PSFs for Vision Science

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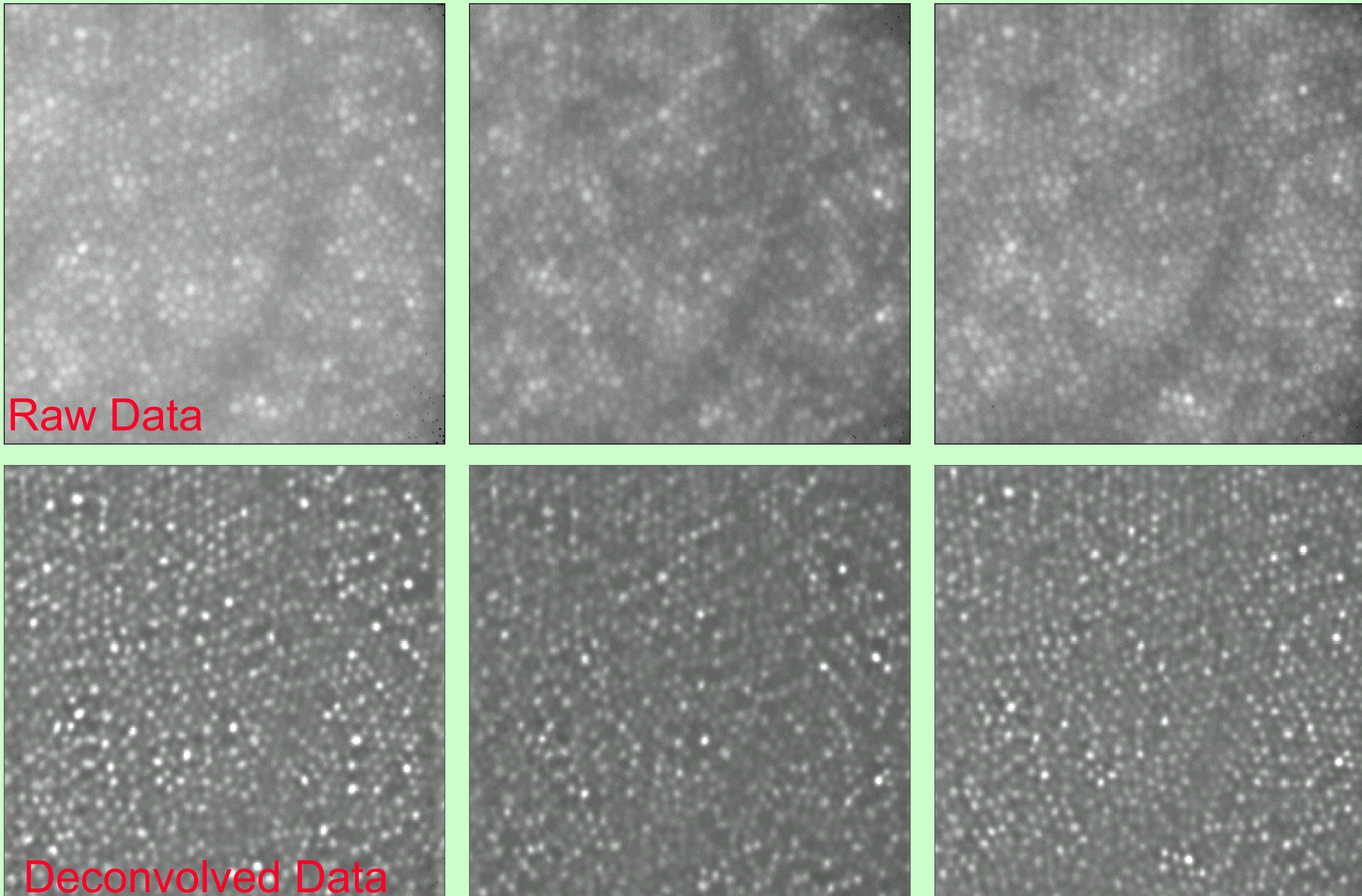
Why do we need to know the PSF?

- Knowledge of the PSF is necessary for deconvolution. The more knowledge the better the resulting object information
- Residual uncompensated aberrations in the wavefront leads to increased PSF blurring and structure leading to confusion of object information (especially quantitative).
- A prime example is measurement of cone classification which uses quantitative radiometric measurements from retinal images.

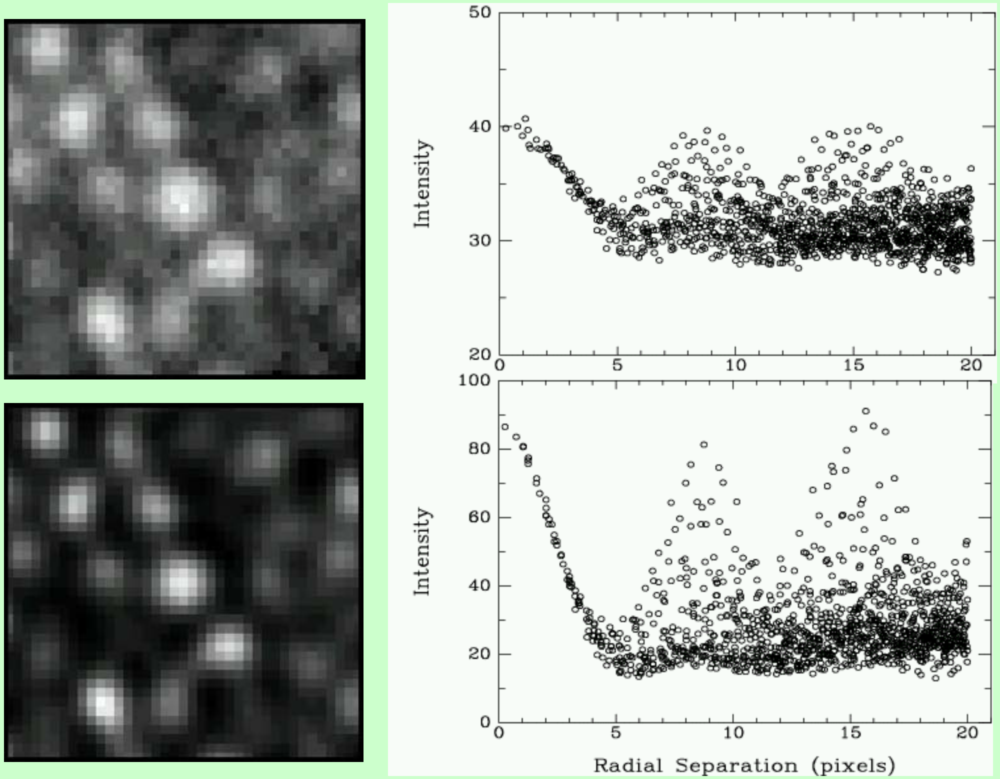
Cone Classification

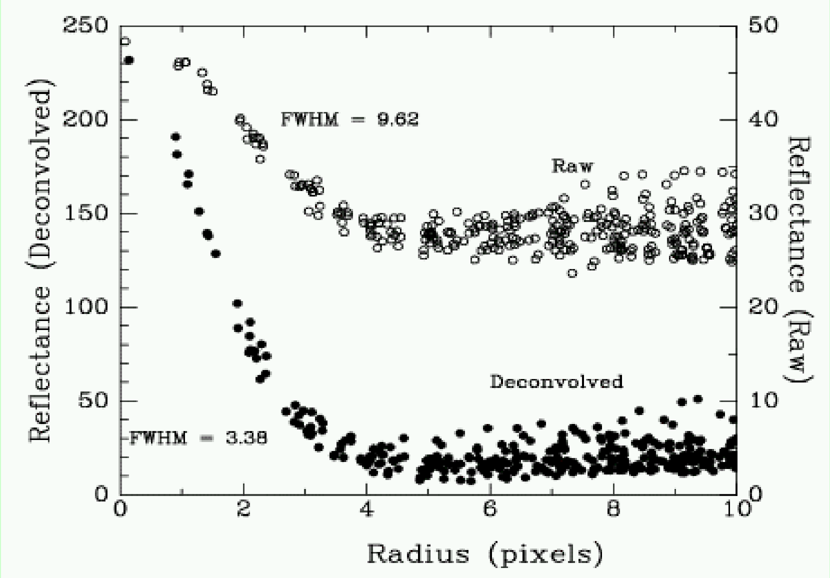
Full Bleach | 470 nm Bleach | 650 nm Bleach



Macaque retina

Reducing source confusion with deconvolution



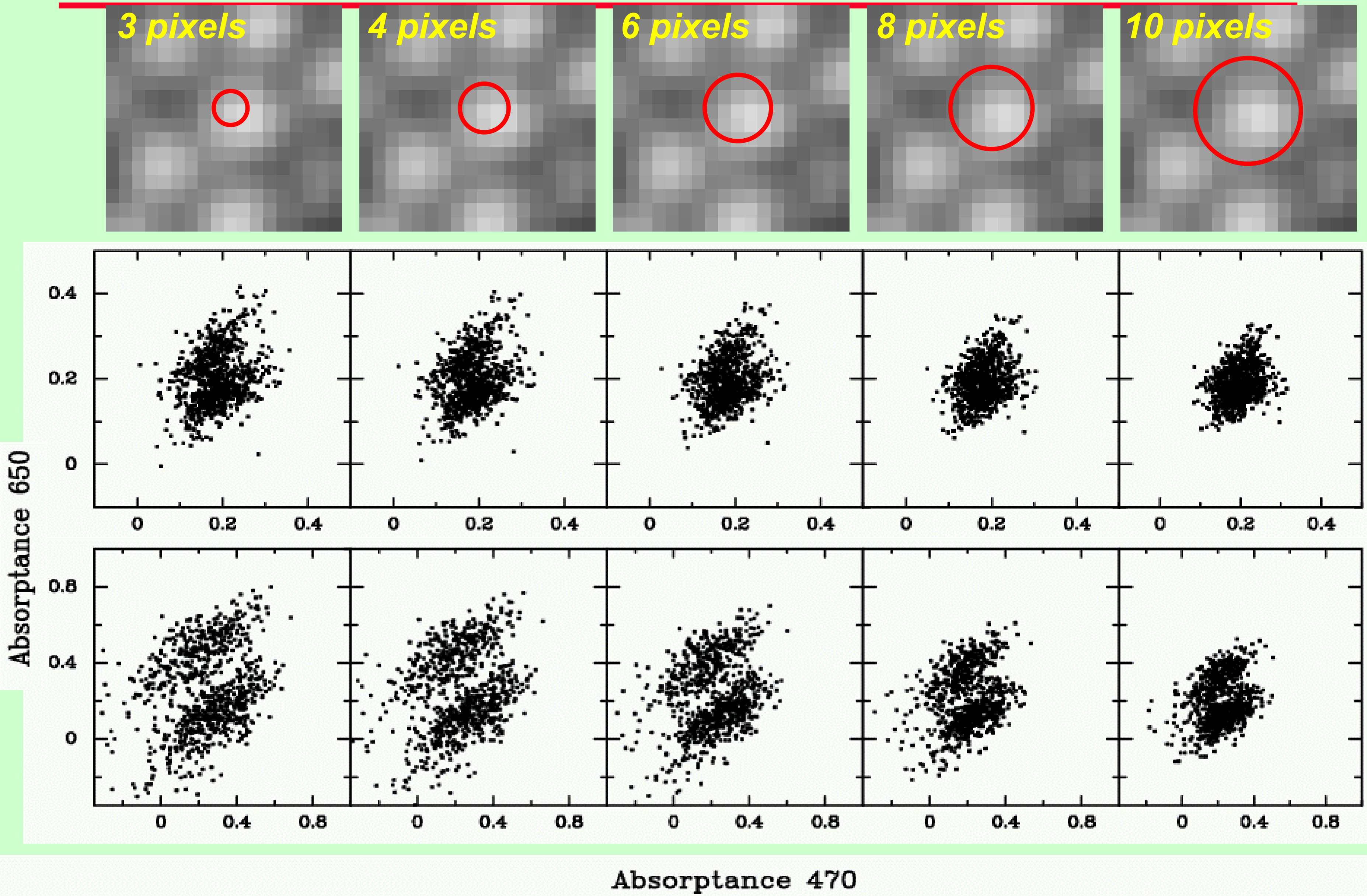


An isolated cone

Contrast Enhancement showing reduction in overlap

Macaque retina

Scatter plots of L and M cones



How to obtain the PSF?

- For the University of Rochester system, the deformable mirror is “frozen” while the retinal image is taken.
- Knowing the wavefront slopes permits a truncated Zernike model of the wavefront to be obtained (typically 65 terms with the first three, i.e. piston, tip, and tilt, set to zero).
- The modal wavefront is then numerically propagated through the “exit” pupil to obtain the focal plane PSF.
- We conducted a series of experiments imaging point sources to evaluate the quality of the reconstructed PSF.

PSF Reconstruction

Reminder:

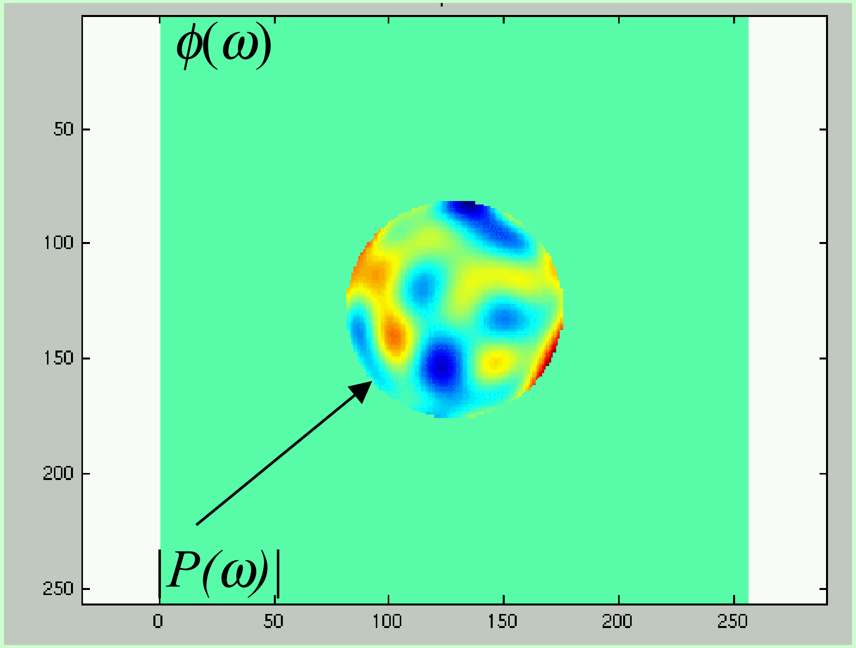
The PSF is the power-spectrum of the complex field at the pupil, i.e.

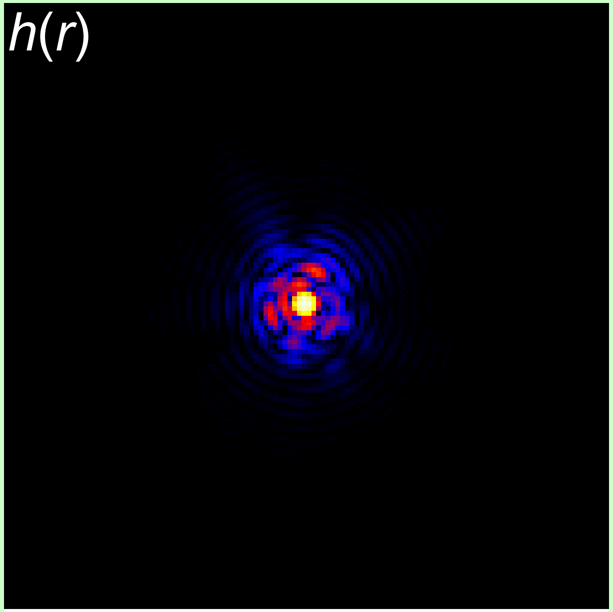
$$h(\vec{r}) = |u(\vec{r})|^2 = |\mathrm{FT}[P(\vec{\omega})]|^2$$

$$P(\vec{\omega}) = |P(\vec{\omega})| \exp[i\phi(\vec{\omega})]$$

Measure the wavefront $\phi(\omega)$ and propagate through to the image domain using the exit pupil $|P(\omega)|$ defined by unity within the pupil and zero outside.

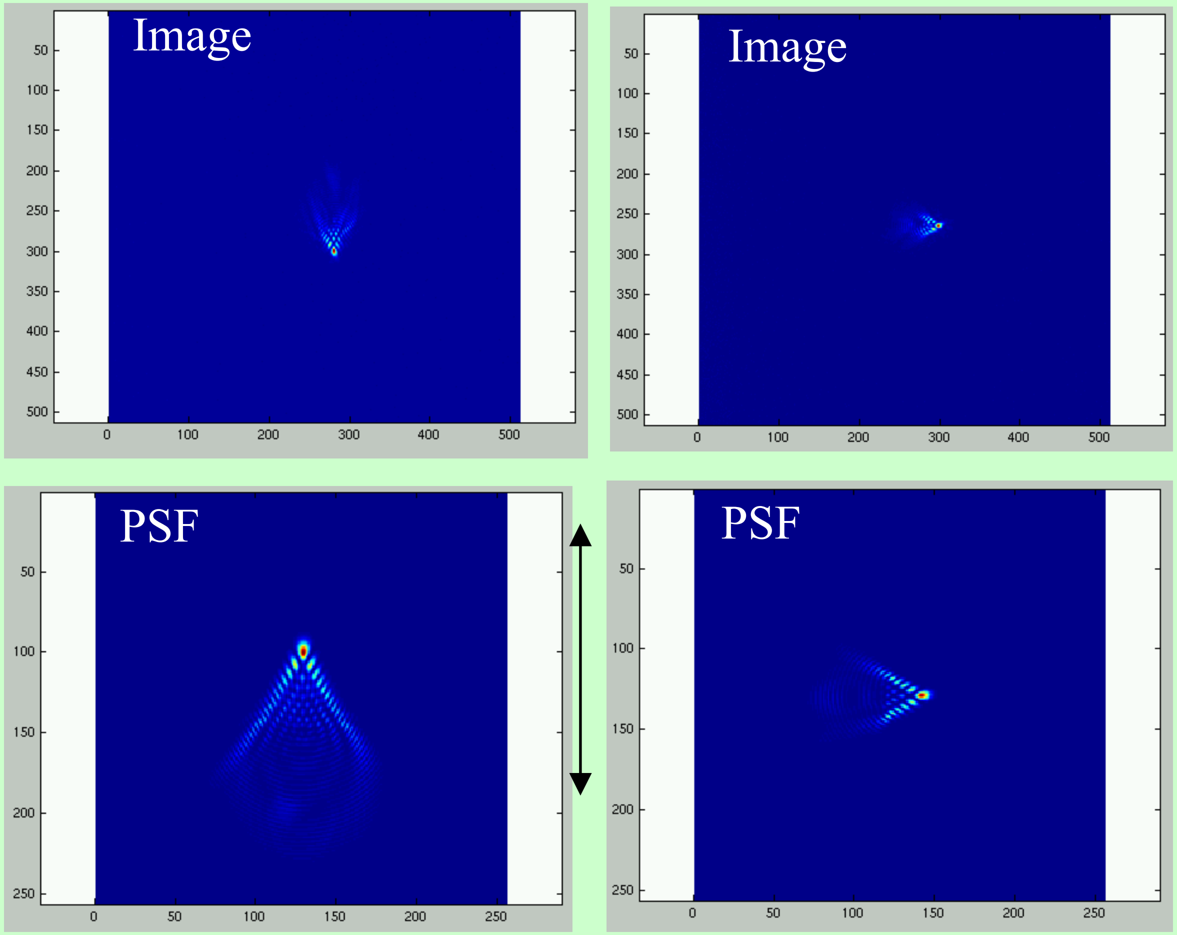
PSF Reconstruction





The Zernike modal wavefront is sampled by the "exit pupil" (left) and Fourier transformed to produce the PSF (right).

Evaluating the PSF - Orientation



Coma 1

Coma 2

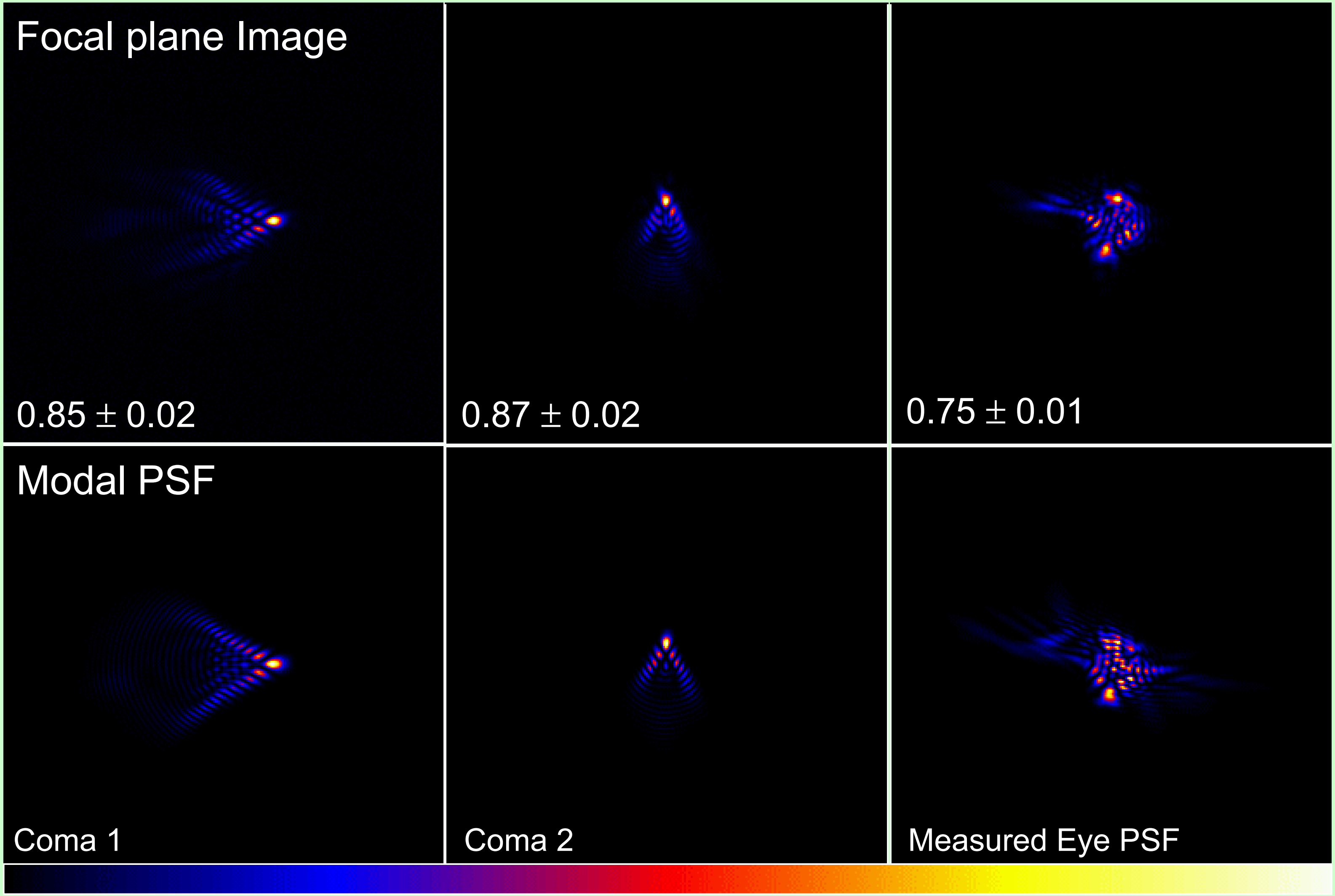
Two coma patterns were generated and applied to the reference beam producing the images on the focal plane array. (Top)

The PSFs were generated using the Zernike Coefficients.

These images demonstrate a flip about the horizontal axis, but not the vertical axis, in orientation between the two plane.

(PSFs are at half the field of the focal plane images)

Comparison of PSFs for fixed DM patterns



Deconvolution from Wavefront sensing

Multi-frame deconvolution with a "known" PSF (also called speckle holography).

The estimate of the Fourier components of the target for a series of short-exposure observations is

$$F'(f) = \frac{\left\langle G(f)H^{*}(f)\right\rangle}{\left\langle |H'(f)|^{2}\right\rangle} = F(f)\frac{\left\langle H(f)H'^{*}(f)\right\rangle}{\left\langle |H'(f)|^{2}\right\rangle}$$

Where $G(f)$ is the measured focal plane image and $|H'(f)|^2 = H'(f)\,H'^*(f)$ where $H'(f)$ is the PSF estimate obtained from the measured wavefront, i.e. the autocorrelation of the complex wavefront at the pupil.

So that $F'(f) = F(f)$ when $H'(f) = H(f)$

The Anisoplanatic Kernel

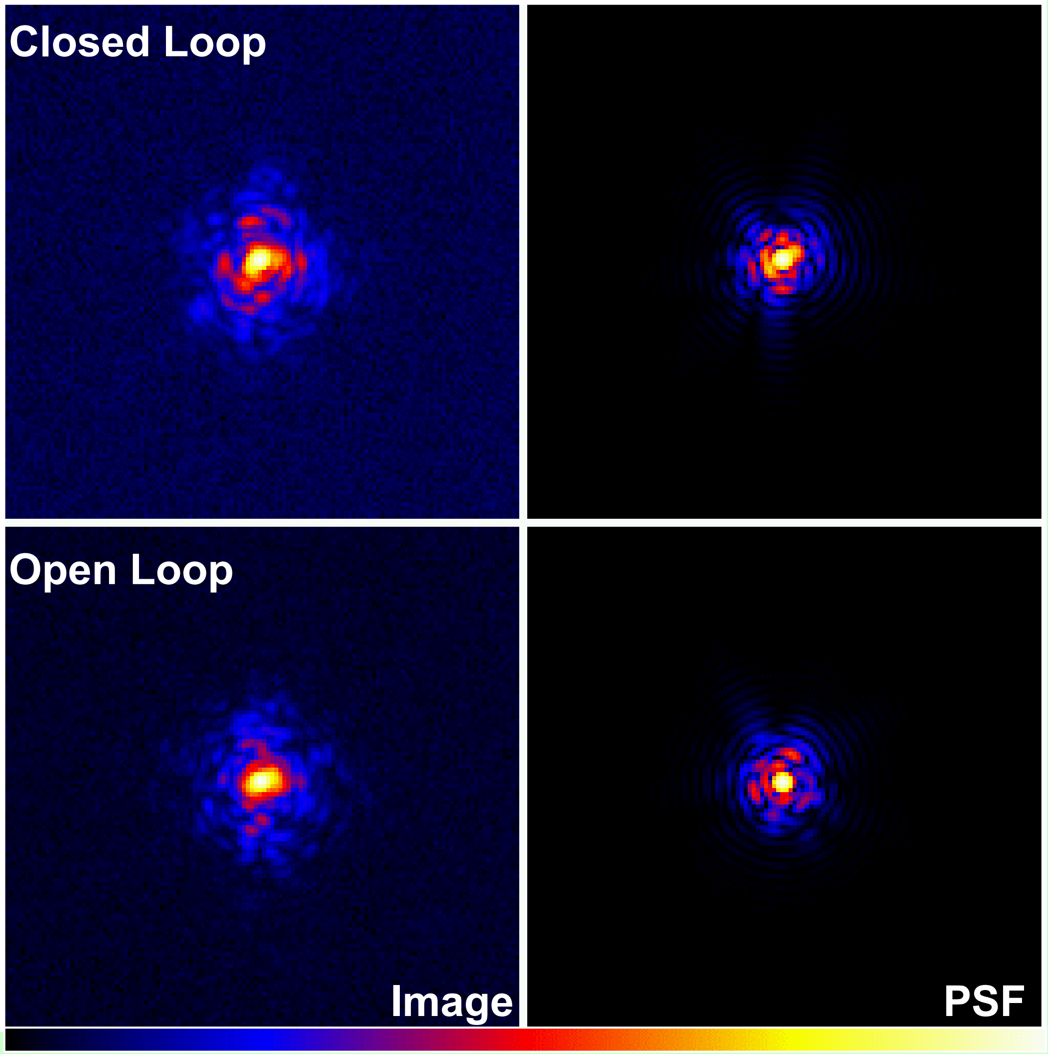
The key term in DFWS is the Anisoplanatic Kernel

where $$\gamma(f) = \frac{\langle H(f) H'^{*}(f) \rangle}{\langle | H'(f) |^2 \rangle}$$

This is a normalised cross-spectrum measurement between the two sets of PSFs. When they are both equal, this term goes to unity for all measured spatial frequencies.

Measuremants of point sources through the AO system permit this to be determined.

Rochester PSF Measurements



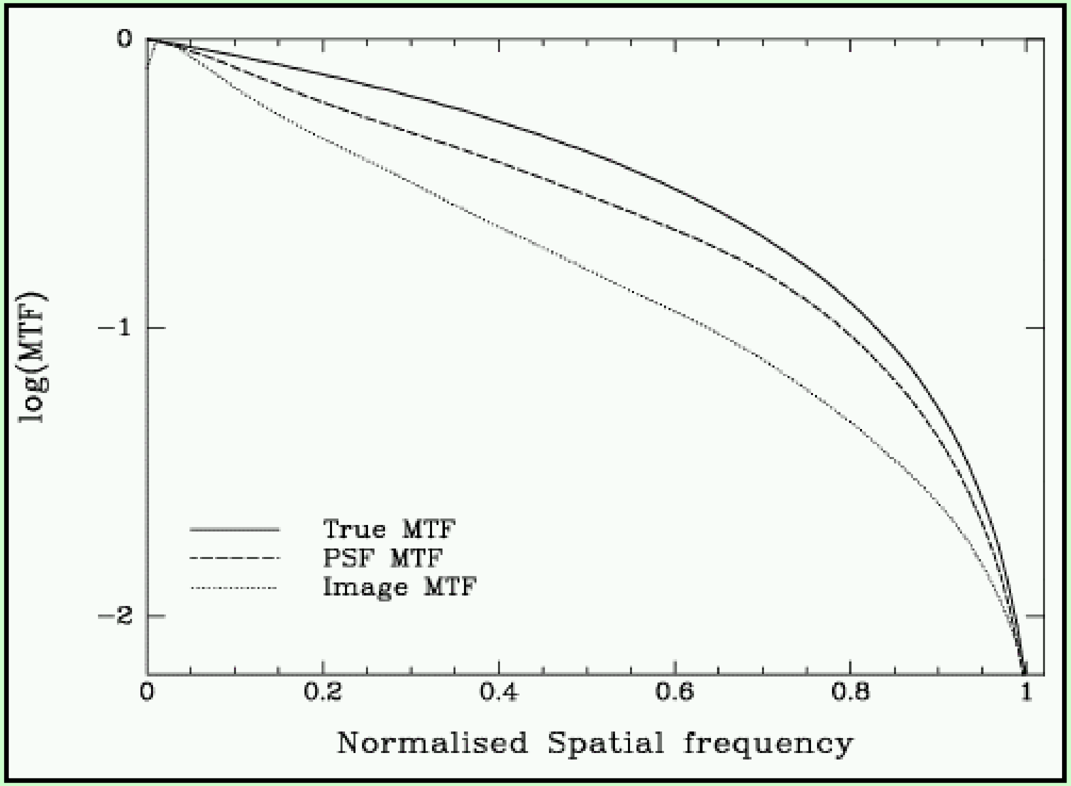
Sample open-loop and closed-loop images of the point source (laser) compared to the corresponding Zernike-derived PSFs.

Note that the focal-plane measurements look “resolved” compared to the PSFs.

The correlation coefficient for the 10-frame pairs were:

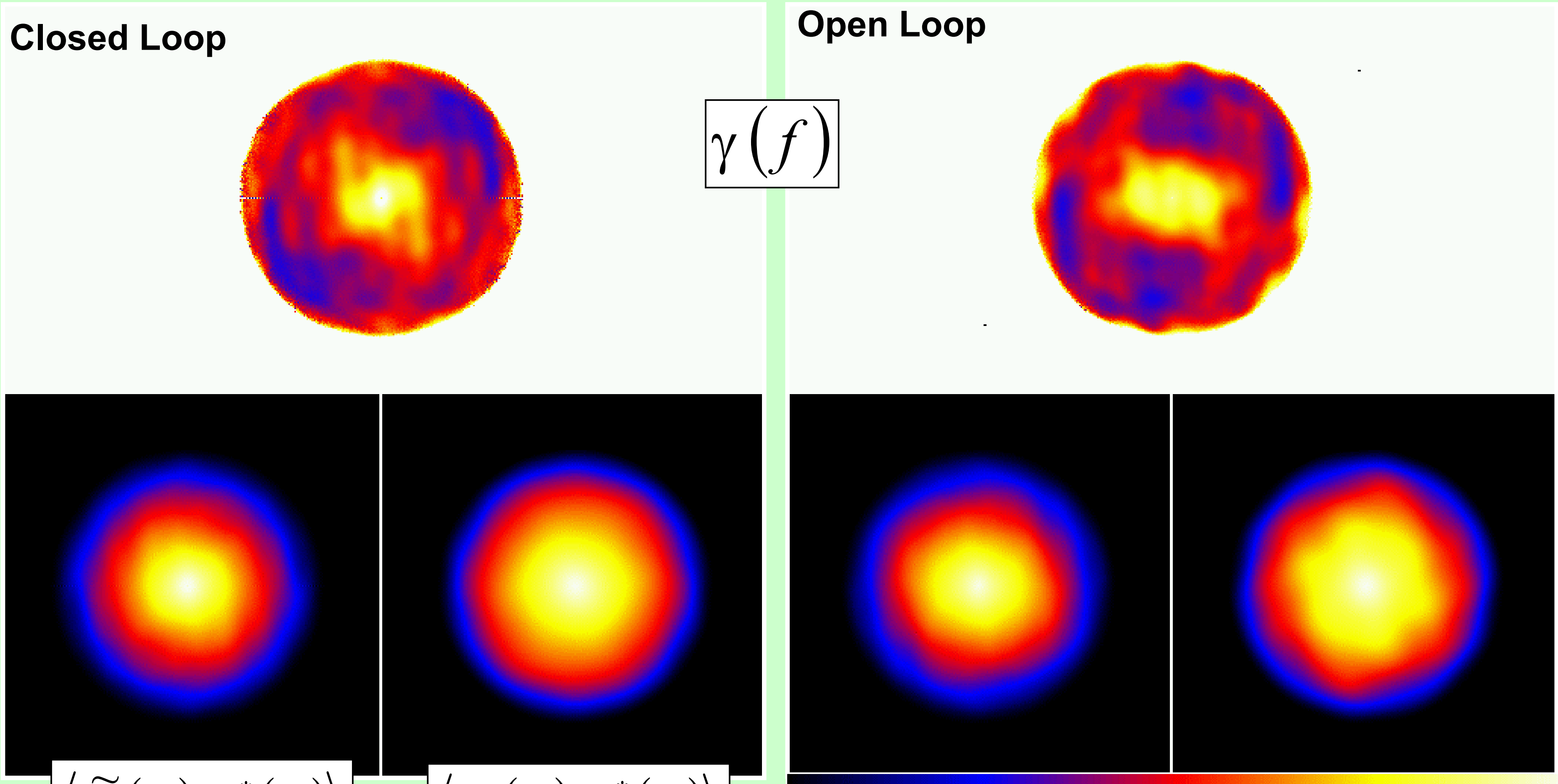
Open-Loop: 0.94 ± 0.02
Closed Loop: 0.91 ± 0.04

Rochester PSF Measurements



Comparison of the MTFs of the Closed Loop data to the "perfect" MTF. The image domain measurements is significantly less than the modal-reconstructed MTF.

The Anisoplanatic Parameter

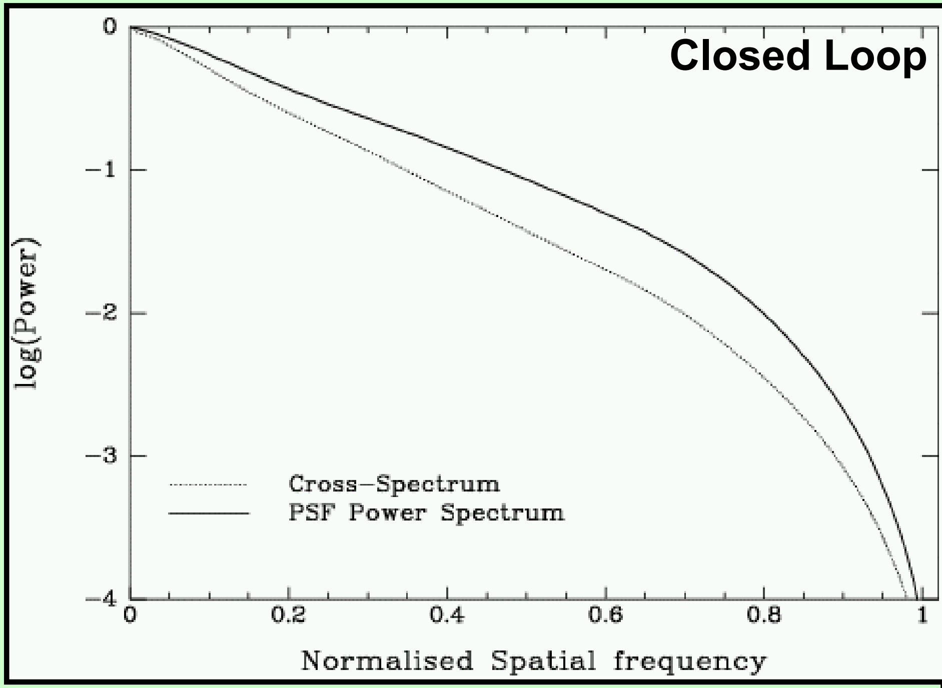


$$\gamma(f)$$

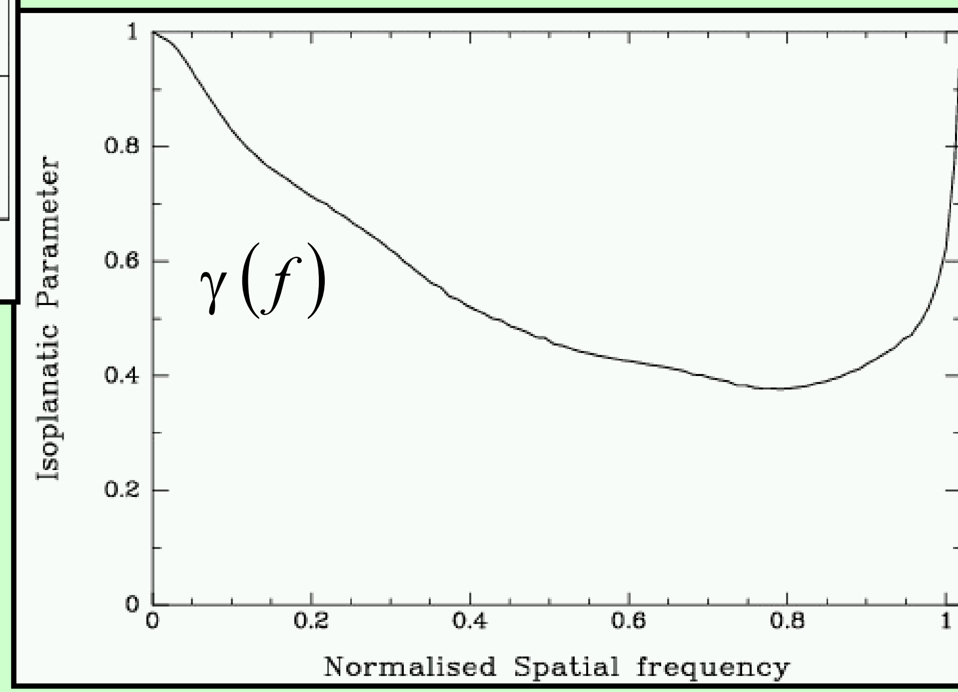
$$\left\langle \widetilde{H}(f) H^*(f) \right\rangle$$

$$\left\langle H(f) H^*(f) \right\rangle$$

The Anisoplanatic Kernel

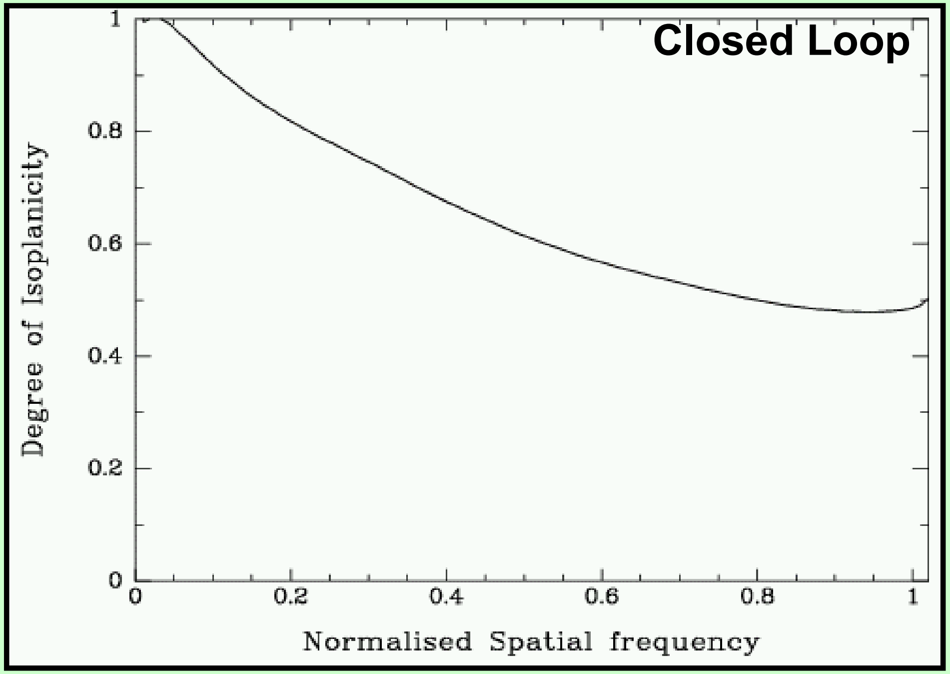


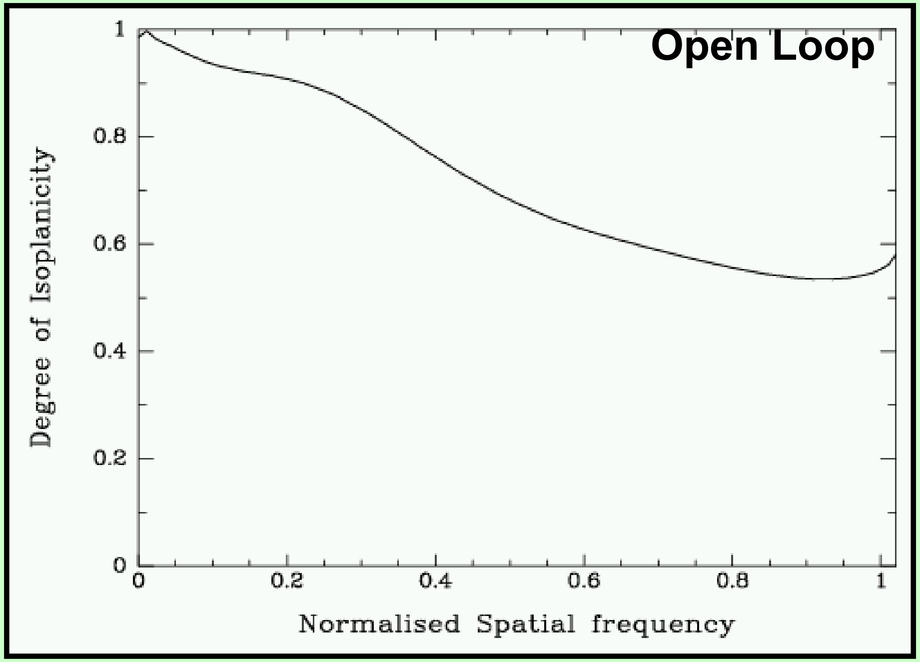
Azimuthally averaged radial profiles of the cross-spectrum, power spectrum and anisoplanatic kernel.



The isoplanatic kernel measures the correlation as a function of spatial frequency.

The Degree of Anisoplanatism





These curves suggest a significantly lower correlation between the two images than measured with a standard correlation coefficient ~ 50% at the diffraction-limit.

Why is the PSF different?

- **Modal Reconstruction as opposed to Zonal reconstruction.**

  - Are the Zernike modes missing essential wavefront information? The loop is closed on a zonally reconstructed wavefront but the PSFs are generated from a truncated modal fit.

  Need to compare a zonal reconstruction to a modal reconstruction.

- **Non-common path errors.**

  - Is there further aberration in the imaging leg not sampled by the WFS?

  If so, need to optimise the SH references for the best focal plane image, as in done for astronomical AO systems, using some sort of sharpness metric.

- **Is the PSF generated at the same spatial scale as the image?**

  - The cut-off frequencies would imply this but how to verify experimentally what the image scale is? (e.g. *Air Force target*)

- **And then there is problem of the PSF matching the corrected retinal image for the eye.**

  - tear film; eye motion …?

Adaptive Optics Performance - Sharpness

- How well does an AO System perform?
- Tools for Measurement:

  - Image Sharpness: Muller and Buffington (1975)

    S_1 or Beam Variance Metric (BVM) – Size of PSF

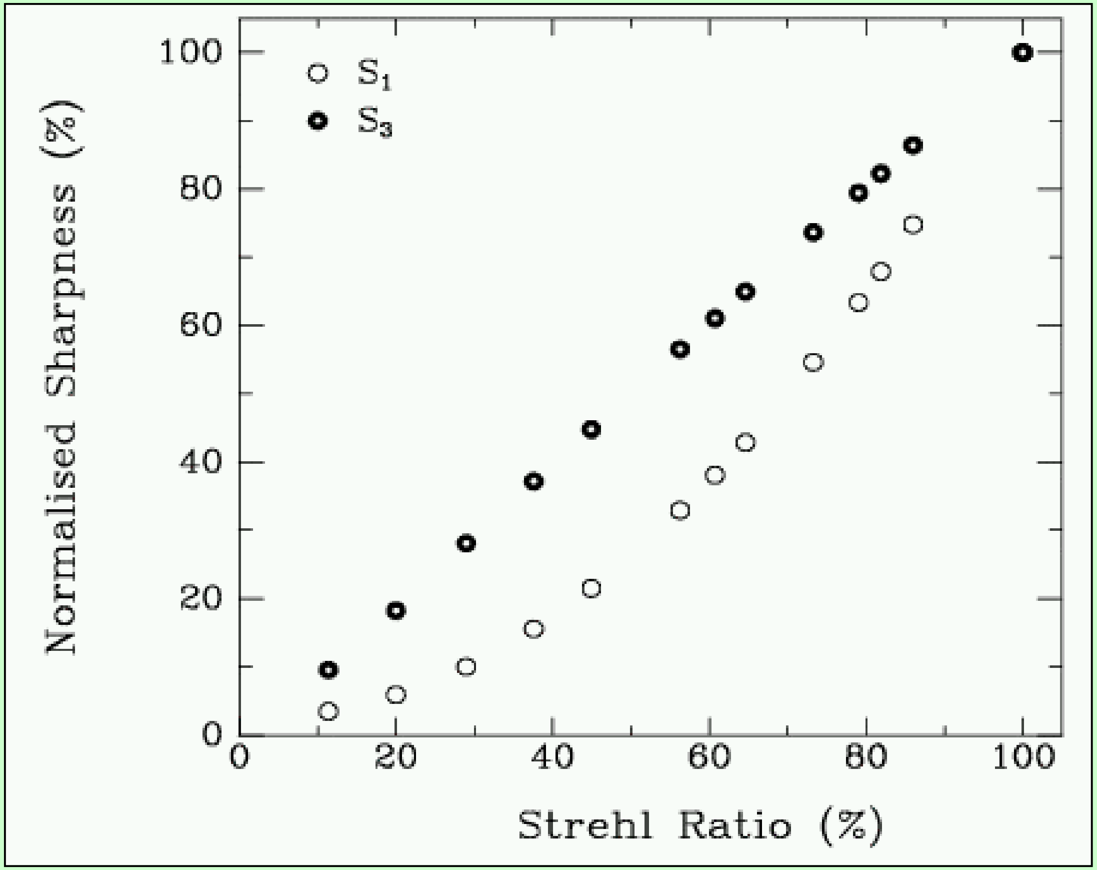
$$S_1 = \frac{\sum \tilde{h}_i^2}{\left[\sum \tilde{h}_i\right]^2}$$

    S_3 or Normalized peak value – related to Strehl Ratio

$$S_3 = \frac{\tilde{h}_{\text{peak}}}{\sum \tilde{h}_i}$$

Adaptive Optics Performance - Sharpness

- Image Sharpness vs. Strehl ratio



Adaptive Optics Performance - Sharpness

- Image Sharpness vs. Wavefront Error