CUSTOM SHACK-HARTMANN SENSOR

FOR STELLAR INTENSITY INTERFEROMETRY

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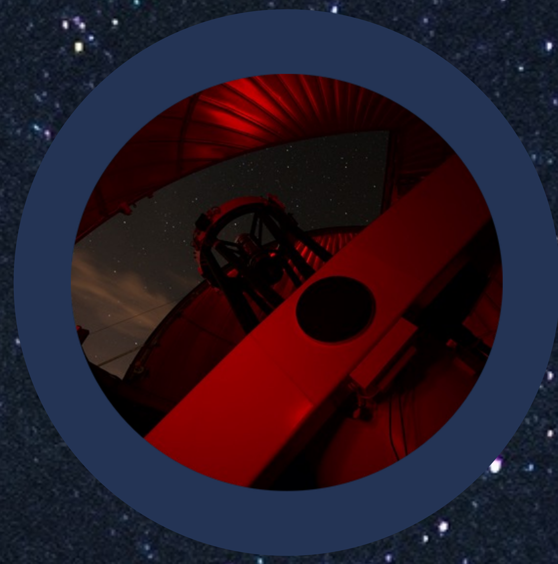
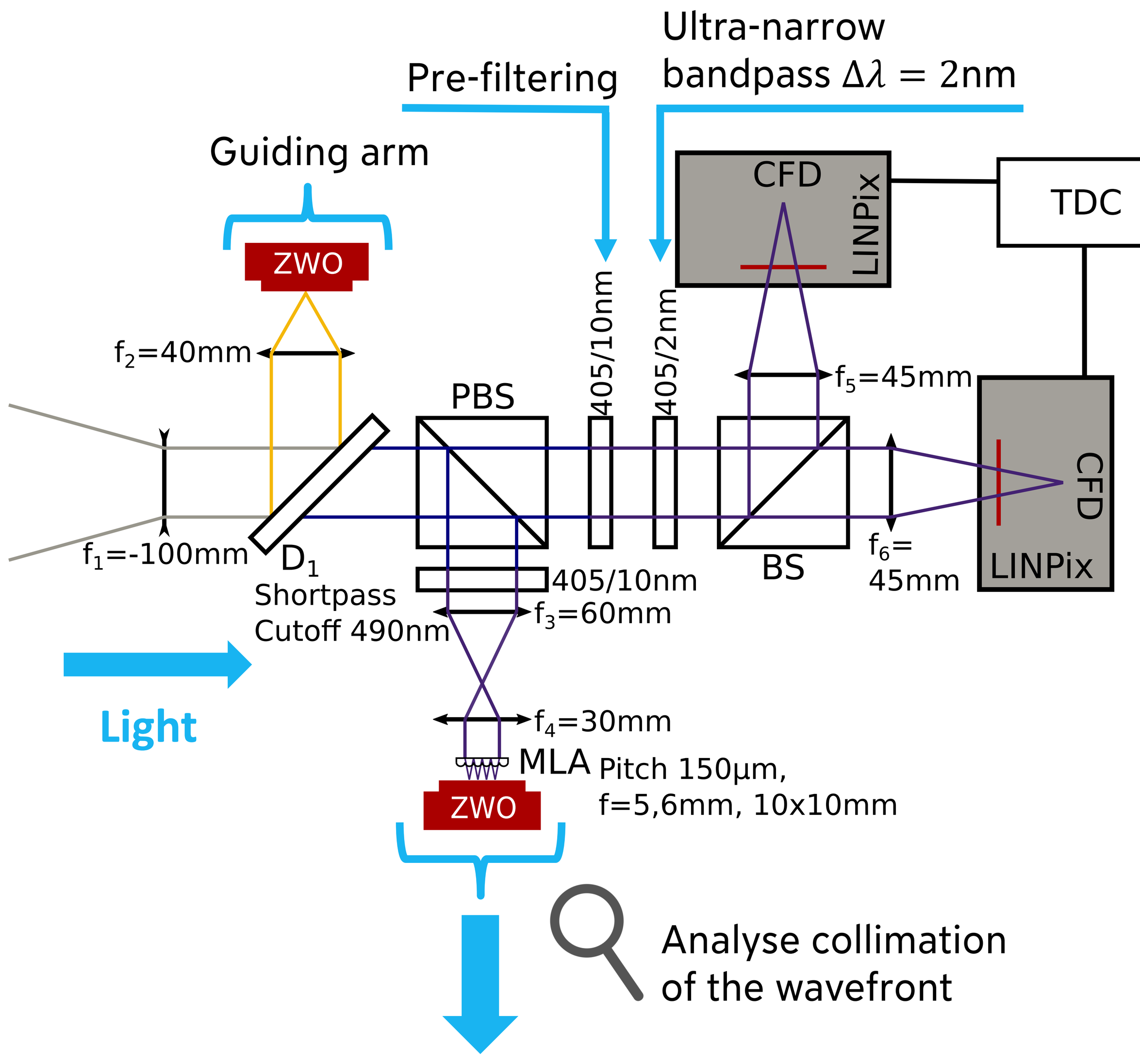


OPTICAL SETUP



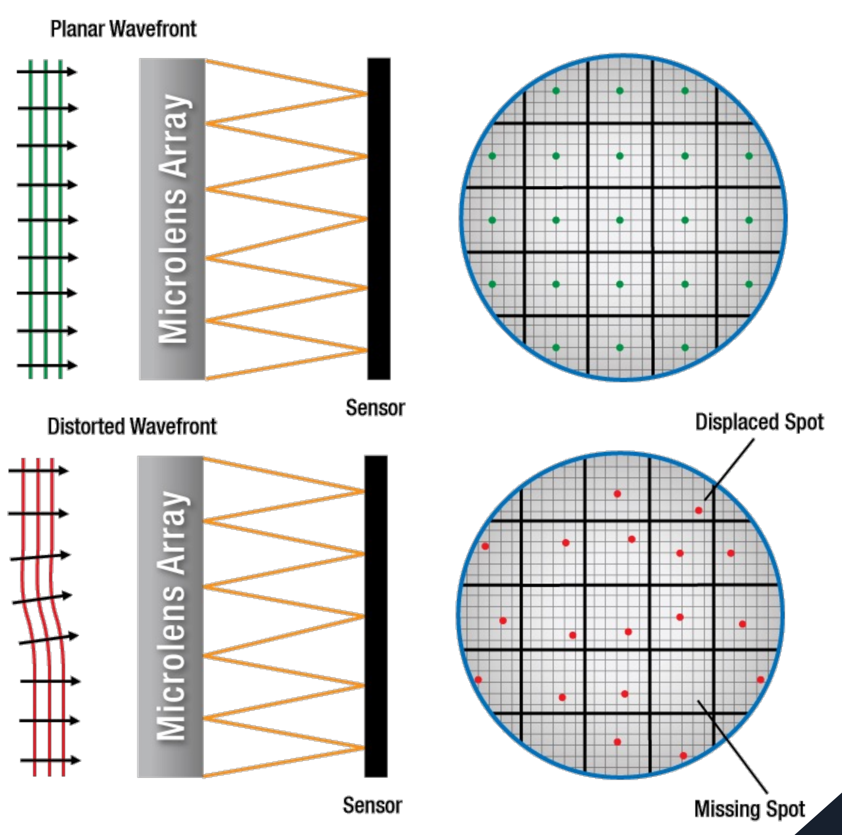
SHACK-HARTMANN ARM

Why is it needed?

- 2nm filter improves contrast for $g^{(2)}$ measurements
- wavefront needs to be collimated
- for distorted wavefront filtering fails

How does it work?

- beam is spatially reduced to fit camera sensor
- microlens array (MLA) creates spot pattern
- spot deviations indicate distortions



https://www.thorlabs.de/newgrouppage9.cfm?objectgroup_id=5287

ZERNIKE POLYNOMIALS

- spot deviations are mapped to polynomials
- any polynomial set can be used
- choose Zernike polynomials as they are orthogonal and represent common aberrations
- cartesian coordinates need to be normalized to unit circle

$$\underbrace{W(x,y)}_{\text{Total wavefront distortion}} = \sum_{i=0}^{N} \overbrace{a_i}^{\text{Zernike coefficient}} \underbrace{Z_i(x,y)}_{\text{i-thZernike polynomial}}$$

Zernike Term	Zernike Polynomial	Name	Normalization Factor
Z_0	1	Piston	1
Z_1	$\rho\cos\theta$	X-Tilt	2
Z_2	$\rho\sin\theta$	Y-Tilt	2
Z_3	$2\rho^2 - 1$	Defocus	$\sqrt{3}$

MOTIVATION

Stellar intensity interferometry (SII) benefits from narrow bandpass filters for improved $g^{(2)}$ contrast requiring fully collimated wavefronts. The Shack-Hartmann sensor ensures this by detecting and correcting wavefront distortions through spot deviation analysis.

TELESCOPE SITE

SII measurements were performed at the Calern Observatory located on a plateau in the South of France near Nice at an altitude of 1270 meters. C2PU offers twin telescopes at a separation of 15m.

Telescope Specifications:

- Primary mirror diameter: 1.04 m
- Focal length: 13 m
- Focal ratio: F/12.5
- Cassegrain secondary focus
- Equatorial yoke mount

FROM SENSOR DATA TO PRECISION

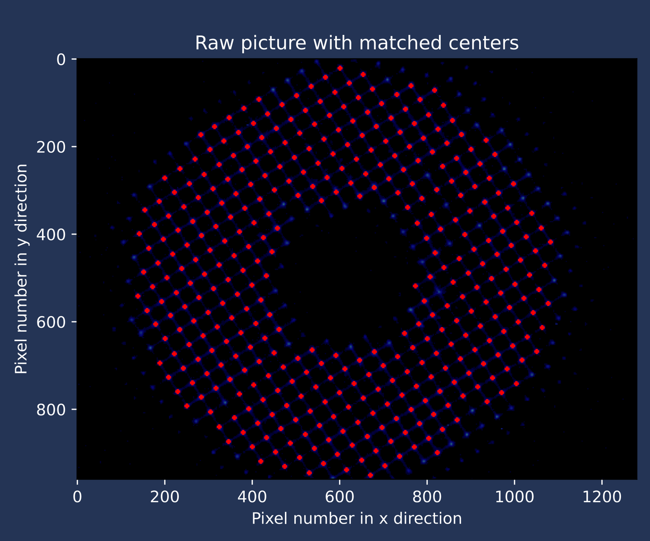
1. Spot Deviations:
   - SH sensor captures deviations $(\Delta x_i, \Delta y_i)$ in spot pattern from regular grid
2. Expansion:
   - wavefront W can be expanded using the Zernike polynomials
   $$W(x,y) = \sum_{i=0}^{3} a_i Z_i(x,y)$$
3. Calculation of the minima:
   - The merit function $G(\vec{a})$ is defined as
   $$G(\vec{a}) = \sum_{i=0}^{M} \left[\frac{\partial W(x_i,y_i)}{\partial x} - \frac{\Delta x_i}{f}\right]^2 + \left[\frac{\partial W(x_i,y_i)}{\partial y} - \frac{\Delta y_i}{f}\right]^2$$
   where M is the number of grid points, $\partial W(x_i, y_i)/\partial x$ is the expansion's derivative at position i and f is the focal length of a mircolens
   - The calculation of the minima of the merit function can be rewritten to a set of linear equations that can be solved by least-squares fitting[1]:
   $$A \cdot \vec{a} = \vec{b}$$
   - The result is the vector $\vec{a}$ containing the Zernike coefficients

[1] Pfund, J., Lindlein, N. and Schwider, J., 1998. Misalignment effects of the Shack–Hartmann sensor. Applied optics, 37(1), pp.22-27.

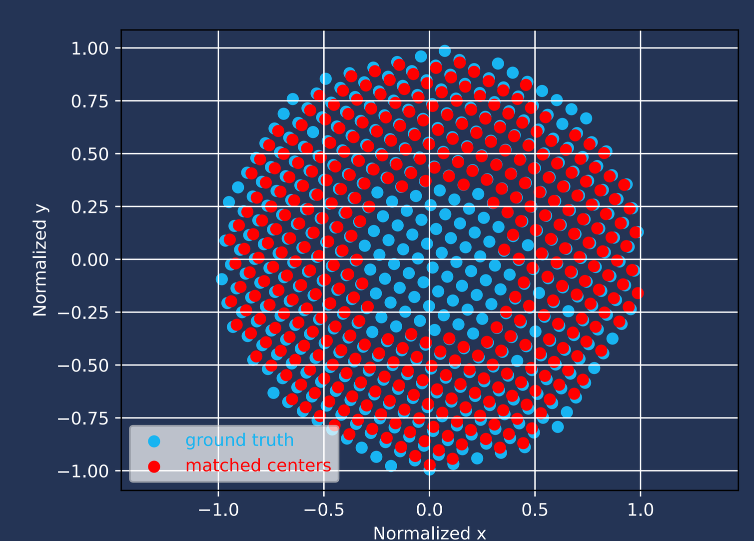
4. Correcting Defocus:
   - necessary shift of secondary mirror Δz can be calculated using defocus coefficient a_3, central wavelength of the filter λ and the numerical aperture NA:
   $$\Delta z = 4a_3\lambda/NA^2$$
   - Motorized secondary mirror can move $\Delta z = \pm 23mm$
   - The realignment moves the focal point ensuring a collimated wavefront at the filter as well as on the SH sensor

IMAGE EVALUATION

- Software reads PNG from ZWO CMOS camera and matches centers up to a certain threshold
- ideal grid is generated using the properties of the mircolens array (MLA)



- ideal grid is translated and rotated to fit the matched raw image = ground truth
- coordinates are normalized to unit circle resembling the aperture diameter
- deviations from the ground truth are calculated



- deviations in x/y-direction and the coordi-nates are feed into the least squares fit

BENEFITS TO THE EXPERIMENT:

- Real-time Correction: Compensates for telescope defocus, improving beam collimation and experimental accuracy.
- Scalability: Supports higher-order polynomials for future aberration correction.

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