Imaging for the MAGIS-100 and AION interferometers

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Outline

- Overview of imaging systems in MAGIS-100
- Camera Specification Considerations
- Photon & Time Budget Tradeoff
- Camera & Optics Testing Procedures

Our work at the moment concentrates on MAGIS-100 camera systems development, but we will use what we learn to optimise also the imager for AION-10

MAGIS Imaging Systems

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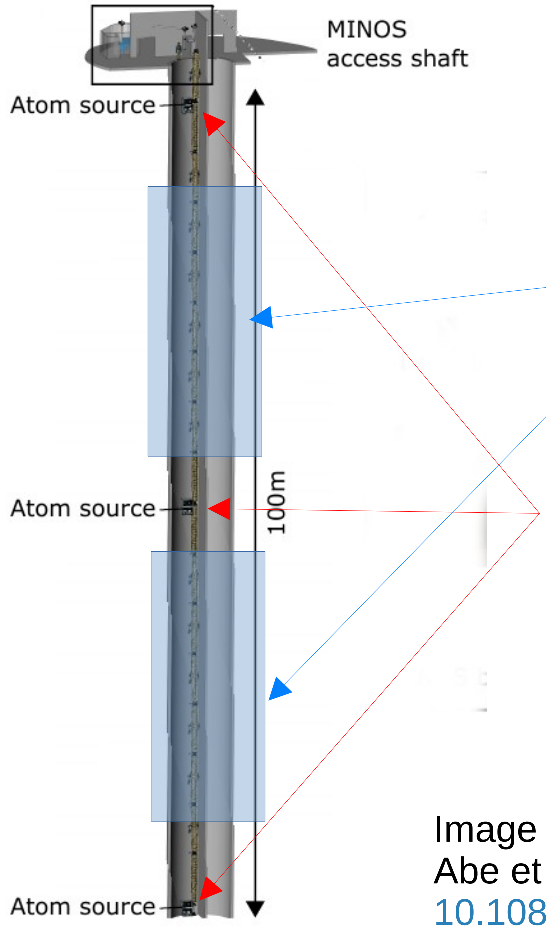

"Diagnostic" Imagers
Located throughout
Interferomer region

"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. Some equipped with slower optics to resolve fringes. Designed & built by SLAC
- **Primary Imaging System –** High sensitivity & resolution cameras located at each connection node used for imaging & phase fitting of atom clouds. Designed & built by Oxford (OPMD group).

Both groups collaborating closely on specification, simulation, test & commissioning of imaging systems

MAGIS-100 Primary Imagers

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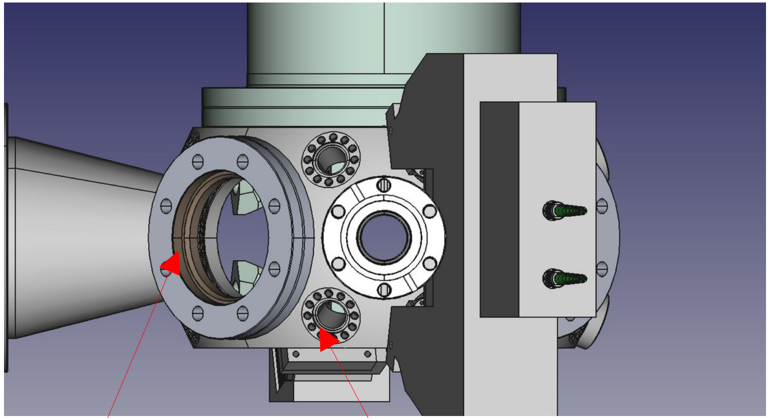
Interferometry Region

Atom Source



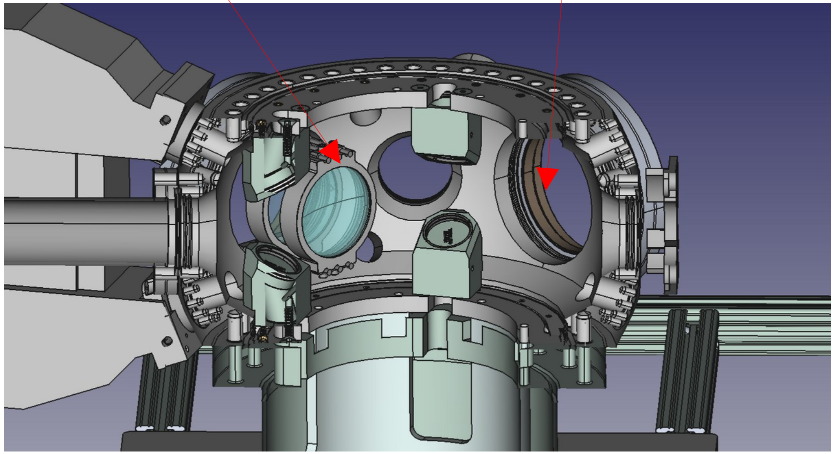
On-axis viewports

Off-axis viewports

Baseline: at least 2 primary imagers at each connection node enabling multi-axis imaging of atom clouds (many viewports available)

In-vacuum optics

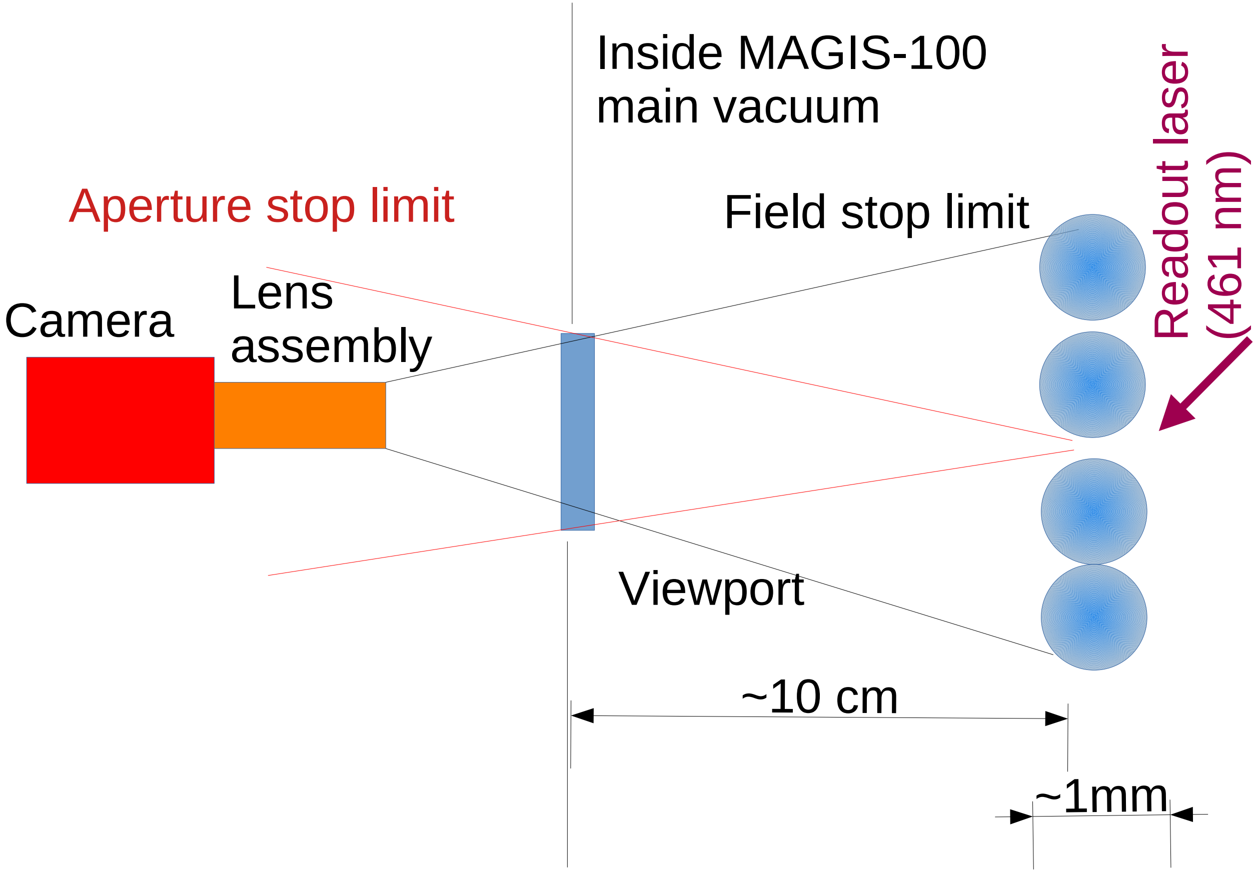
Clear Viewport



For applications involving low luminosity clouds, in-vacuum optics available at some viewports. Trade-off is loss of depth of field (& hence fringe contrast)

Detector at each Viewport

- Atoms illuminated by 461nm laser and emit light by fluorescence.
- Clouds have a radius of ~1mm. Up to 4 clouds (2 ports of 2 interferometers) visible in each primary imager, which are about 3 radii apart
- To avoid the imaging system being the limiting error source, we must achieve imaging limited by the **atom shot noise**. In MAGIS-100, the target is for each cloud to contain $N \sim 10^6$ atoms.



Integration Time & Photon Budget

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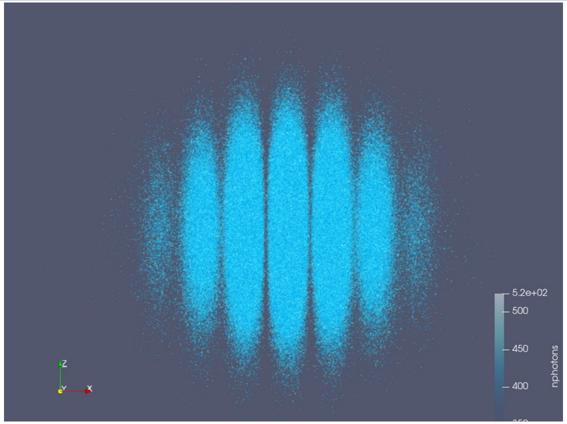
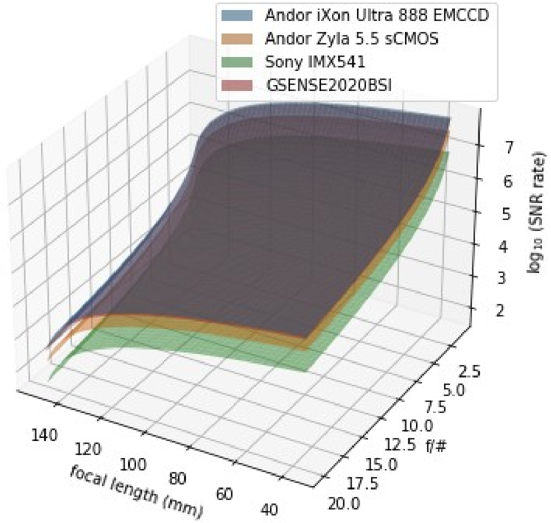
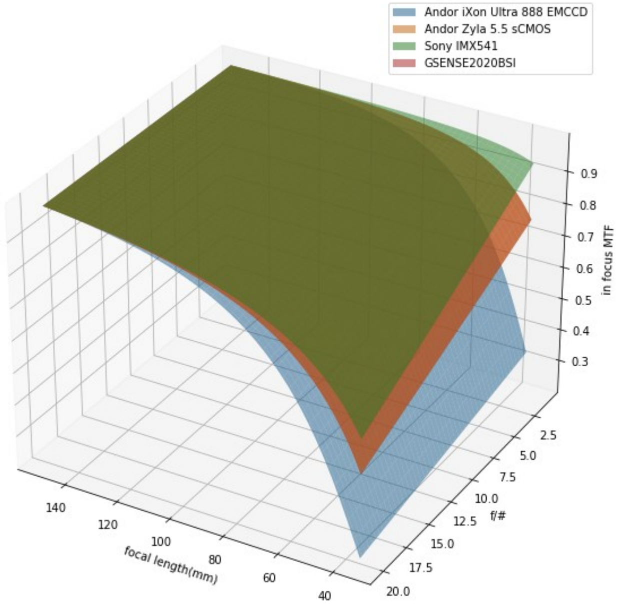




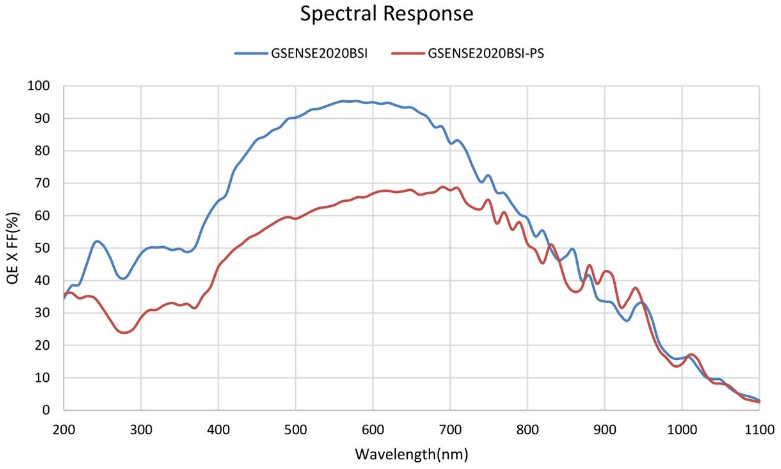
- Photon shot noise decreases relative to atom shot noise as integration time increases
- **Minimum integration time** to achieve atom shot noise limit given by **camera noise**, quantum efficiency, optics numerical aperture (current baseline ~5 us)
- After some time (~100 us), spatial resolution degrades due to **atom recoil** from fluorescence ("diffusion").
- Eventually, dark current in camera also degrades signal to noise ratio directly
- In practice, **longest integration time** limited by **full well capacity** of the camera in most realistic scenarios
- Detailed simulations (atom fluorescence + optics model + detailed detector model – ESA Pyxel) underway to numerically optimise camera, but simple approximations give good guidance to begin optimisation
- Can trade off (with limits due to spatial resolution constraints) between **dynamic range** and **noise per area** by changing optics focal length (or sensor pixel pitch)

- **Top Left:** Example simulated atom positions at beginning of camera integration
- **Bottom Left:** Example SNR rate calculation for various camera sensors (assuming spatial Nyquist condition is fulfilled)

Sensor – QE, MTF, Noise, Full well



- In order not to waste photons, a high QE back illuminated sensor with good AR coating is required (**below:** typical response for modern BI sCMOS imager)
- Sensor MTF at expected fringe frequency is important – it is likely we will want to oversample the optics MTF with the detector MTF to better enable correction of optical aberration



Above: calculated limiting MTF performance for several sensors in different optical conditions

- Sensor read noise itself is mostly not a concern, though **read noise per unit area** and **effective dynamic range** are both key figures of merit to reach atom shot noise limited imaging in the widest possible operating range

Optics – MTF, aberrations, f/#

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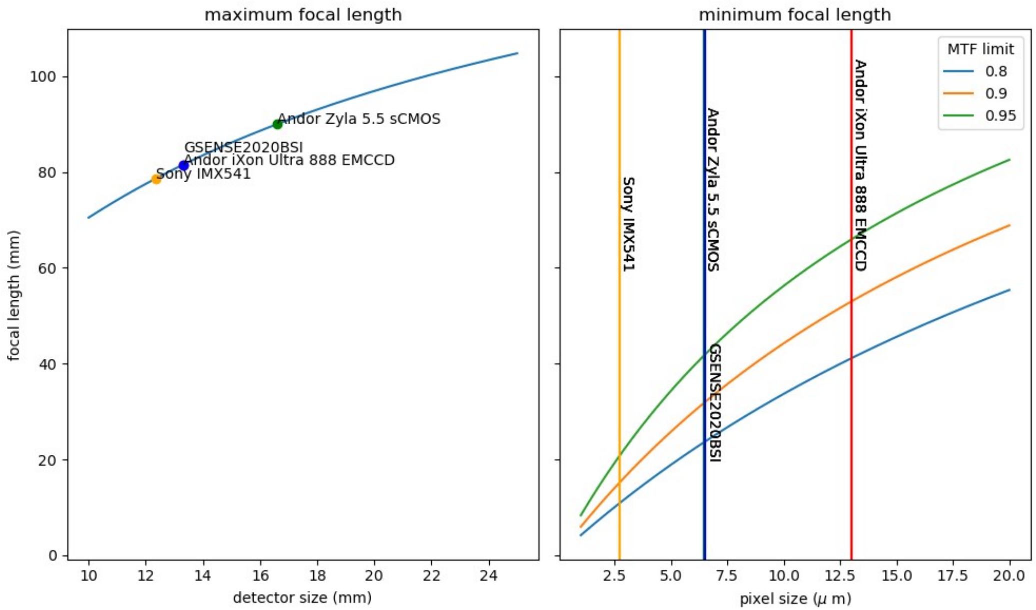
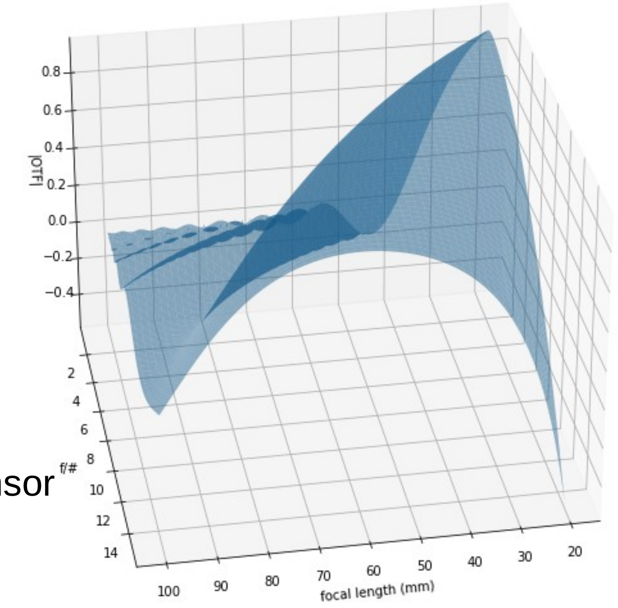
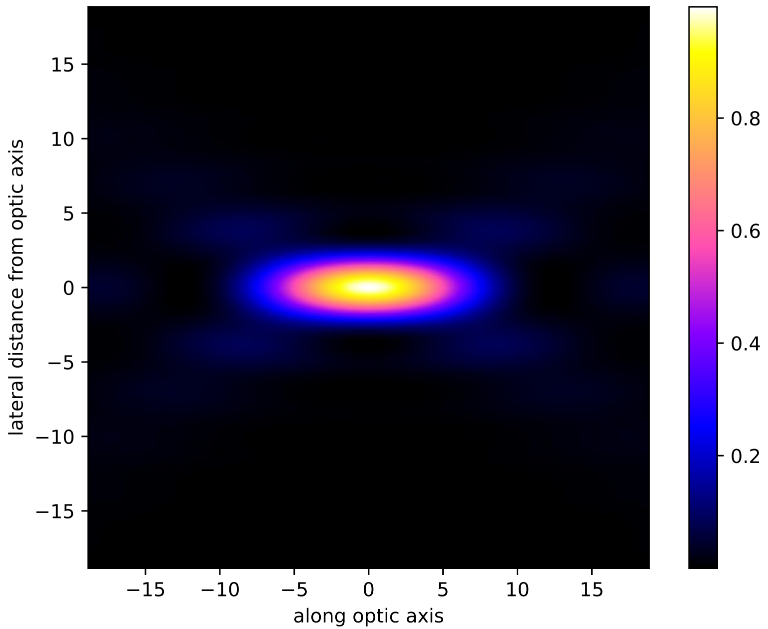




- Focal length is limited at the maximum by the need to fit 4 clouds on the sensor field of view, and at the minimum by the need to achieve oversampled MTF performance at target frequency **(above left)**
- We use simulated MTF at the front and back edge of the cloud as a performance metric to further limit the considered f/# and focal length combination of the optics (**above right)**
- **Vignetting** and **spherical aberrations** must be considered carefully also (for 4 clouds we are stretching the limits of the paraxial approximation)

Optics – MTF 2, Depth of Field



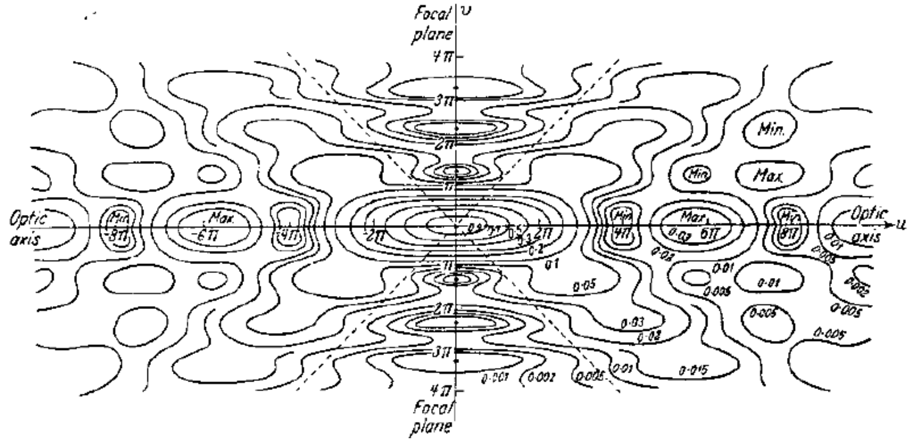
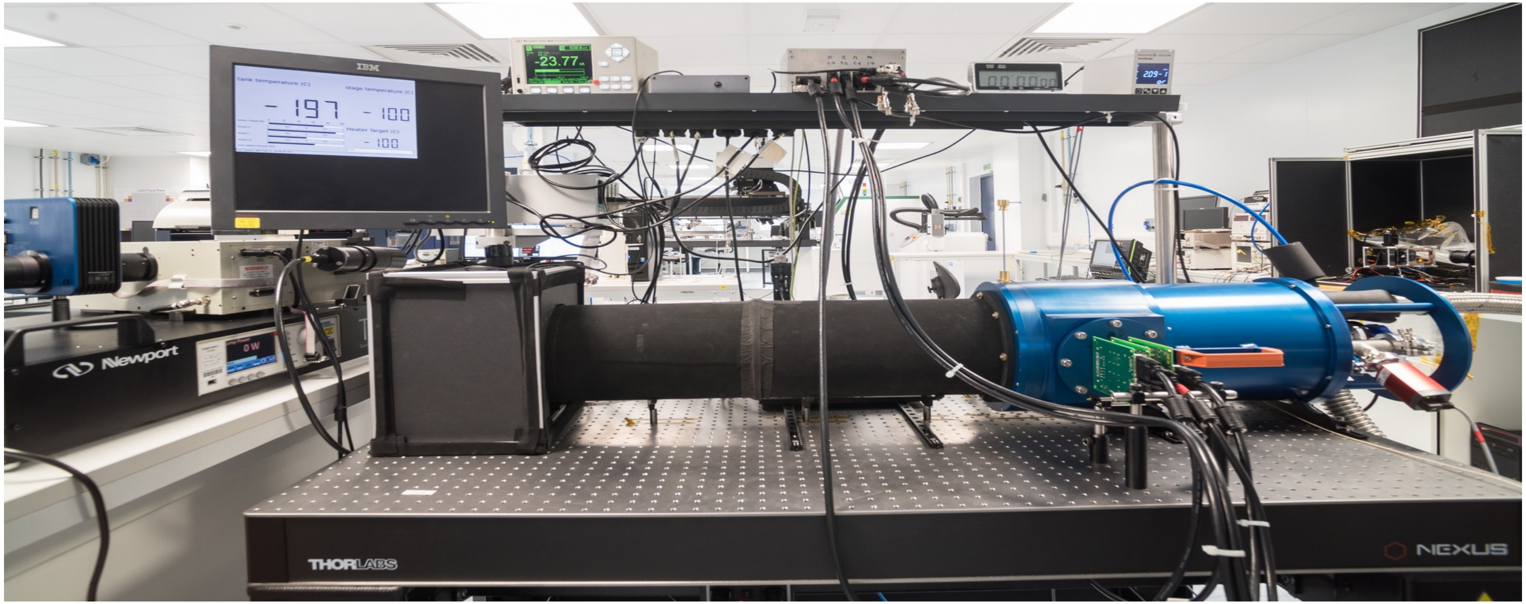


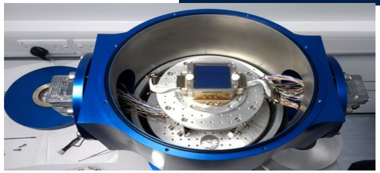
Fig. 8.41. Isophotes [contour lines of the intensity $I(u, v)$] in a meridional plane near focus of a converging spherical wave diffracted at a circular aperture. The intensity is normalized to unity at focus. The dotted lines represent the boundary of the geometrical shadow. When the figure is rotated about the u-axis, the minima on the v-axis generate the AIRY dark rings.

(Adapted from E. H. LINFOOT and E. WOLF, *Proc. Phys. Soc.*, B, **69** (1956), 823.)

- A key limitation on aperture (and hence photon budget) is the need to maintain depth of field sufficient to resolve fringes spatially.
- This is hard to calculate simply, but we have implemented full 3D optical transfer calculations and this effect is included in our verification simulations for the imaging system

OPMD Sensor Test System





OPMD lab has long experience optimising and characterising optical detectors (in particular for the LSST camera). We will be using these systems to carefully characterise and calibrate each primary MAGIS camera individually for: gain, linearity, quantum efficiency, non-uniformity, noise spectrum & dark current rate

- Accurate radiometry, flat fielding and tunable light source with monochromator allow us to calibrate these parameters per camera to a high degree of accuracy, improving quality of raw images before physics analysis
- MTF of each sensor will be characterised via both the knife edge method and (using 450nm laser light) via laser speckle.

Lens & MTF Testing

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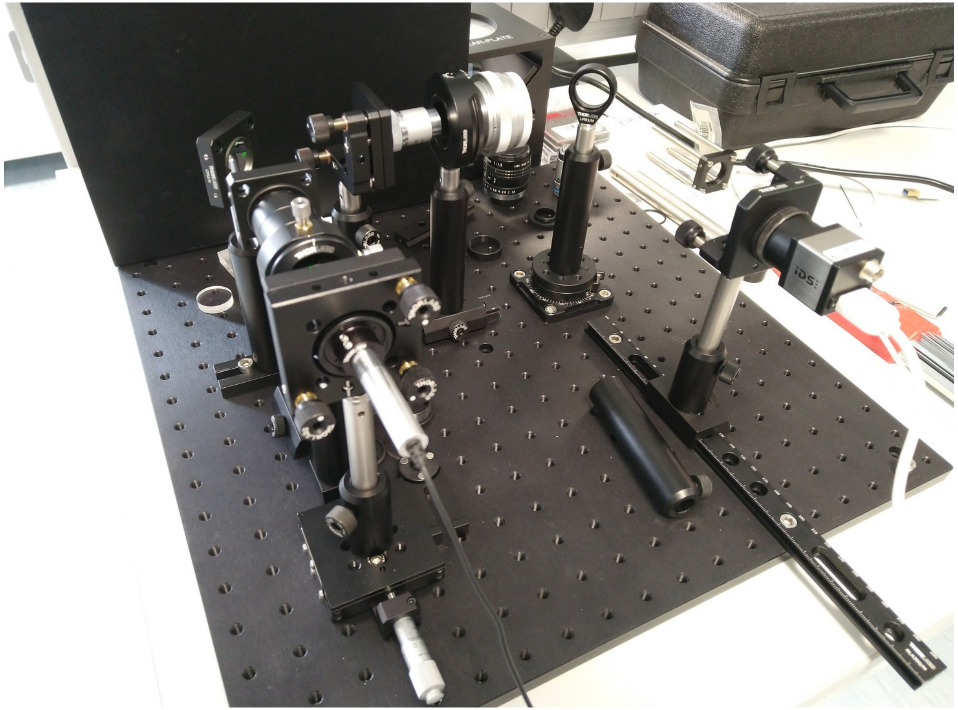
- Lens assemblies will be characterised in OPMD for aberrations via lateral shear interferometry, allowing for some correction of spherical aberrations & coma
- Each lens assembly will also be tested via flat field illumination for vignetting performance and using a specialist depth of field target to verify focussing and aperture performance
- The lens assemblies will be mated with the sensors and then the overall system will be finally verified for both MTF and throughput performance using test targets and calibrated sources
- Several candidate optics & sensor systems are currently under evaluation and test in our lab – notably, sensor MTF is rarely specified in vendor documentation and must be verified prior to commitment



Thanks

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All questions, comments & suggestions very enthusiastically received

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The rest of the OPMD AION/MAGIS team:
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MAGIS-100

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AION

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