Adaptive Optics
Wavefront Control and Performance

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Wavefront Control and AO Performance

Now that I have (access to) an AO system...

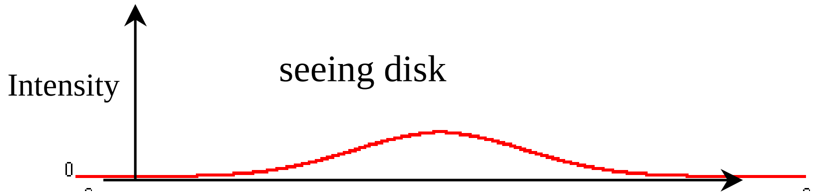
- What does an AO system do?
- What objects can I look at?
- How do I plan my observations?
- What PSF can I expect?

and afterward...

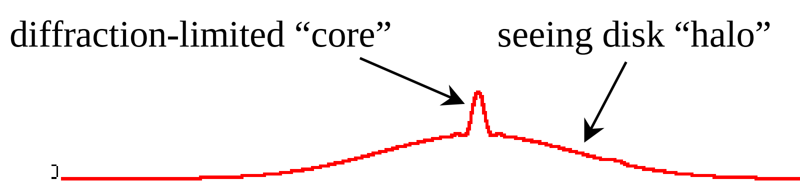
- What was the PSF?
- How do I reduce the data?

AO Systems gather star light (point-sources) into a tighter area on the focal plane

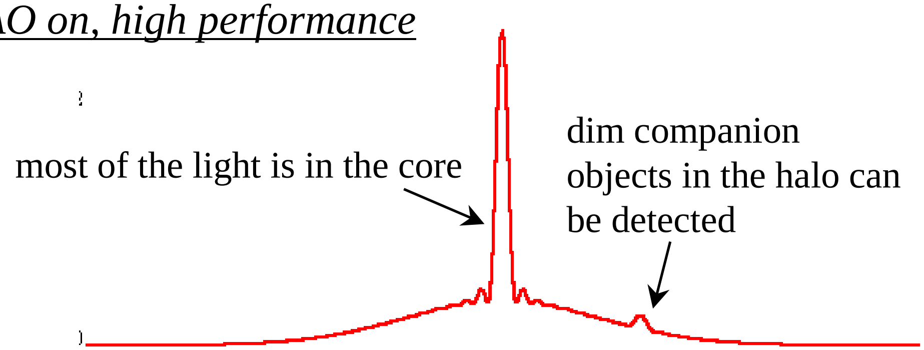
No AO

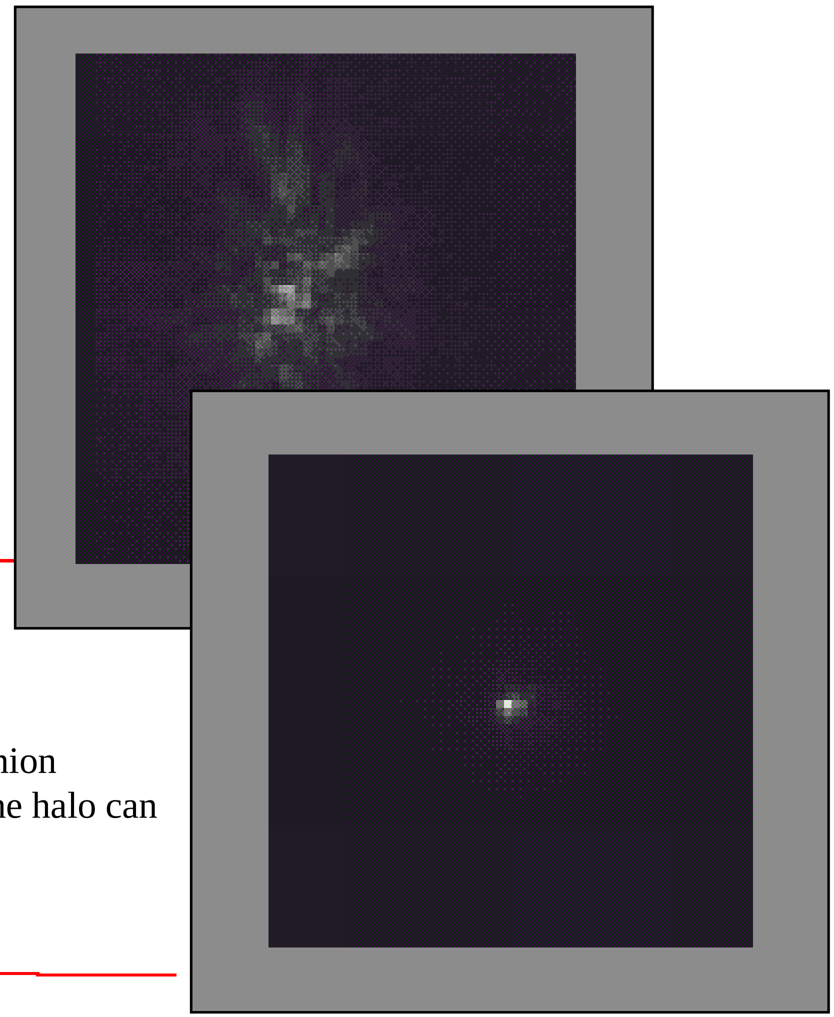


AO on, moderate performance

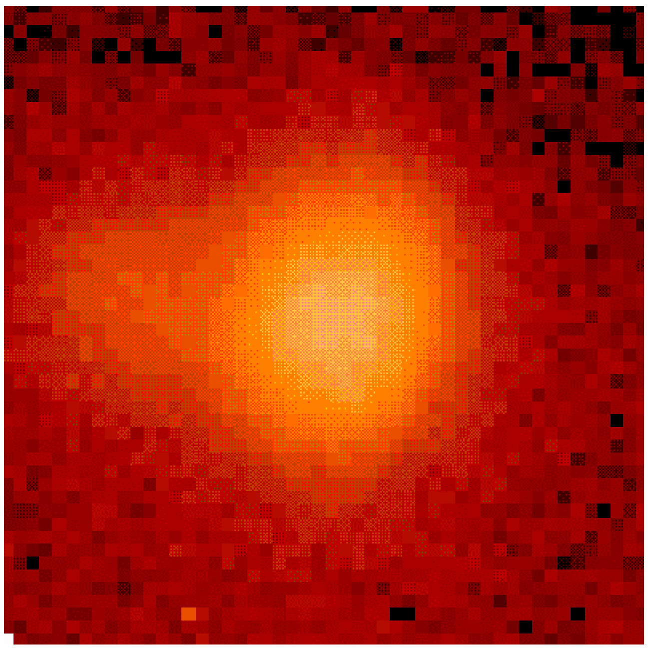


AO on, high performance

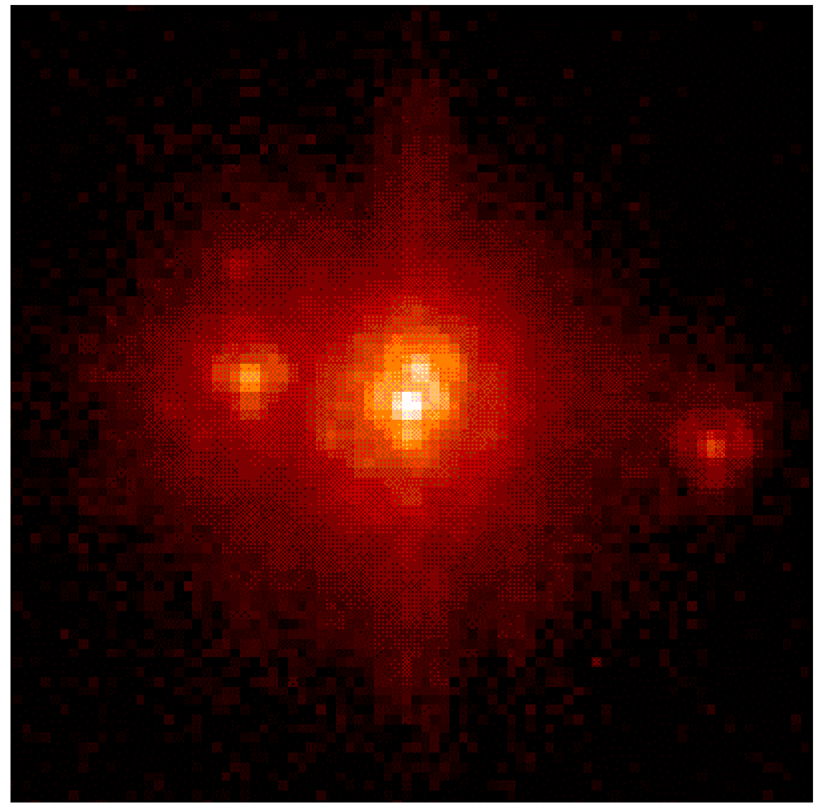




LkHα 234
Lick Adaptive Optics

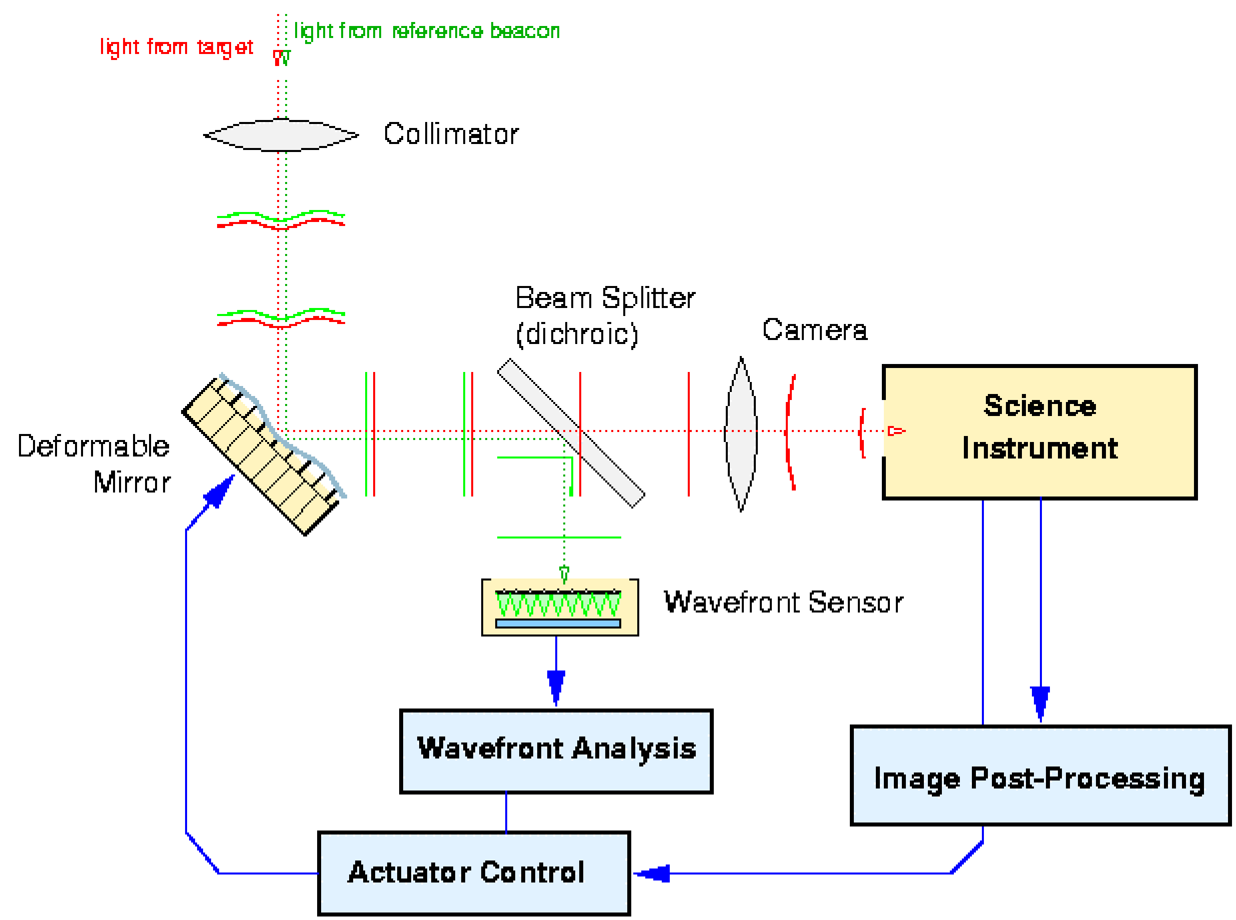


AO off



AO on

What does an AO system do?



Note that the closed loop operation “null-seeks” so that, nominally, the wavefront sensor measures a nearly-flat wavefront, justifying perturbation analysis of performanc.

(from the CfAO web site http://www.ucolick.org/~cfao/)

Wavefront reconstruction - in a nutshell

sensor: $\{I_A, I_B, I_C, I_D\} = \int_{A,B,C,D} p\left(x - f \cdot \int_{i} \nabla\phi(u)du\right)dx$

computer: 1) $s_{xi} = \frac{(I_A + I_C) - (I_B + I_D)}{I_A + I_B + I_C + I_D}$

$s_{yi} = \frac{(I_A + I_B) - (I_C + I_D)}{I_A + I_B + I_C + I_D}$

2) $a_j = \sum_i H^*_{ij} s_i$

offline calculation: $\mathbf{H}^* = \mathbf{W}_a \mathbf{H}' \mathbf{W}_s$

- Hartmann sensor Physics
- Calculations that must be done in real-time
- Offline calibration and calculation

- H is the “push” matrix (sensor response per unit actuator motion) - it is pre-calibrated, typically the day before observing
- H* is the pre-calculated “reconstructor matrix”
  - Zonal or Modal
  - Weighted least squares fit
  - “Waffle” mode removed

What objects can I look at?

1. Make sure there is a science benefit to using AO
2. A bright guide star (NGS-AO) must be nearby

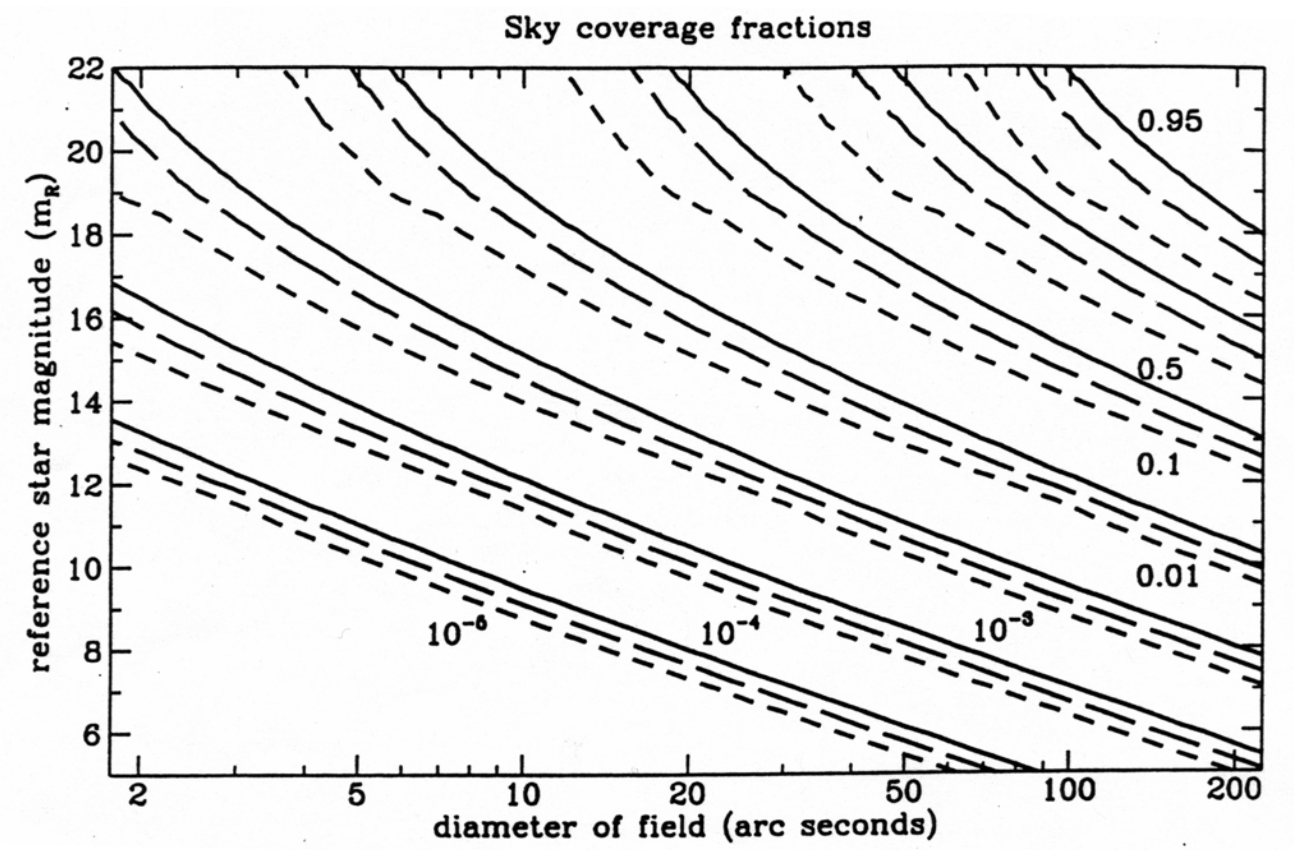
NGS
$m_r <\sim 12$ at Lick
$m_r <\sim 13$ at Keck

2*. LGS-AO also uses a natural guide star, for tip-tilt correction

LGS tip-tilt
$m_r <\sim 16$ at Lick
$m_r <\sim 18$ at Keck

AO resolution of various science targets

	seeing	Lick AO	Keck AO
Moon	1.8 km	300 m	100 m
Jupiter (5 au)	3600 km	550 km	160 km
Solar neighbor (5pc)	5 au	0.7 au	0.2 au
T Tauri (200 pc)	200 au	30 au	9 au
M31 (670 kpc)	3 pc	0.5 pc	0.15 pc
NGC 1068 (11 Mpc)	53 pc	8 pc	2 pc
3C2 (Z=1)	24 kpc	3.6 kpc	1.1 kpc



(sky coverage chart -contours of constant sky coverage vs separation & magnitude)

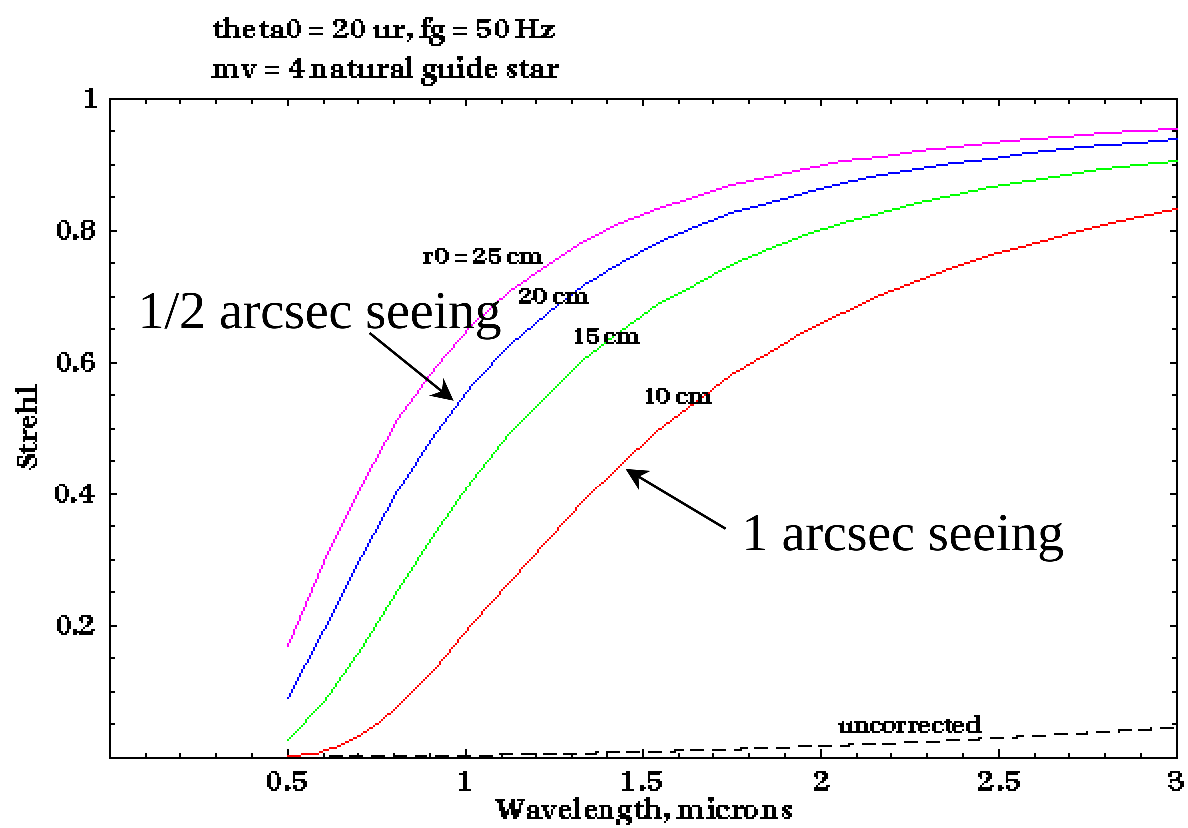
AO performance measures

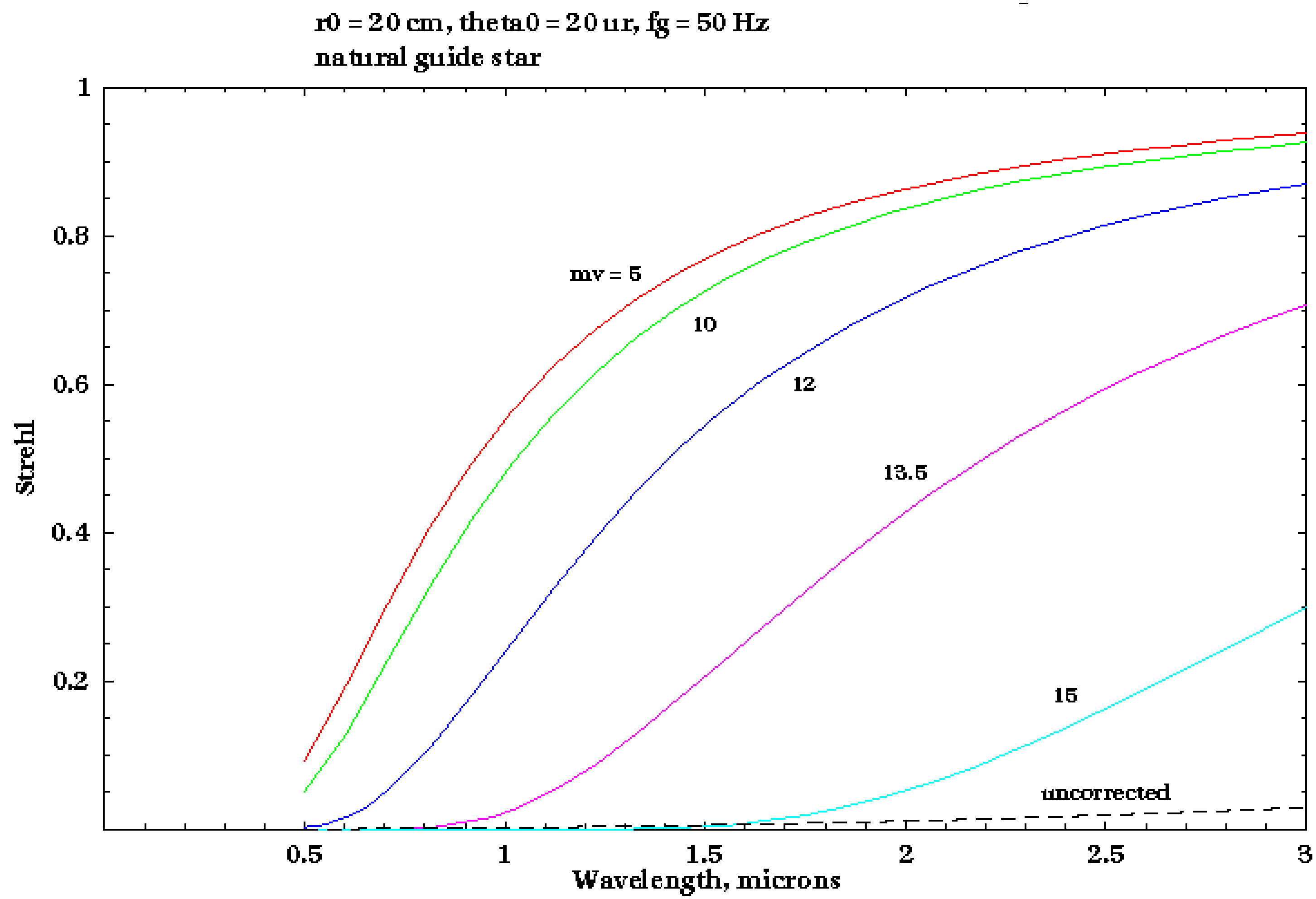
- FWHM - Full Width, Half Maximum -
  - AO systems typically produce diffraction-limited FWHM
  - Can separate 2 equally bright point sources λ/d apart
- Contrast ratio - ratio of the peak of a dimmer source within the halo to the brightness of the halo
  - Important for dim companion searches, brown dwarfs, extra-solar planets
- Strehl ratio - ratio of AO-corrected PSF peak to the diffraction-limited PSF peak
- Encircled energy - vs radius
  - Important for photometry, centroiding accuracy
- Energy in a slit
  - Spectroscopy

AO performance is affected by

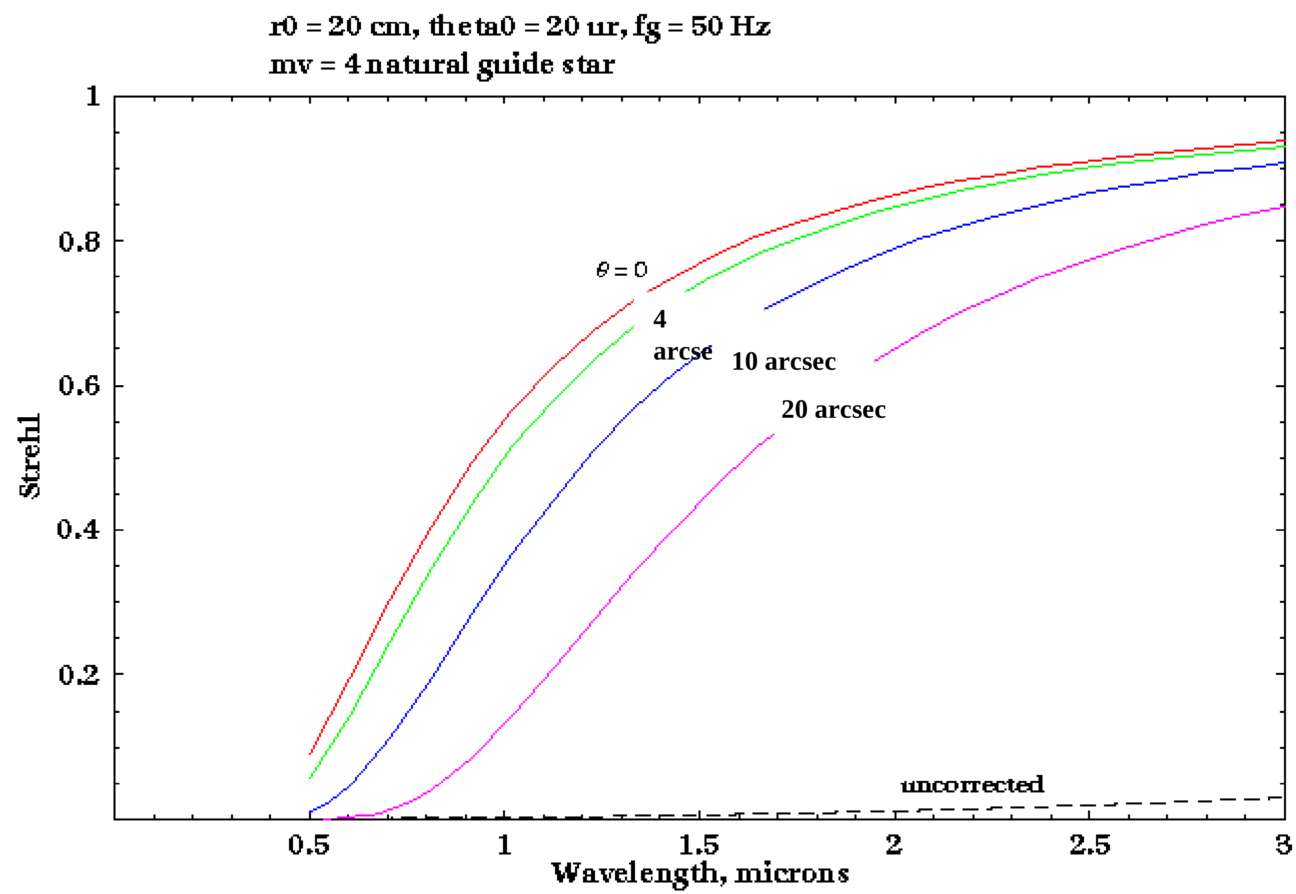
- Seeing conditions (r_0), wind (τ_0)
- Number of DM actuators
- Controller bandwidth
- Separation of guide star from science target
- Brightness of guide star*

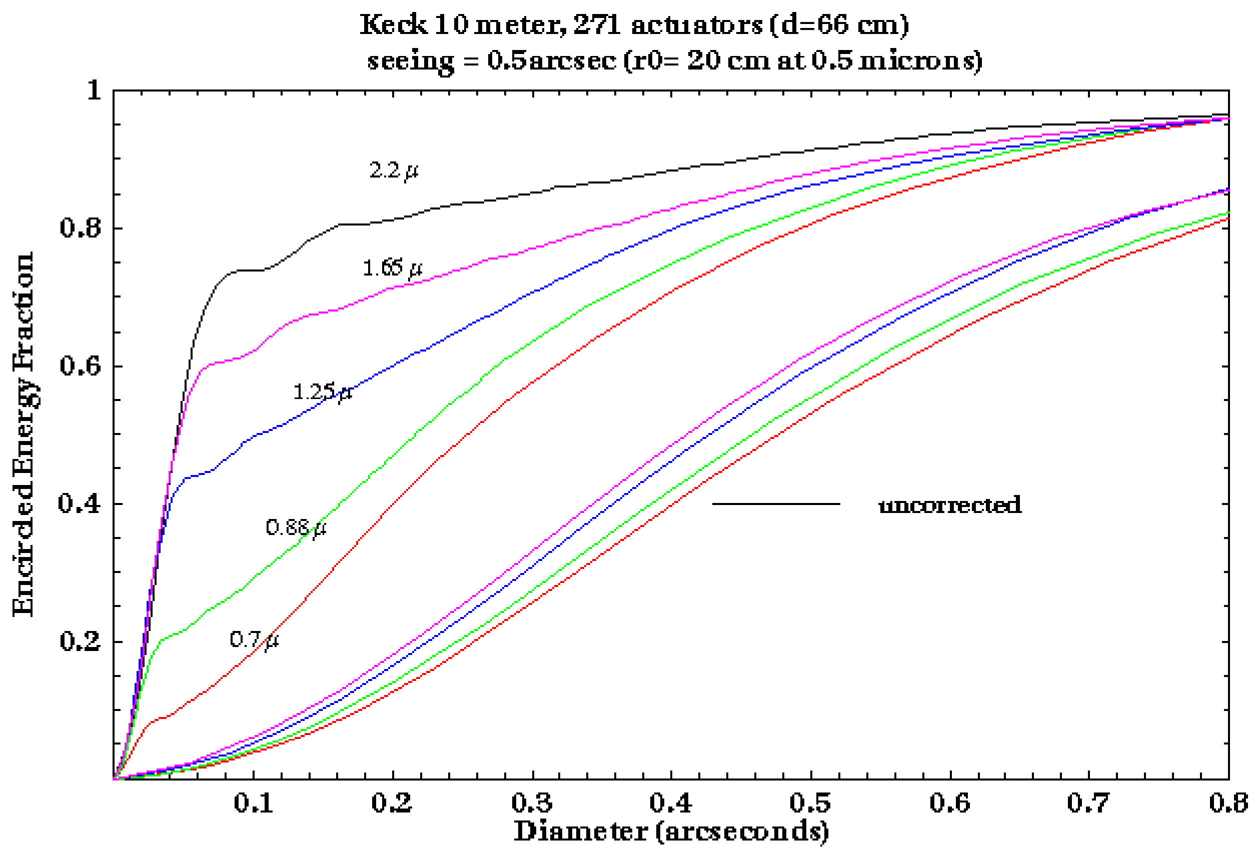
*and extent (e.g. planet, nebula, LGS)


theta0 = 20 ur, fg = 50 Hz
mv = 4 natural guide star
Strehl
Wavelength, microns
r0 = 25 cm
20 cm
15 cm
10 cm
uncorrected
1/2 arcsec seeing
1 arcsec seeing
0.2
0.4
0.6
0.8
1
0.5
1
1.5
2
2.5
3



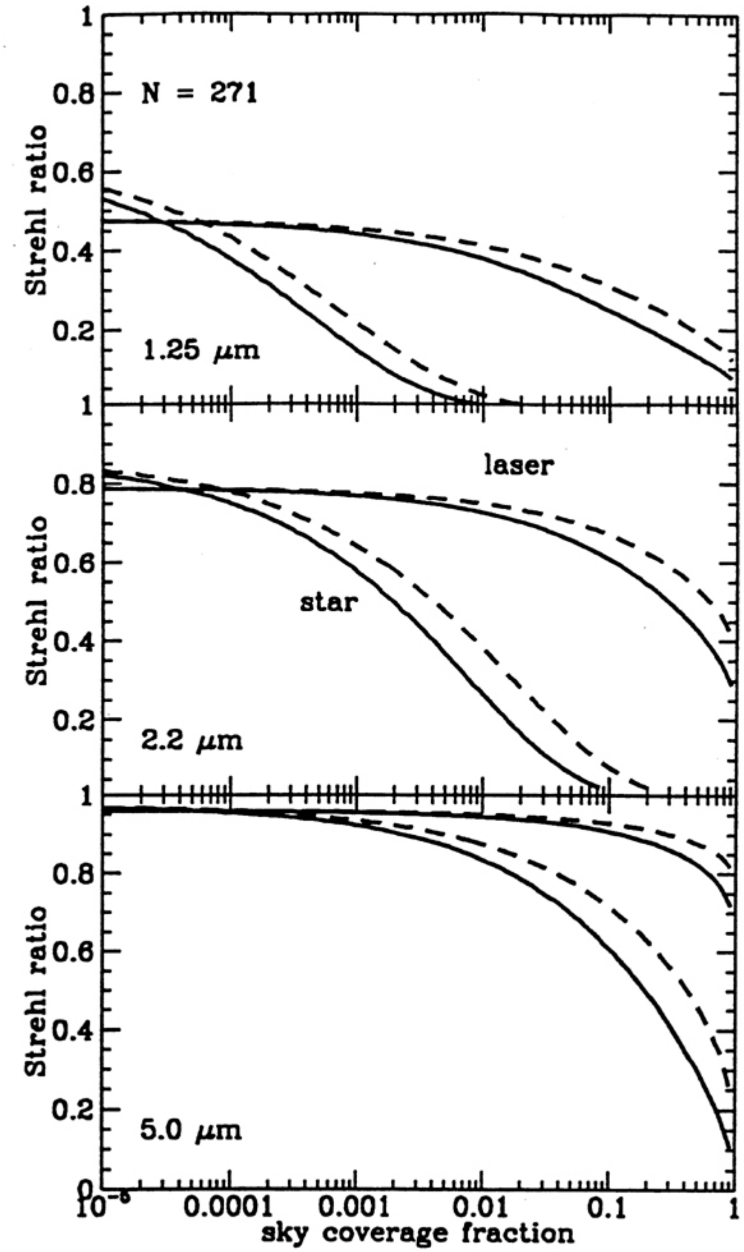
r0 = 20 cm, theta0 = 20 ur, fg = 50 Hz
natural guide star
Strehl
1
0.8
0.6
0.4
0.2
0.5
1
1.5
2
2.5
3
Wavelength, microns
mv = 5
10
12
13.5
15
uncorrected

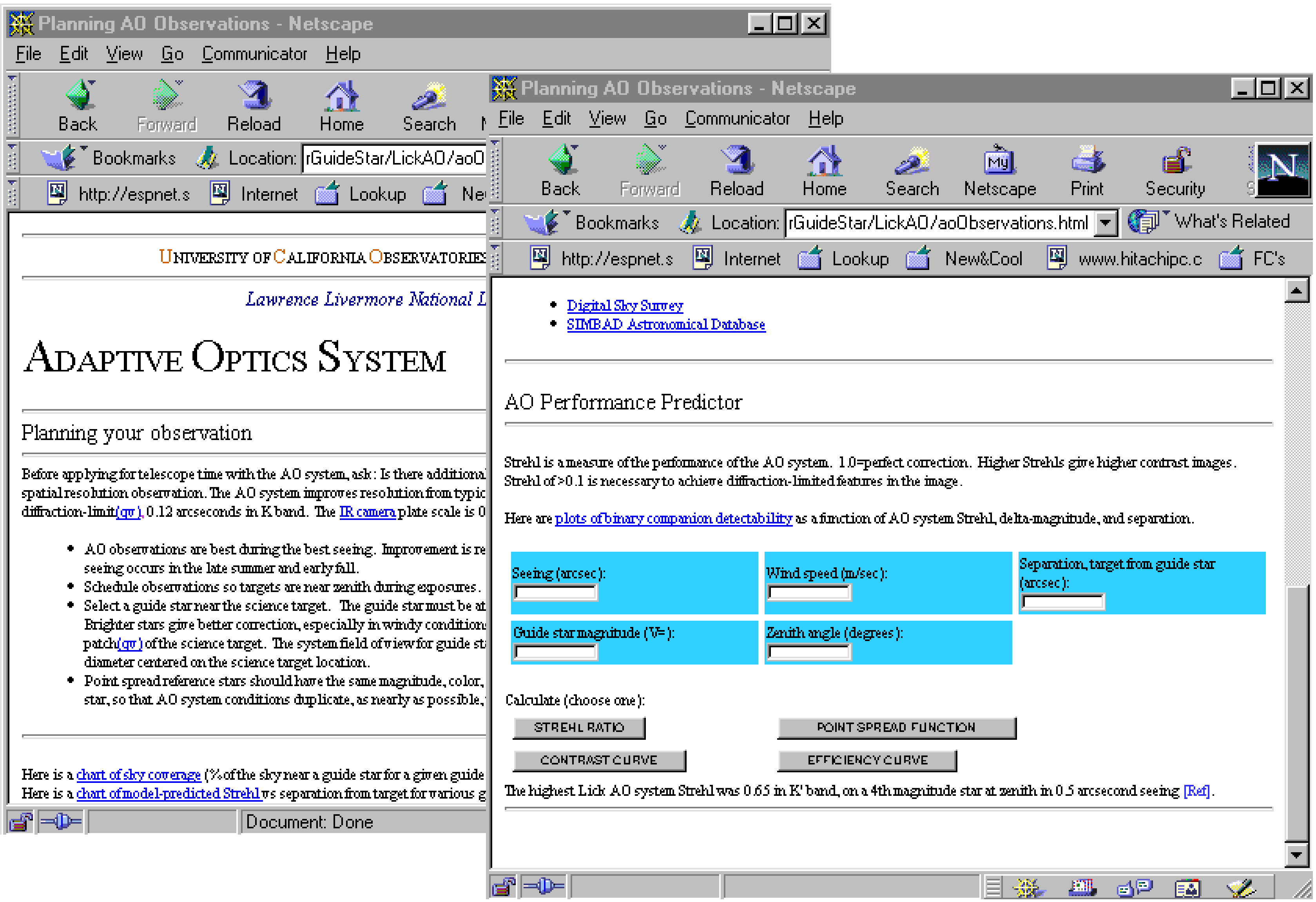

r0 = 20 cm, theta0 = 20 ur, fg = 50 Hz
mv = 4 natural guide star
Strehl
Wavelength, microns
θ = 0
4
arcse
10 arcsec
20 arcsec
uncorrected
0.2
0.4
0.6
0.8
1
0.5
1
1.5
2
2.5
3



Keck 10 meter, 271 actuators (d=66 cm)
seeing = 0.5arcsec (r0= 20 cm at 0.5 microns)
Encircled Energy Fraction
Diameter (arcseconds)
2.2 μ
1.65 μ
1.25 μ
0.88 μ
0.7 μ
uncorrected
1
0.8
0.6
0.4
0.2
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

Comparison of Laser and Natural Guide Stars




Planning AO Observations - Netscape
File Edit View Go Communicator Help
Back Forward Reload Home Search
Bookmarks Location: rGuideStar/LickAO/aoO
http://espnet.s Internet Lookup
UNIVERSITY OF CALIFORNIA OBSERVATORIES
Lawrence Livermore National L
ADAPTIVE OPTICS SYSTEM
Planning your observation
Before applying for telescope time with the AO system, ask: Is there additional
spatial resolution observation. The AO system improves resolution from typic
diffraction-limit(gr), 0.12 arcseconds in K band. The IR camera plate scale is 0
AO observations are best during the best seeing. Improvement is re
seeing occurs in the late summer and early fall.
Schedule observations so targets are near zenith during exposures.
Select a guide star near the science target. The guide star must be at
Brighter stars give better correction, especially in windy condition
patch(gr) of the science target. The system field of view for guide st
diameter centered on the science target location.
Point spread reference stars should have the same magnitude, color,
star, so that AO system conditions duplicate, as nearly as possible,
Here is a chart of sky coverage (% of the sky near a guide star for a given guide
Here is a chart of model-predicted Strehl vs separation from target for various g
Document: Done
Planning AO Observations - Netscape
File Edit View Go Communicator Help
Back Forward Reload Home Search Netscape Print Security
Bookmarks Location: rGuideStar/LickAO/aoObservations.html What's Related
http://espnet.s Internet Lookup New&Cool www.hitachipc.c FC's
Digital Sky Survey
SIMBAD Astronomical Database
AO Performance Predictor
Strehl is a measure of the performance of the AO system. 1.0=perfect correction. Higher Strehls give higher contrast images.
Strehl of >0.1 is necessary to achieve diffraction-limited features in the image.
Here are plots of binary companion detectability as a function of AO system Strehl, delta-magnitude, and separation.
Seeing (arcsec):
Wind speed (m/sec):
Separation, target from guide star (arcsec):
Guide star magnitude (V=):
Zenith angle (degrees):
Calculate (choose one):
STREHL RATIO
POINT SPREAD FUNCTION
CONTRAST CURVE
EFFICIENCY CURVE
The highest Lick AO system Strehl was 0.65 in K' band, on a 4th magnitude star at zenith in 0.5 arcsecond seeing [Ref].

How do I plan my observations?

Good planning is crucial to success with AO

- Guide stars near targets
- PSF calibrator stars, photometric standards...
- Observing wavelength (1-5μ Keck, 1-2.5μ Lick)
- Field of view, nodding
- Seeing conditions (r_0), wind (τ_0)
- Sodium abundance (!)
- Exposure time

The future of AO: Queue scheduling the observations for optimum conditions

How do I reduce the data?

- IR post-processing techniques (Bruce Macintosh’s talk)
- Deconvolution
  - Iterative methods to solve

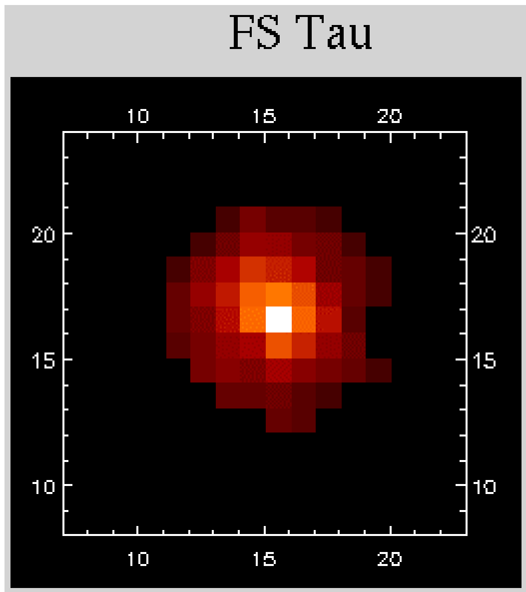
$$I = (P * O) + N$$

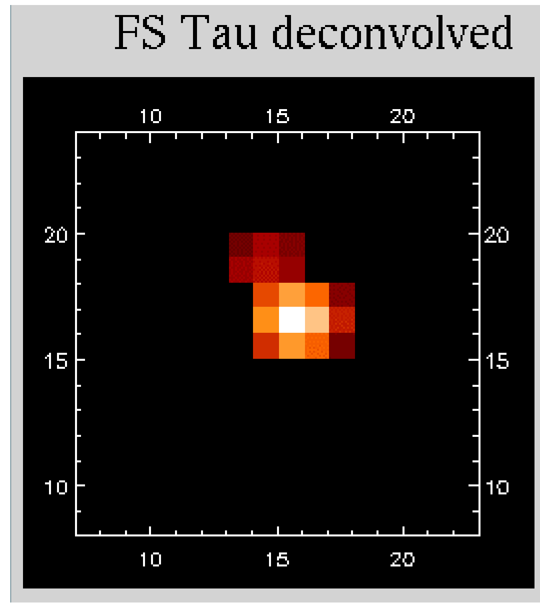
Image (I), PSF (P), True Object (O), Noise (N)

.. and what was the PSF?

- PSF determination
  - PSF calibrator stars (plan backups, many are double-stars)
  - J. P. Veran’s algorithm: PSF determined “in-vivo” using the AO system telemetry data

FS Tau with Lick Adaptive Optics and Laser Guide Star





Conclusions

- AO is powerful instrumentation that can improve spatial resolution by factors of 10-50
- Sky coverage is limited with NGS AO
- LGS AO covers most of the sky at 1-2μ
- Calibration issues are much more demanding at these high resolutions
- PSF is variable, complicated, seeing dependent. Special techniques for PSF recovery are in progress. Developing AO data reduction pipelines is one charge of the CfAO.