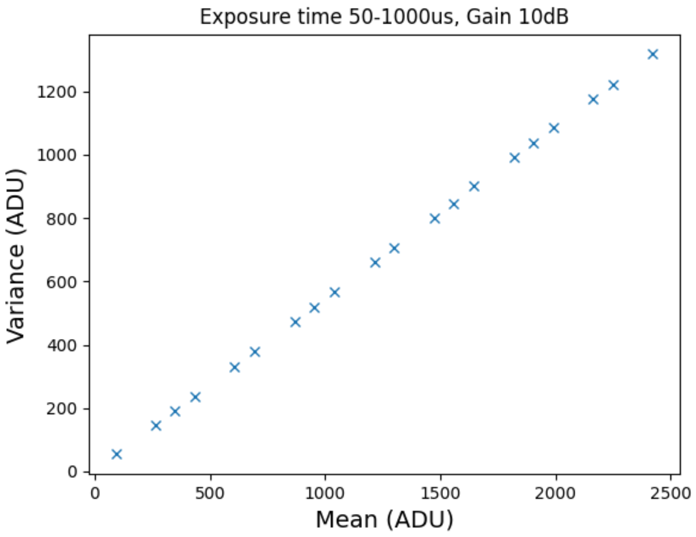
DoF with 30mm diameter lens

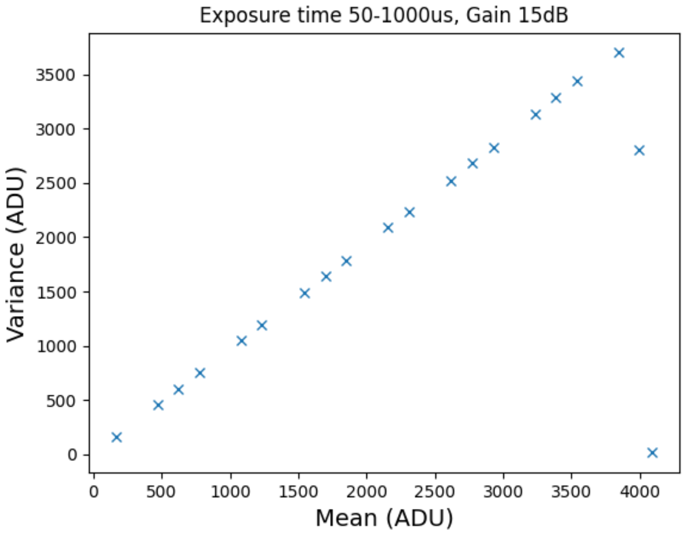


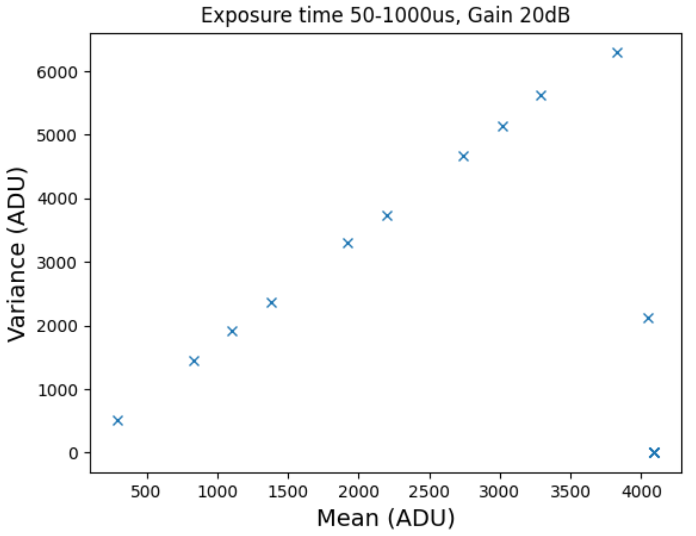
Initial CMOS testing











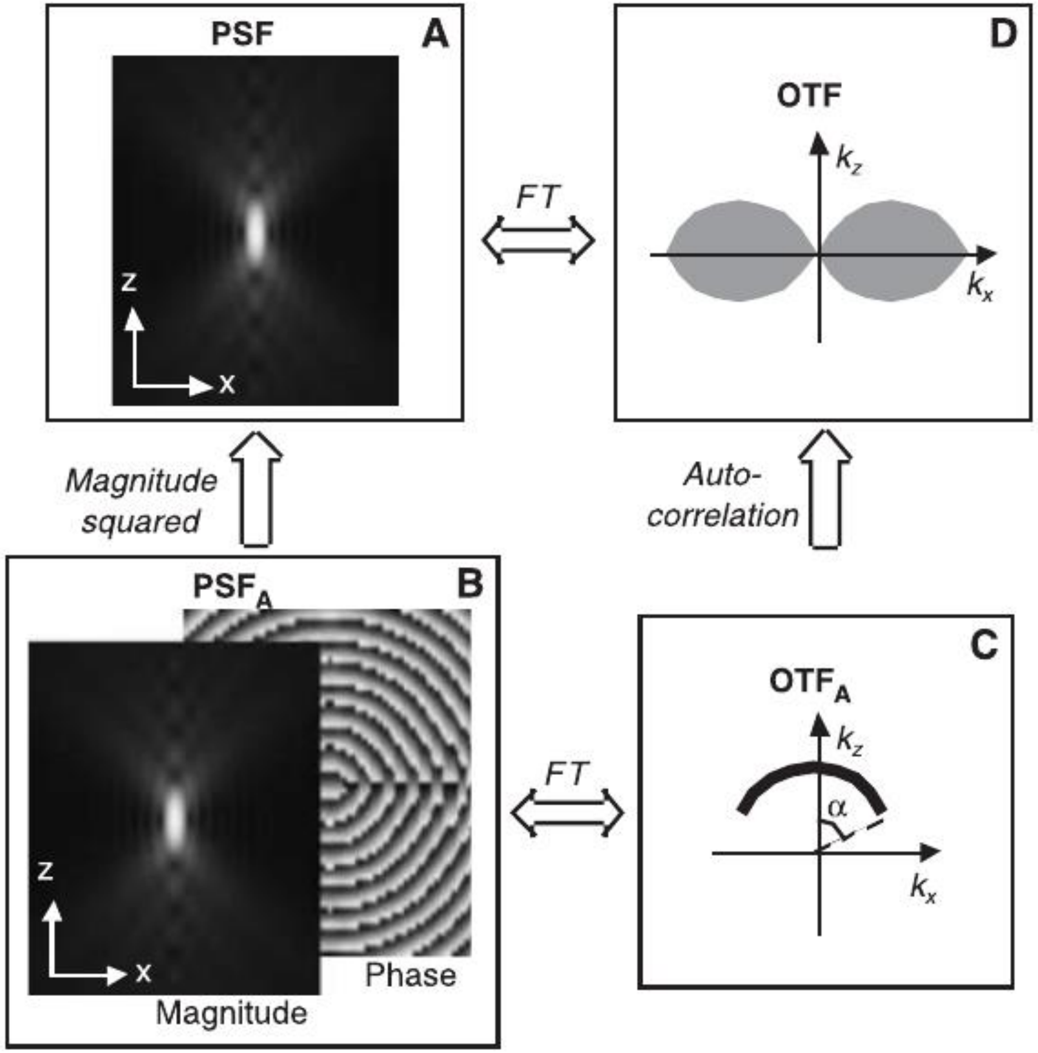
Adjustable gain

Read noise ~2.5e

Optical characterisation

For simulating (and de-convolving) images we want to know the incoherent OTF/PSF.

To also correct for defocus and tilt, we want to know the **pupil function.**



(image from Hanser et al, 2004)

Measurement of incoherent OTF using conventional test (knife edge + laser speckle)

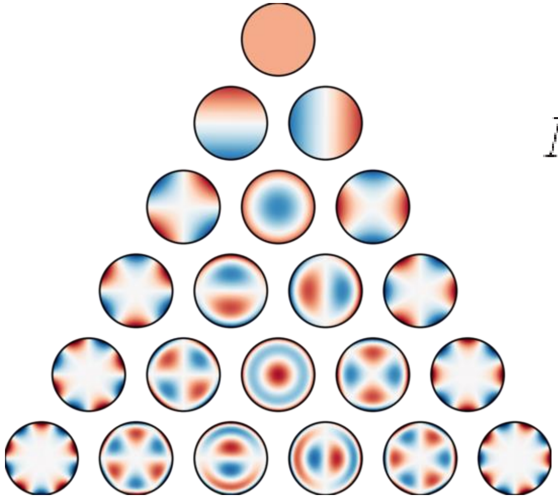
Also measure coherent OTF using **shearing interferometry**

⟷ **Pupil Function!**

MTF Contributions

Optics

- Diffraction limit
- Zernike's – defocus, spherical aberration etc.
- Vignetting / off axis effects – can be included in full 3D OTF

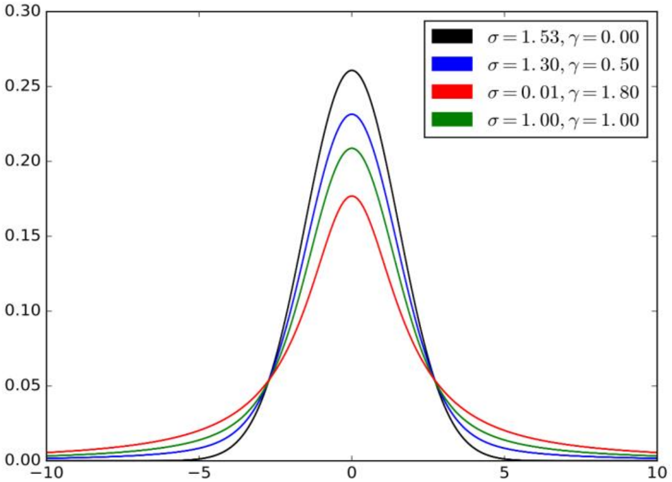


$$MTF(k_x, k_y) = \frac{M_e(k_x, k_y) + M_{zce}(k_x, k_y)}{M_e(0,0) + M_{zce}(0,0)}.$$

Djite-Estribeau model of charge diffusion MTF

Environmental

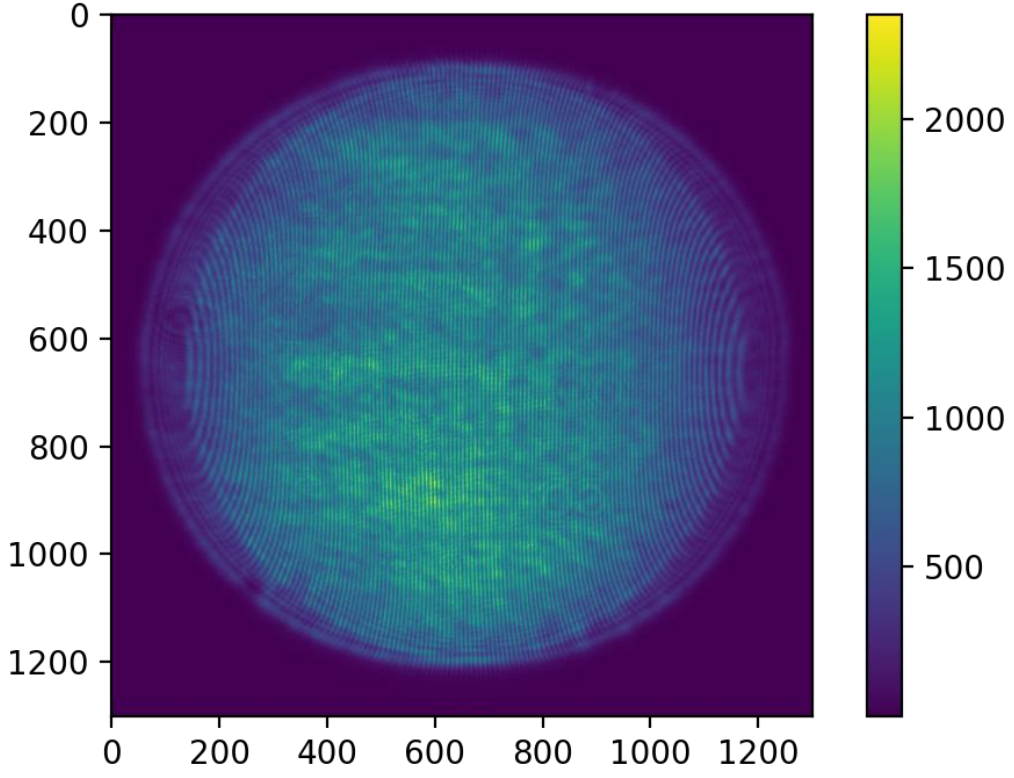
- Vibrations – usually modelled as Voigt (right) if period shorter than exposure time, and more complicated if not.

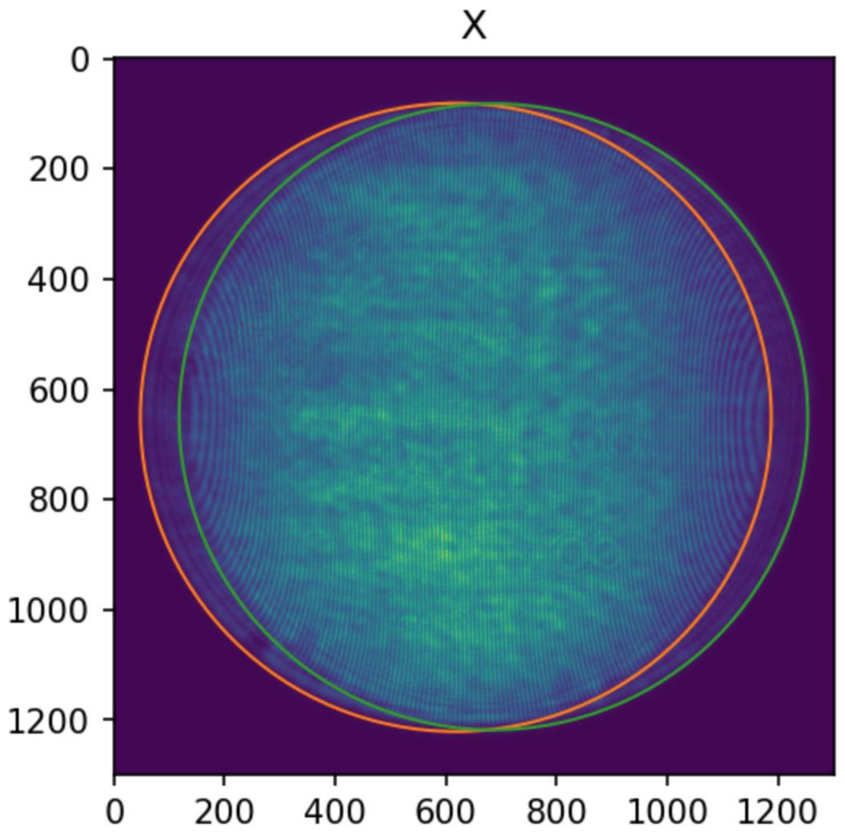


Detector

- Charge Diffusion (not fully depleted).
- Sampling & Pixel size – proportional to sinc.

Pupil function - clean images



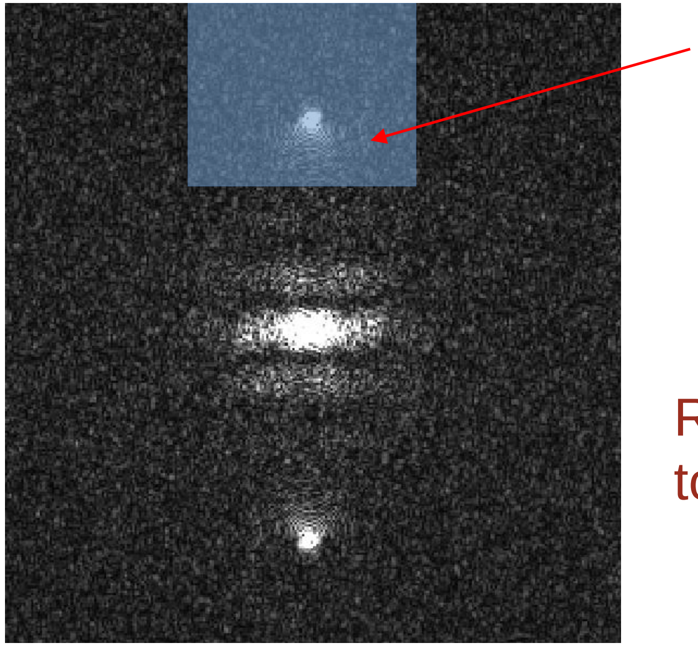


Start with an image, large amount of defocus introduced as a linear carrier fringe.

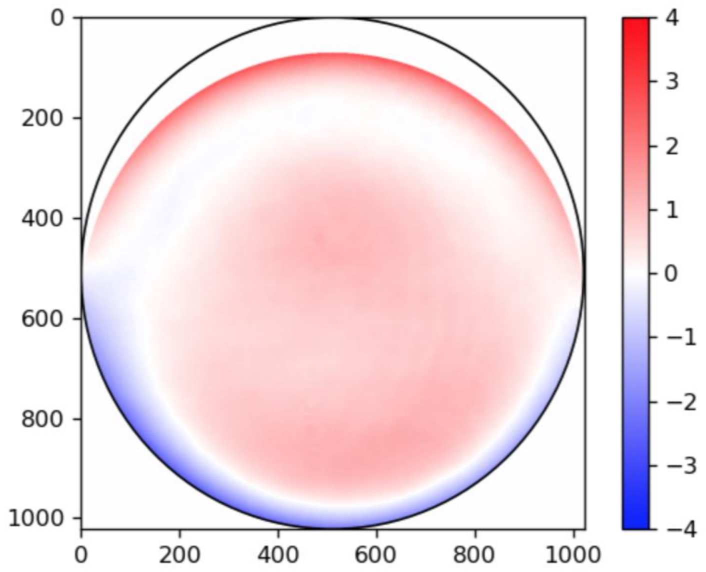
We use skimage based tools to register the offset pupils and work out the shear amount

Pupil function - heterodyne detection

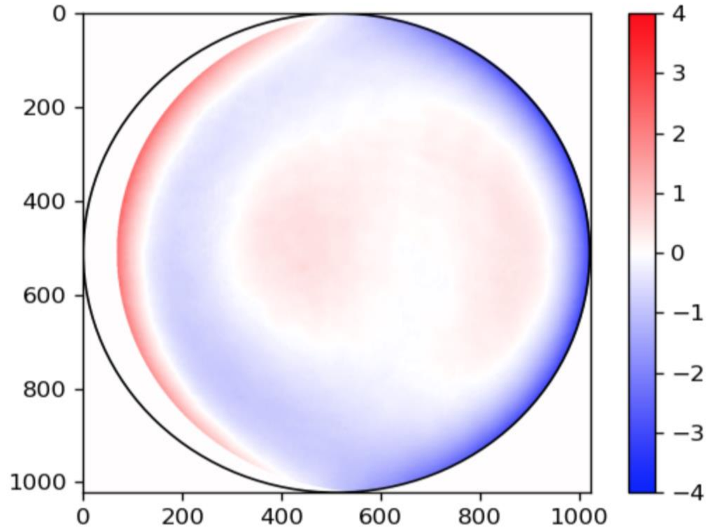
Use a Gabor-type bandpass filter to isolate the first order peak in Fourier space, and then shift it back down to zero frequency, removing the imprinted linear fringe component ("heterodyne detection")



Keep just this bit

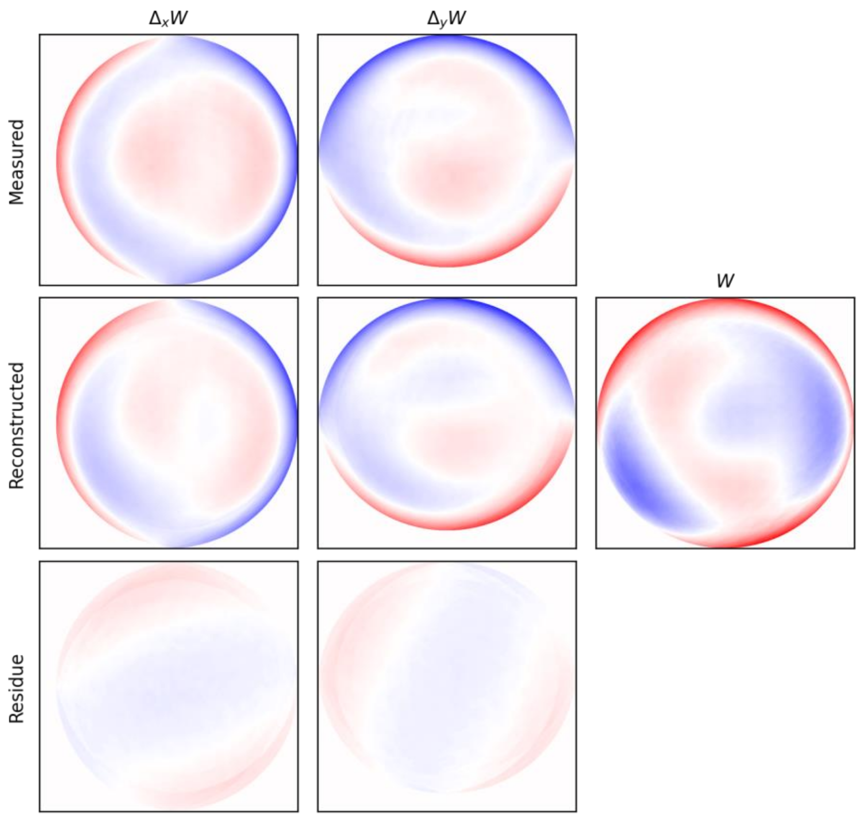


Rotate lens under test by 90 degrees to get two orthogonal shear directions



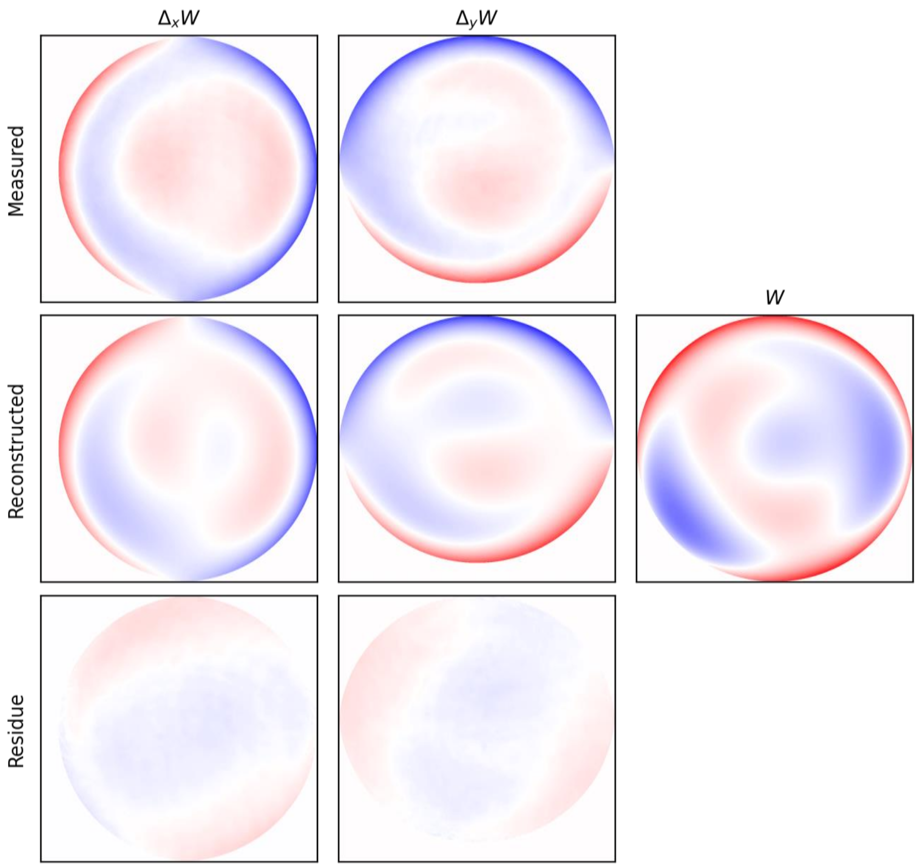
Pupil function - pupil recovery

Several methods in literature are documented. We have implemented two and they agree remarkably well with each other. Residuals are below ~1% and the methods agree to within similar margins.



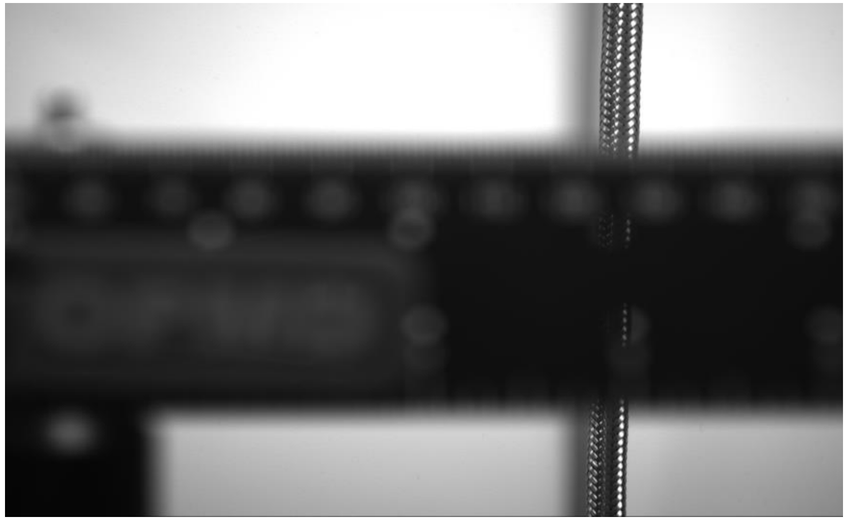
Fit Zernikes to derivative and integrate to get W

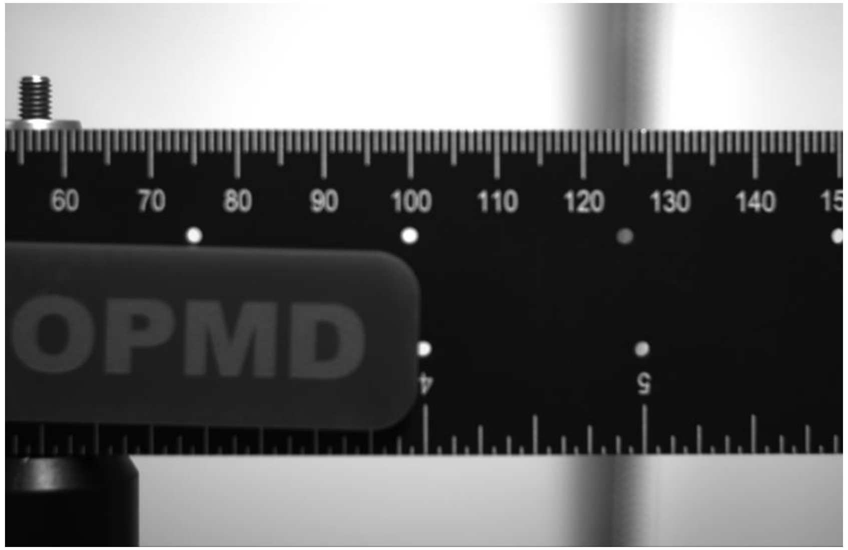
Or: solve the difference equation directly, using Tikhonov regularisation.

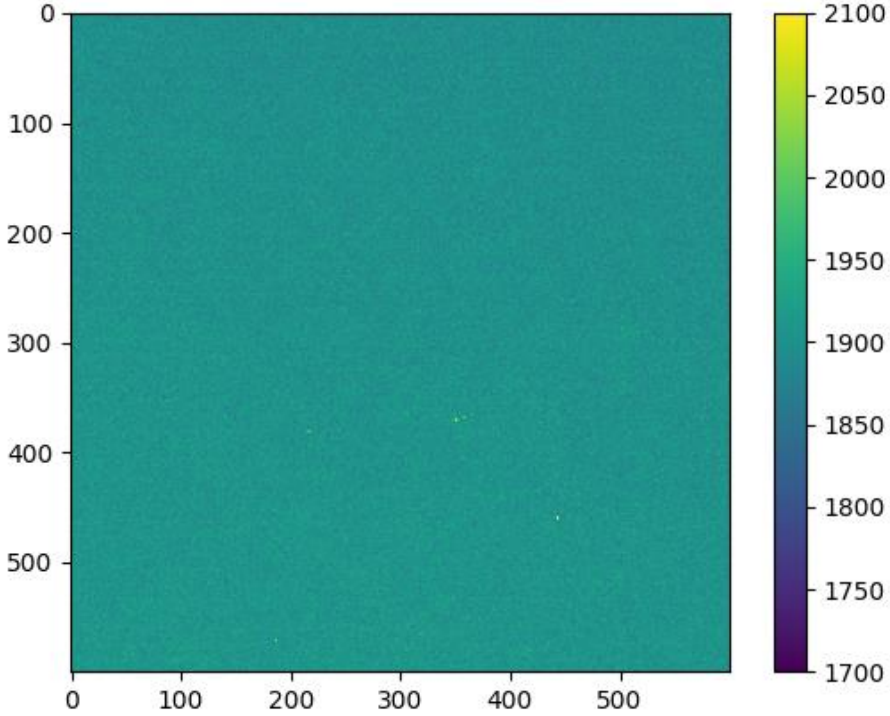


Initial CMOS testing

First light and DoF example







Example flat-field image with high-intensity tuneable blue LED source