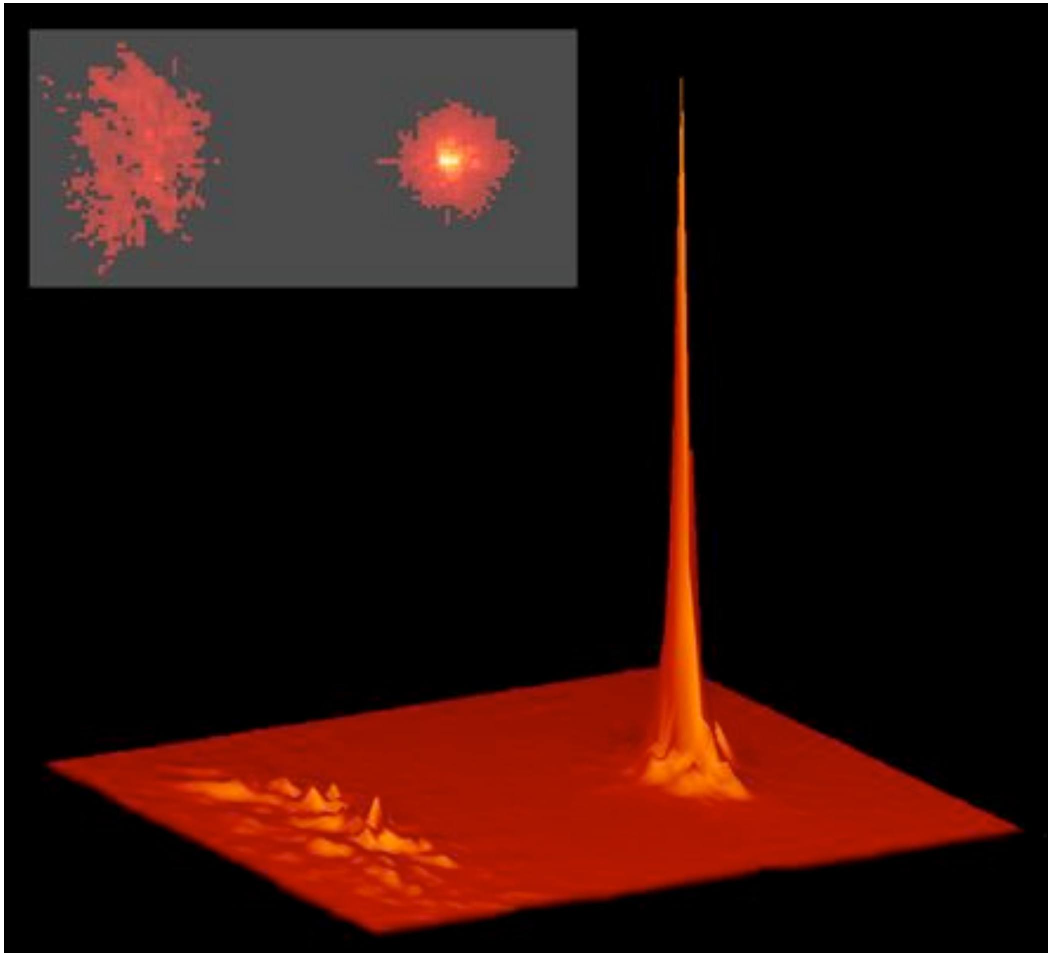
Lecture 15: Adaptive Optics

Outline

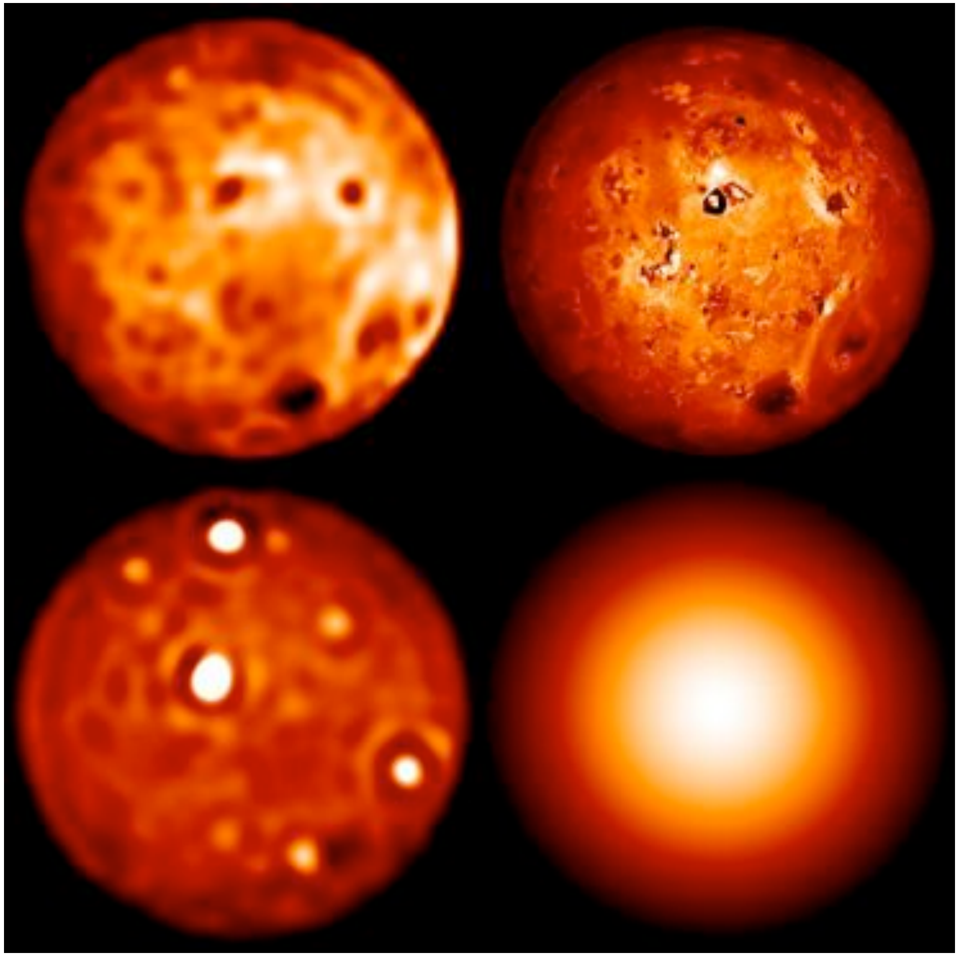
1. Seeing
2. Concept of Adaptive Optics
3. Wavefront Sensing
4. Wavefront Correctors
5. Adaptive Optics Control
6. Laser Guide Stars
7. Multi-Conjugate Adaptive Optics

Star with and without AO



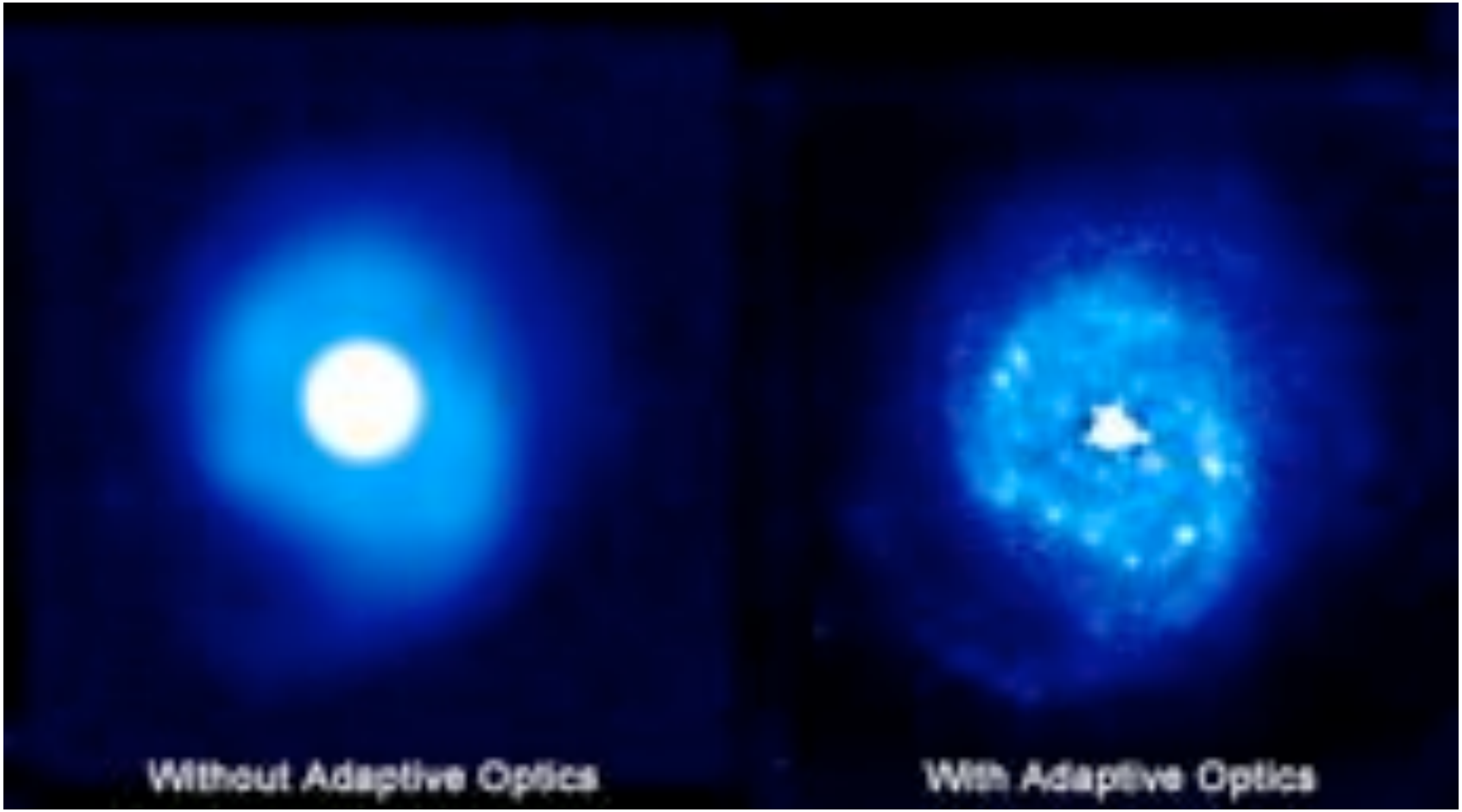
http://cfao.ucolick.org/pgallery/stellar.php

Io with and without AO



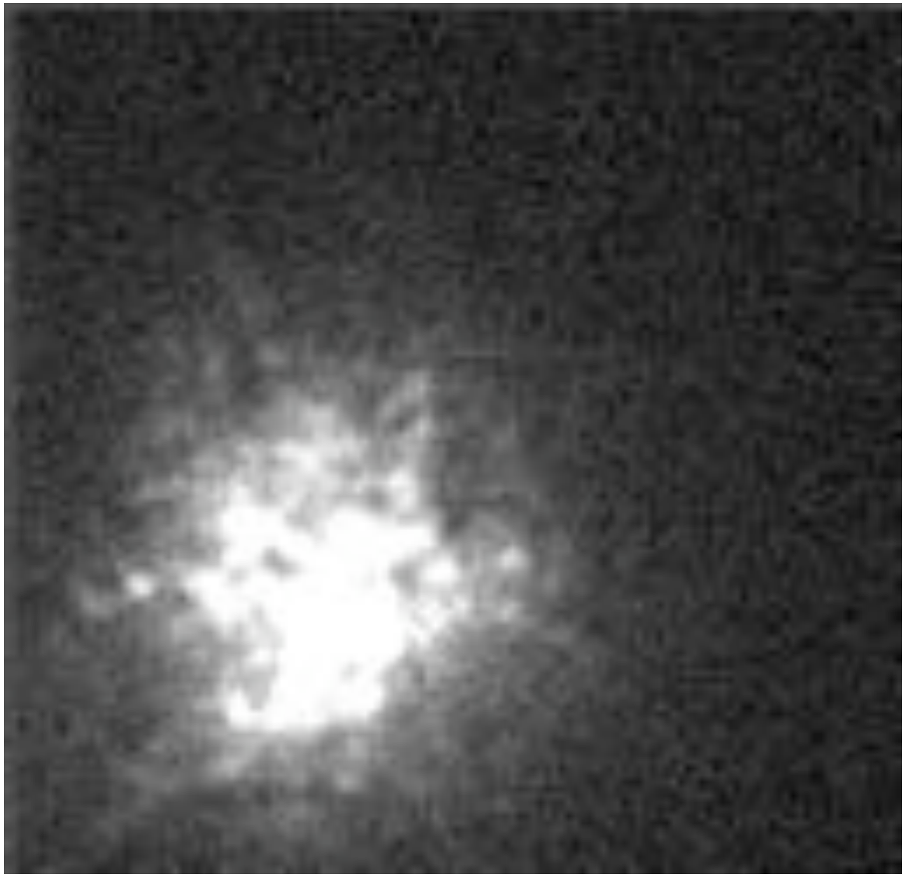
http://cfao.ucolick.org/pgallery/io.php

NGC 7469

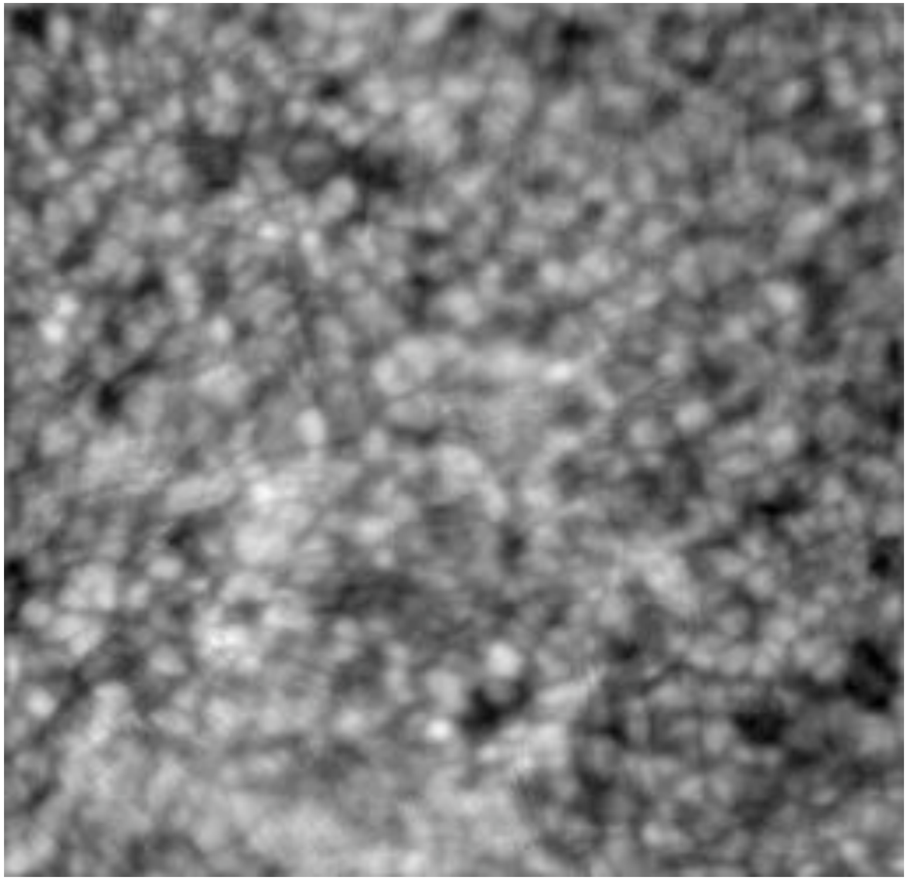


- http://cfao.ucolick.org/ao/why.php

Seeing



star



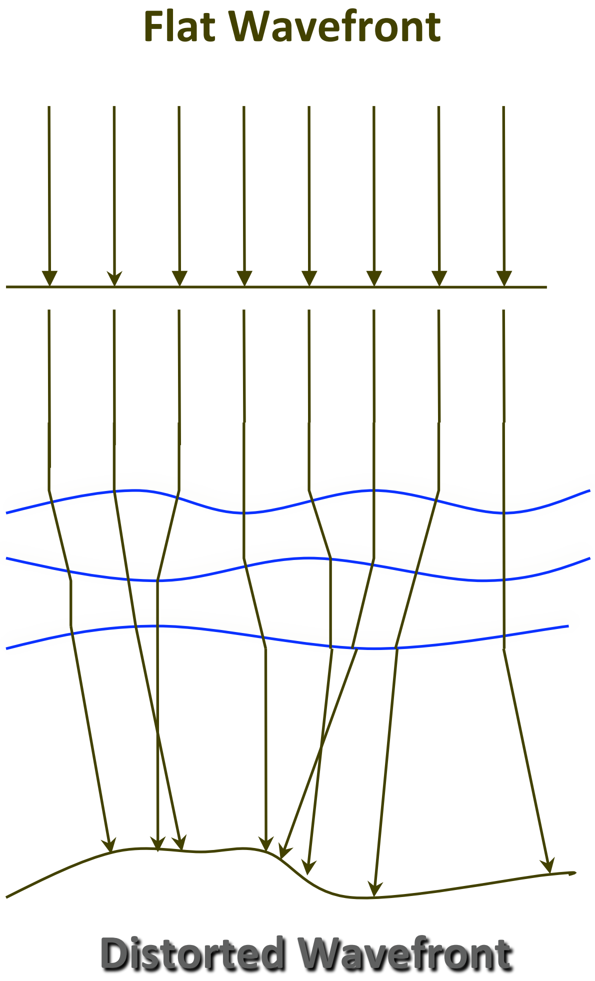
surface of the Sun

Index of Refraction of Air

- Wavelength dependence of index of refraction about $1 \bullet 10^{-6}/\lambda^2$
- 1 K temperature difference changes n by $1 \bullet 10^{-6}$
- Temperature of atmosphere is not uniform
- Variation of 0.01K along path of 10km: 10^4m * 10^{-8}=10^{-4}m=100 waves at 10um
- Air is ‘achromatic’
- Refractive index of water vapour is less than that of air, moist air has smaller refractive index

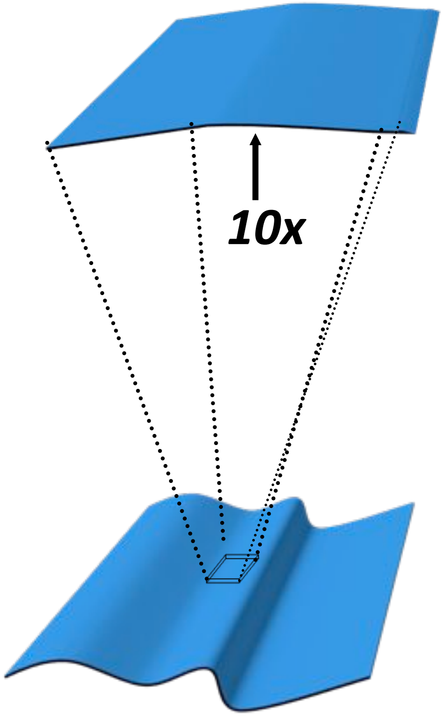
The Source of the Problem

- Light from astronomical source travels in straight line through space
- Nonuniform refractive index fluctuation - masses of warm or cold air refract light differently
- Different parts of wavefront interfere with each other in image plane
- on the ground, it looks like the astronomical object is at several places in the sky at the same time
- temperature fluctuations change about a hundred times per second
- blurred image when telescope could provide much better angular resolution



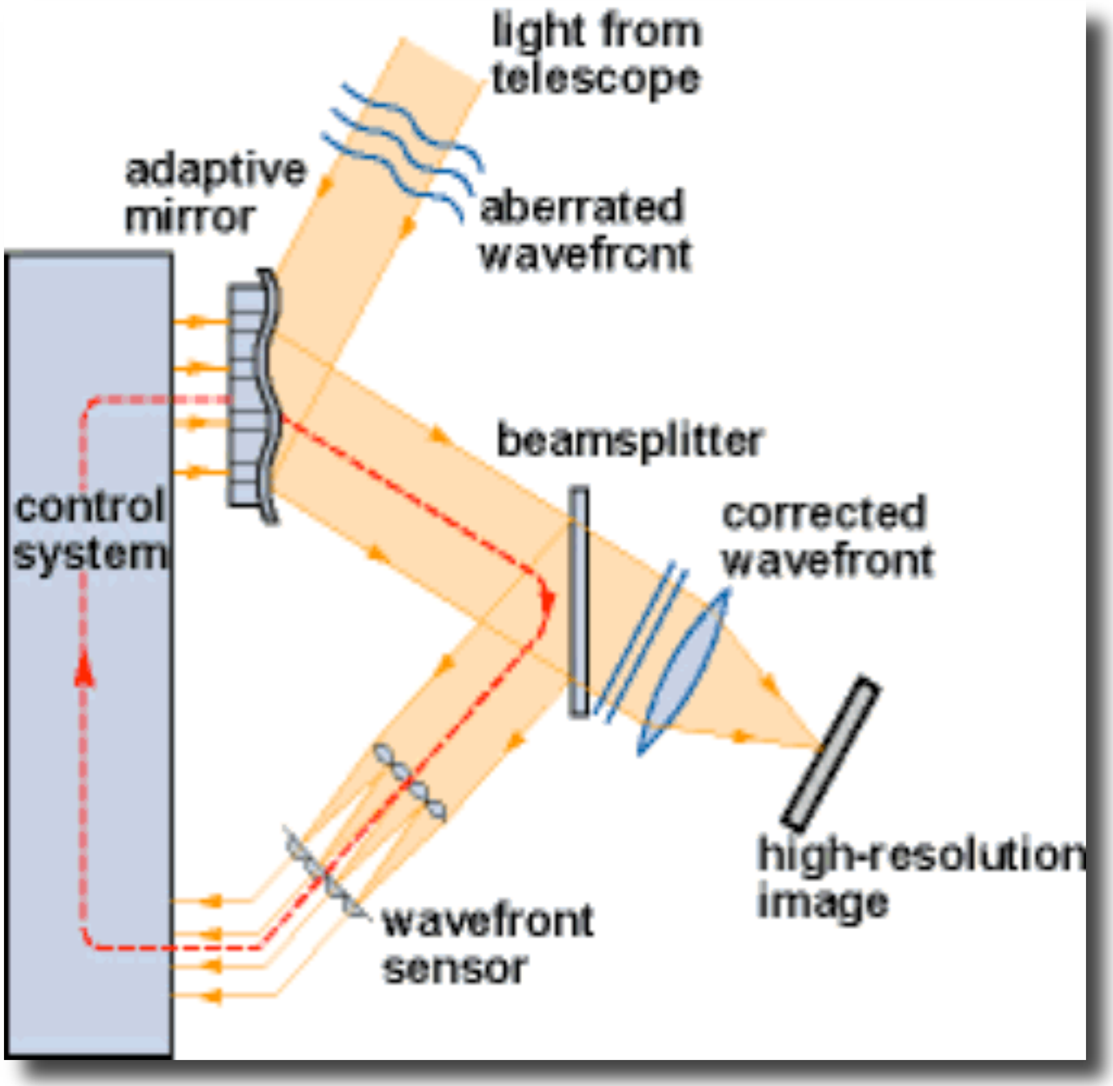
Atmospheric Disturbance Analysis

- Kolmogorov theory — Strength of turbulence quantified with C_n^2, the atmospheric structure constant
- Fried's parameter r_0 (limiting useful coherent aperture) varies with C_n^2, the zenith angle, and the wavelength
- Wavefront can be considered flat over r_0
- Seeing limits resolution to lambda/r_0
- Sources in different directions will not see the same aberrations unless they are within the isoplanatic patch

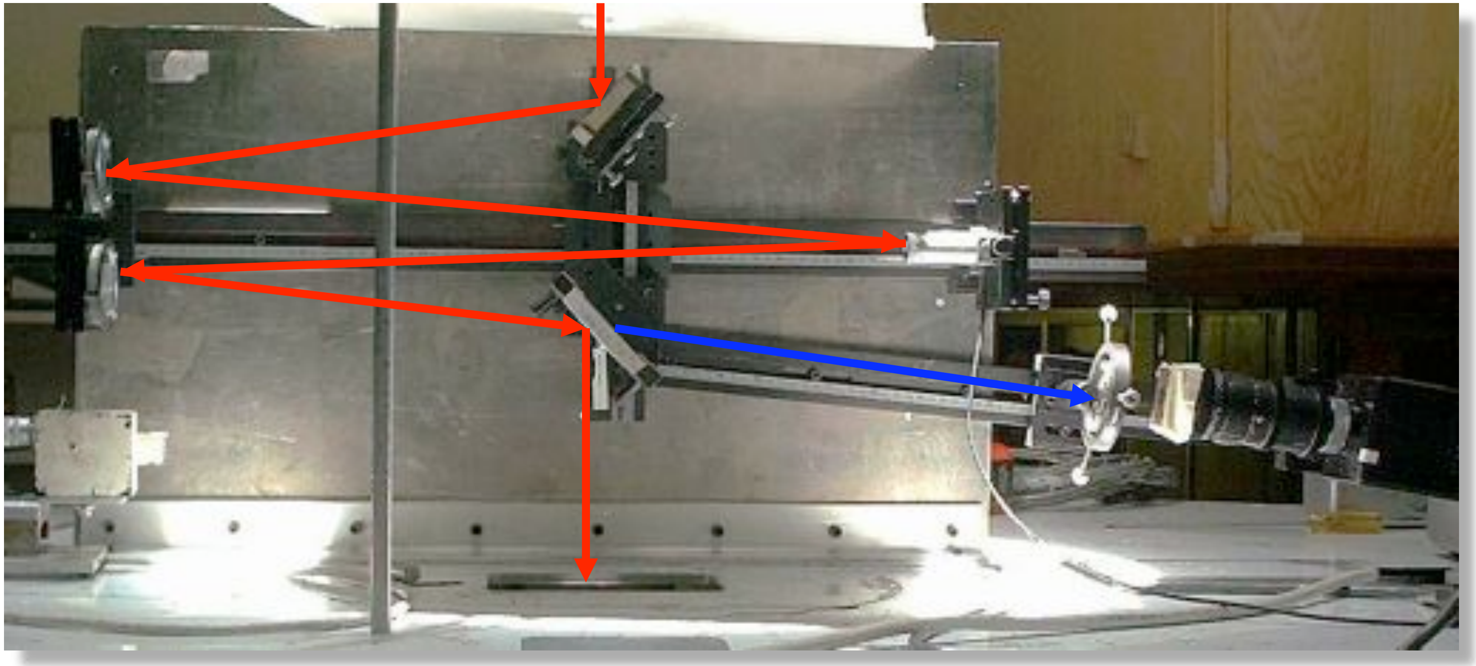


The Solution: Adaptive Optics

- wavefront sensor determines wavefront distortion after adaptive/ deformable mirror
- control system directs deformable mirror to compensate distortion
- repeated several hundred times per second

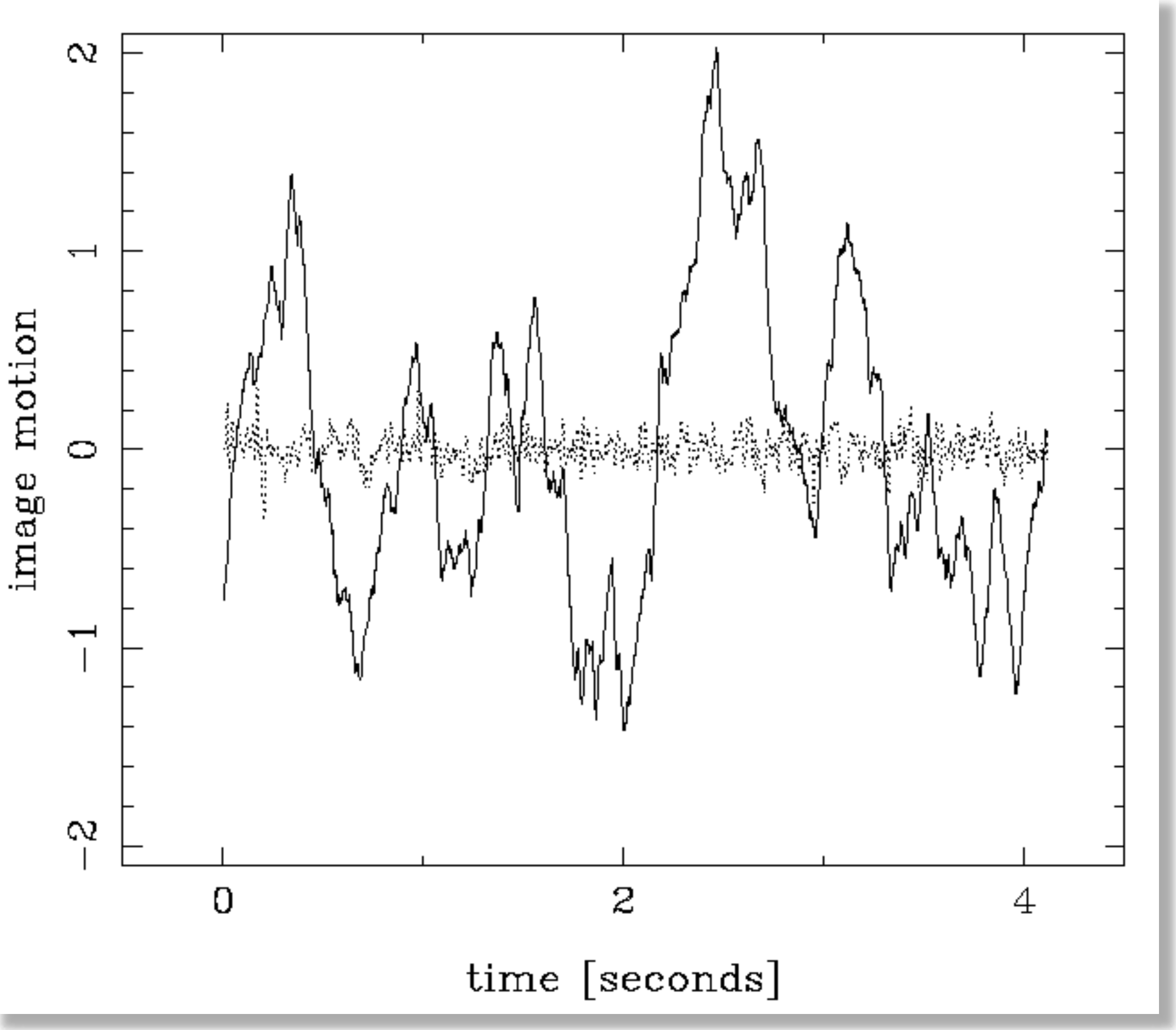


Tip-Tilt Correction



- Simplest correction only corrects image motion
- Center-of-gravity of cross-correlation with reference image to determine image motion (wavefront tilt)

Solar Limb-Tracking Performance

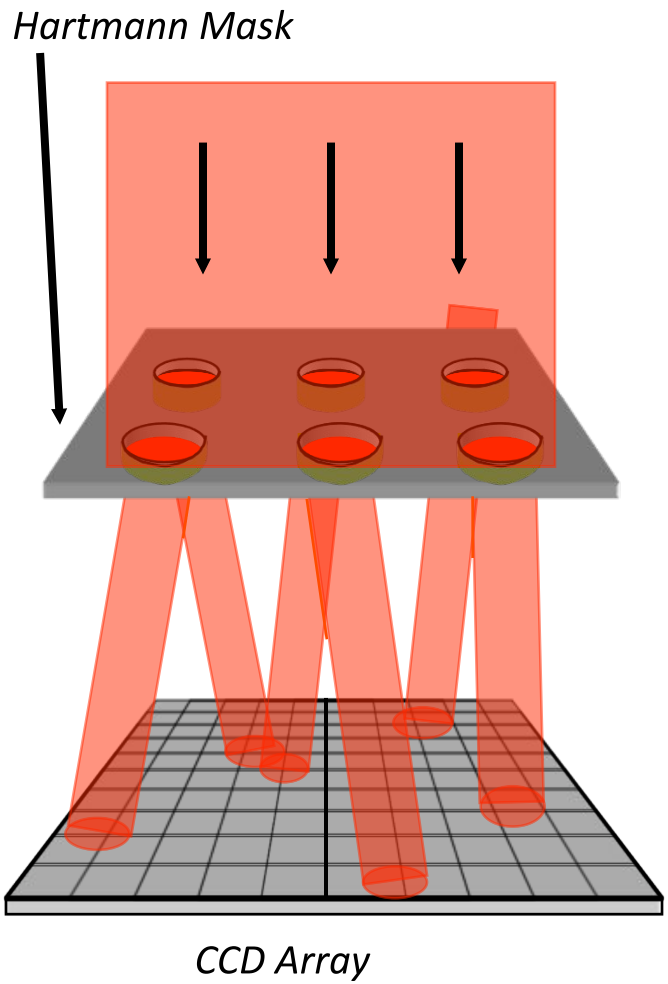


Wavefront Sensing

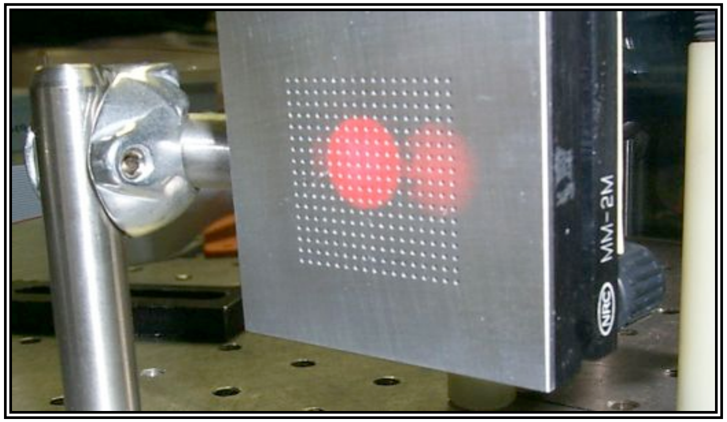
- Need to measure wavefront shape to control deformable mirror
- Most astronomical AO systems work with point sources

The Hartmann Array

- array of holes
- measure spot offsets to find the tilt of each individual beam
- Wavefront information not passing through holes is lost - Shack-Hartmann uses lenslet array



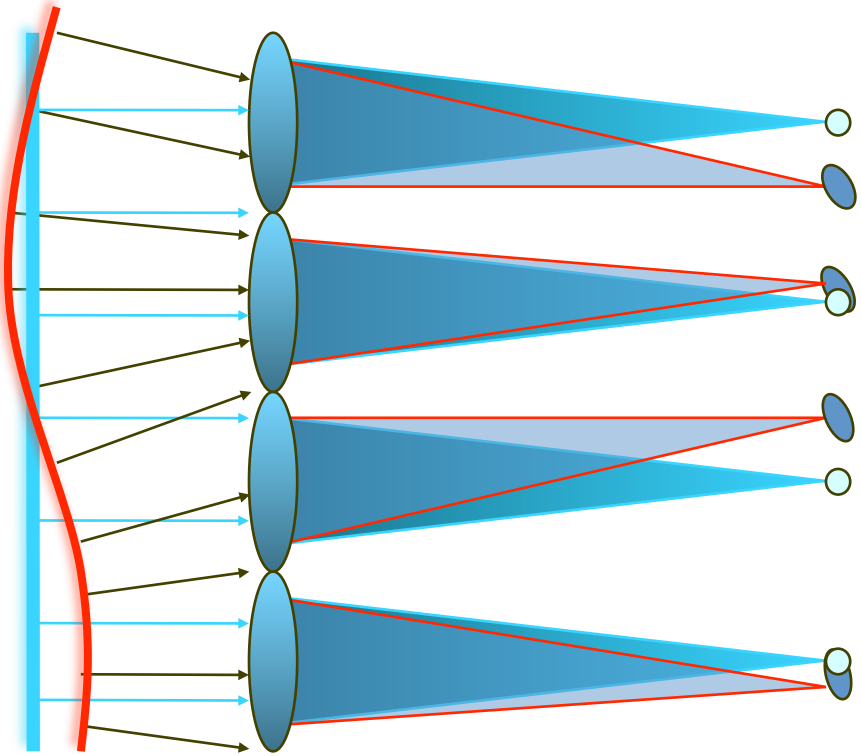
Hartmann Wavefront Sensor



Hartmann Mask

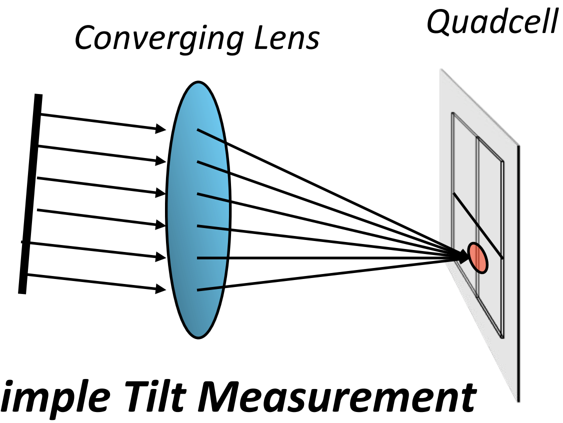
Shack-Hartmann Wavefront Sensor

- create a lot of small telescopes using an array of microlenses: subapertures
- measure the position of the star in each subaperture
- deviation from expected position corresponds to local tilt of wavefront distortion

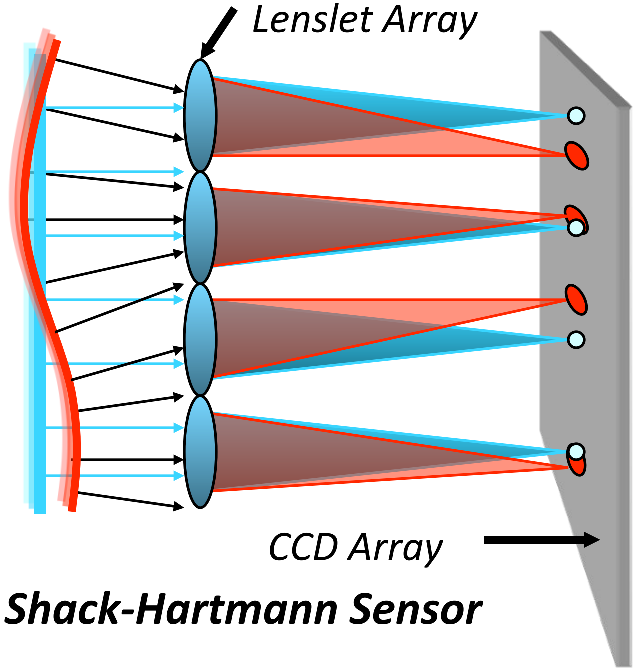


Shack-Hartmann Wavefront Sensor

- Simple tilt measurement - Observe beam in focal plane and record focal point offset with quadcell CCD
- Offset proportional to average derivative of wavefront function
- Shack-Hartmann - breaks up beam with lenslet array and measures tilt of each part
- Computer control can use reconstruction techniques to find the wavefront that would produce the set of derivatives

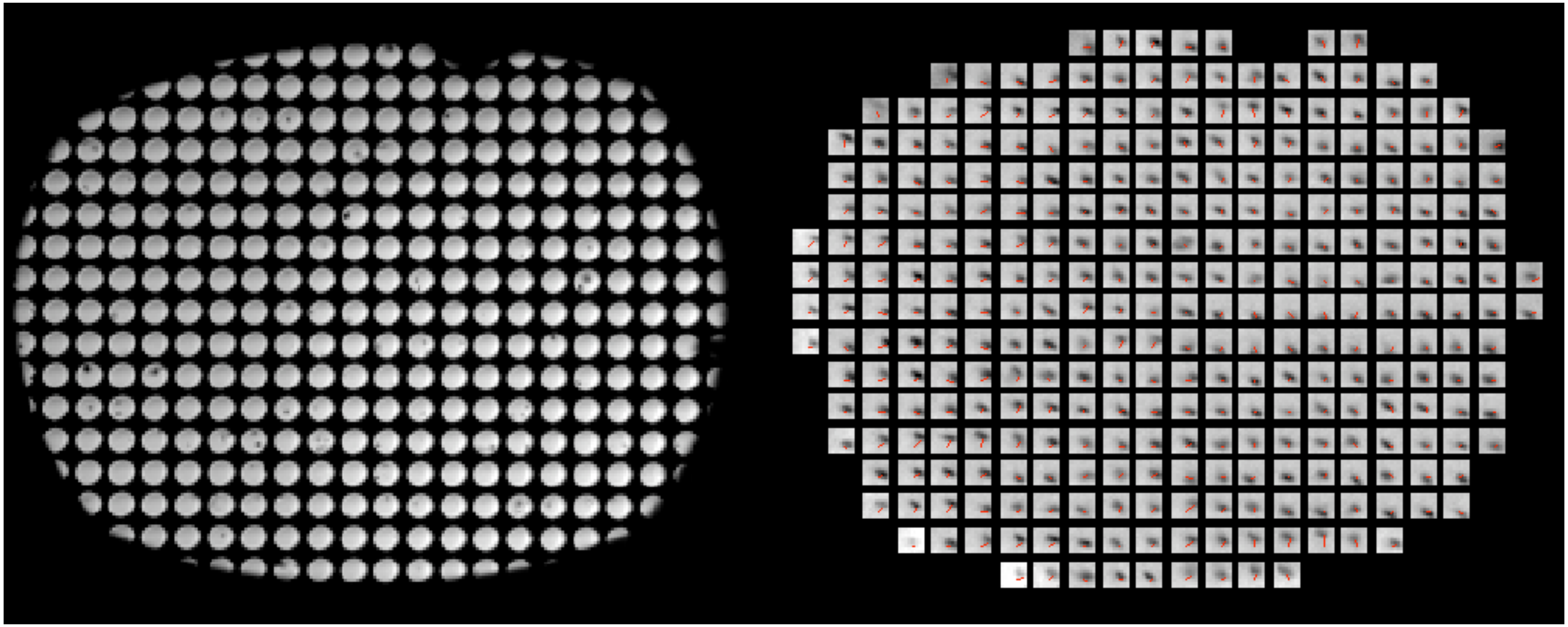


Simple Tilt Measurement



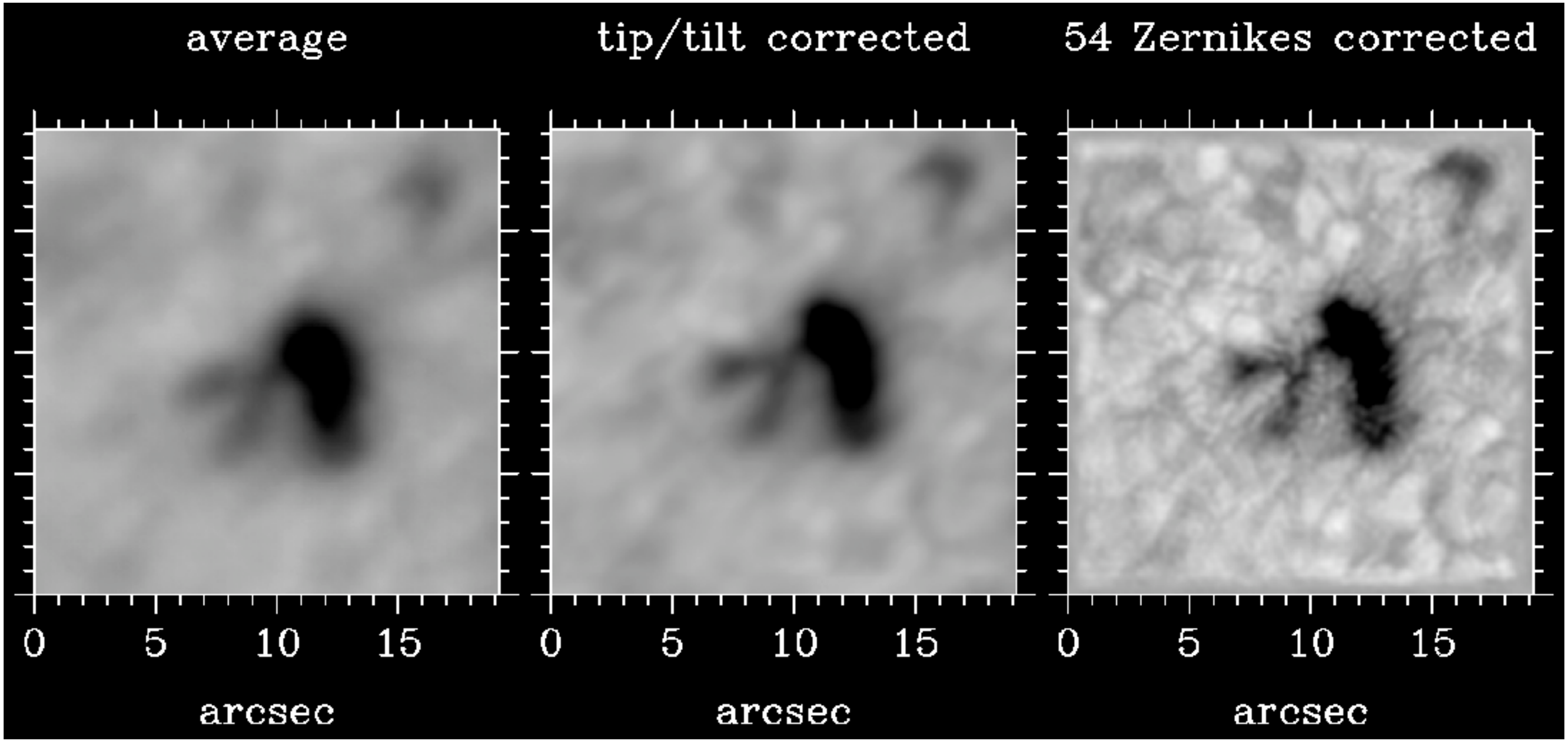
Shack-Hartmann Sensor

Solar Wavefront Sensing



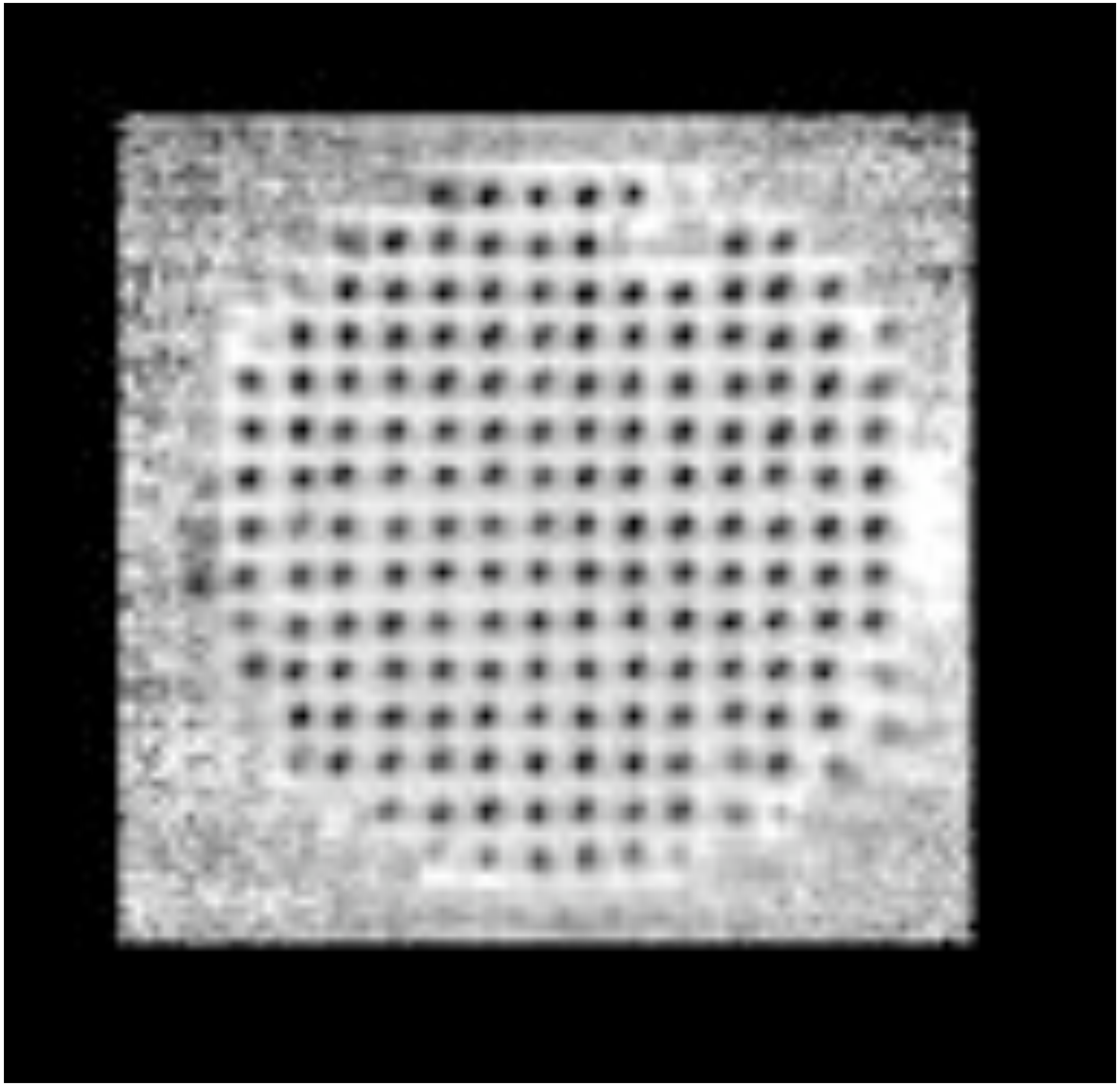
- Left: pupil plane
- Right: image plane of wavefront sensor with sunspot

Deconvolution from Wavefront Sensing



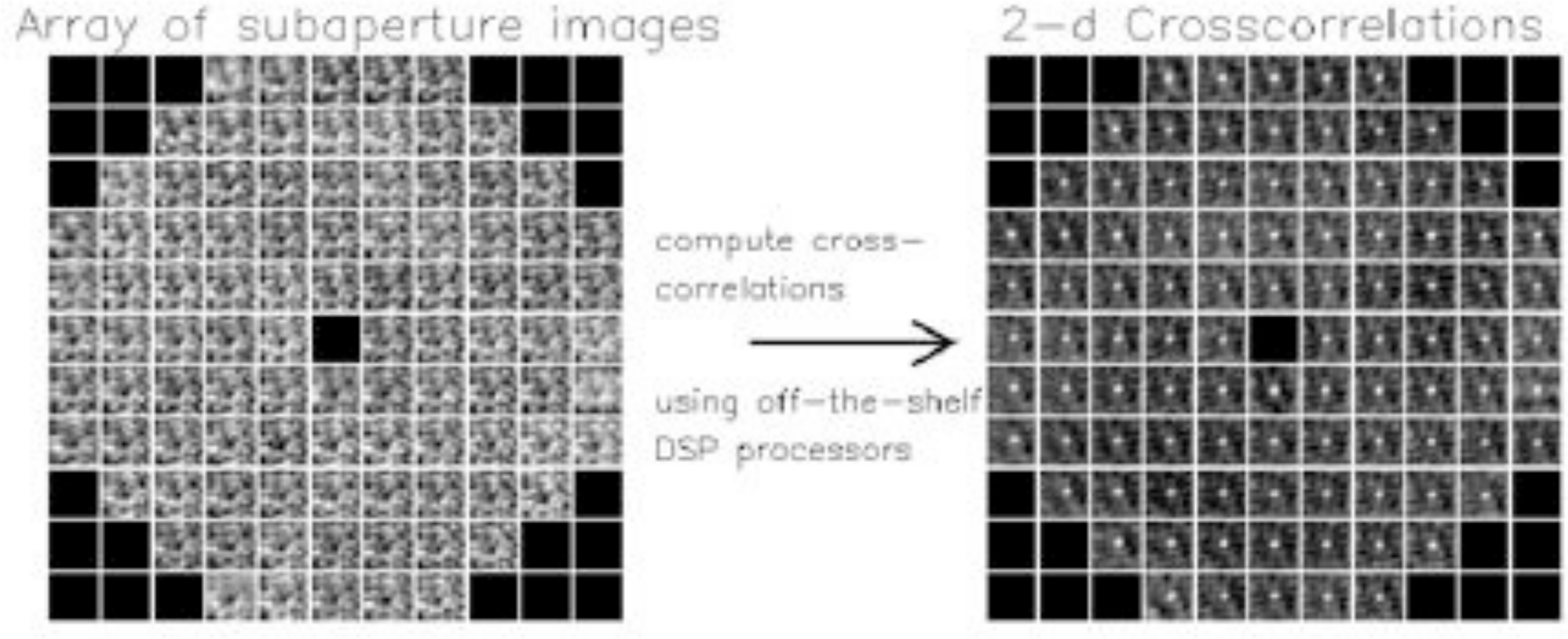
- deconvolution from wavefront sensing provides AO-like results
- 106 subapertures over 1m aperture at 950 nm at McMath-Pierce telescope

Wavefront Sensing

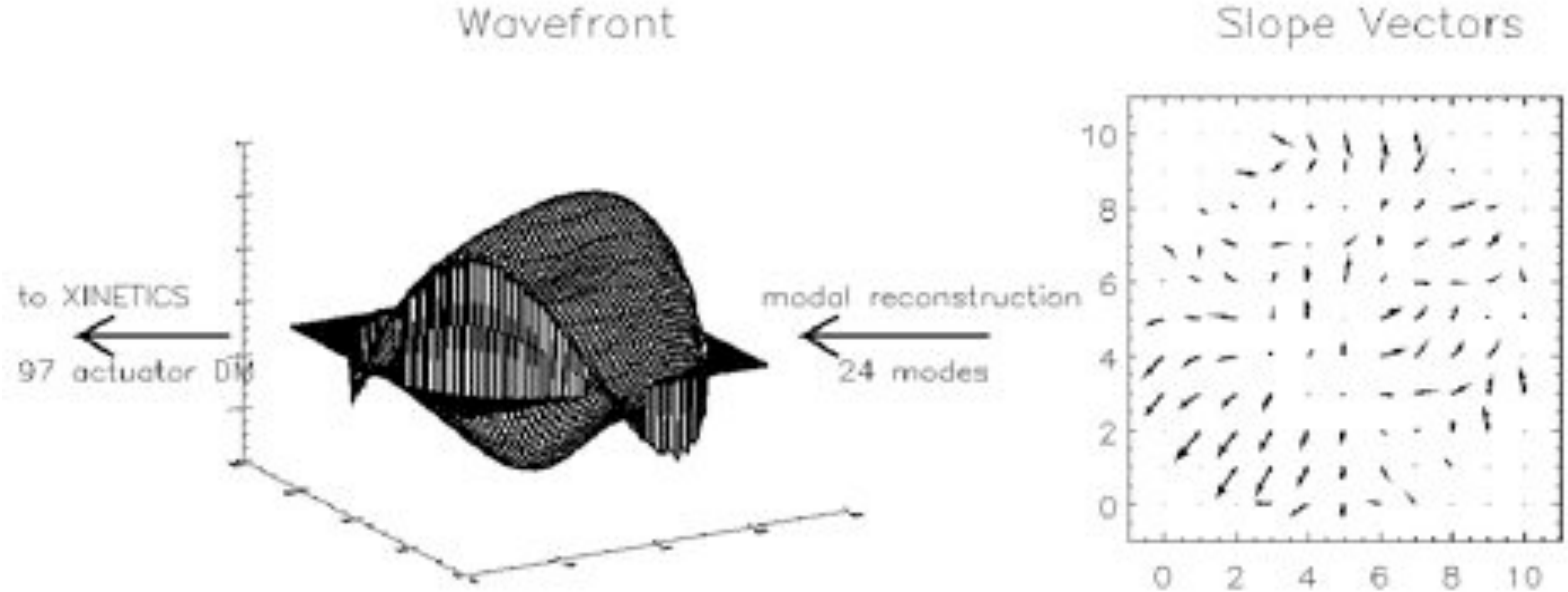


Sunspot wavefront sensor images

Correlating Shack-Hartmann Wavefront Sensor



Low-order Adaptive Optics

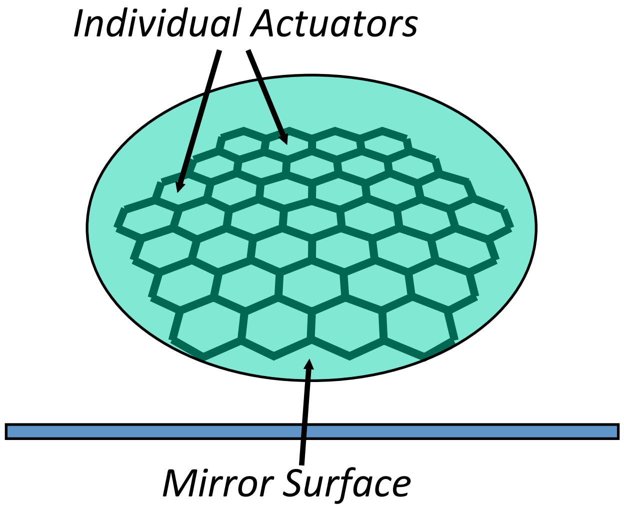


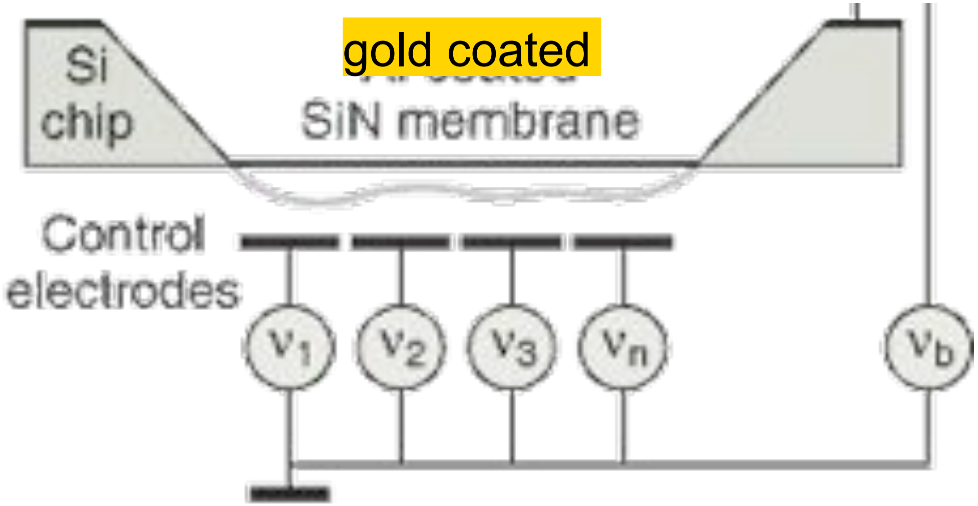
Deformable Mirrors (DM)

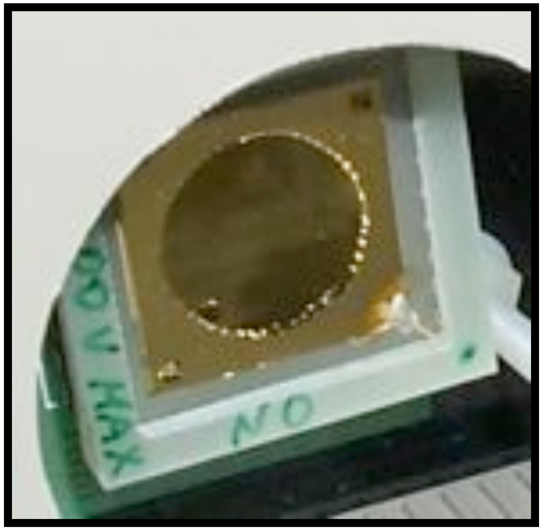
- Mirror with controllable surface shape provides achromatic wavefront correction
- Many technical approaches:
  - Piezo-electric and voice-coil actuators
  - Electrostatic membranes and MEMS
- Up to 4000 actuators

Membrane Deformable Mirror

- micromachined deformable mirror (OKOtech/Flexible Optics) with 37 actuators
- 600-nm thick, 15-mm diameter silicon nitride membrane
- electrostatic actuators

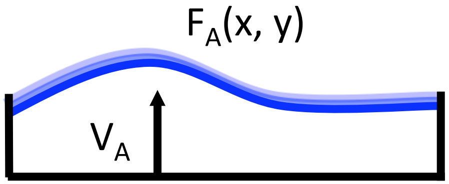




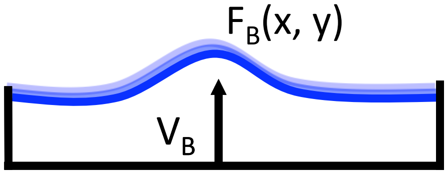


Summation Response

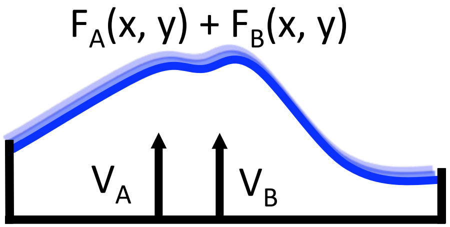
- Simple mirror response model — relates shape of mirror to voltage distribution
- Mirror shape formed by combination of actuator voltages is the sum of responses due to each individual actuator
- Assumption breaks down when mirror reaches elastic limit:
    - At combinations of large voltages
    - When voltages vary greatly over spatial range (bumpy surface)



Actuator A = V_A



Actuator B = V_B



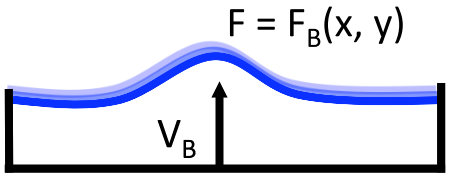
Actuator A = $V_{A,}$
Actuator B = V_B

Linear/Voltage-Squared Response

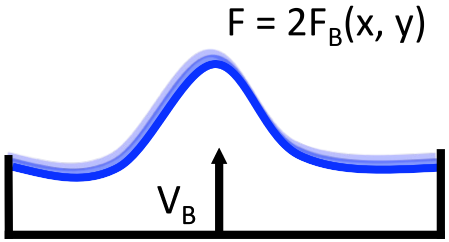
- For individual actuators, mirror function is proportional to voltage squared (electrostatic force is proportional to voltage squared)
- Combining summation and linear/voltage-squared models, the response of the mirror is:

$$\varphi(x,y)=\sum_{k=1}^{37} a_k \varphi_k(x,y)$$

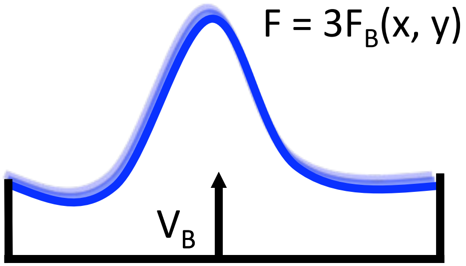
- Accurately describes OKO mirror except for:
  - Large voltages
  - Spatially varying distributions
  - Response near edge of mirror - clamping effect introduces non-linear terms



Actuator B = V_B



Actuator B = $4V_B$



Actuator B = $9V_B$

TNO TU/e Deformable Mirror

AO Control

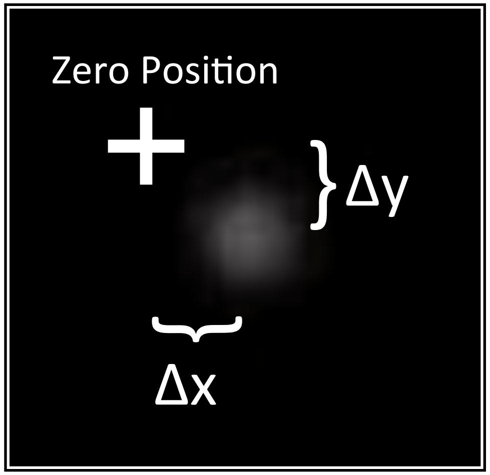
- Analyse wavefront sensor camera image and translate data into wavefront
- Calculate optimum mirror actuator positions
- Must operate at about 1kHz

Computer Control

- performs centroid (center of gravity) calculation on each spot:

$$x_{pos} = \frac{\sum_{i=i_{\min}}^{i_{\max}} \sum_{j=j_{\min}}^{j_{\max}} I(i,j)\cdot i}{\sum_{i=i_{\min}}^{i_{\max}} \sum_{j=j_{\min}}^{j_{\max}} I(i,j)}, \quad y_{pos} = \frac{\sum_{i=i_{\min}}^{i_{\max}} \sum_{j=j_{\min}}^{j_{\max}} I(i,j)\cdot j}{\sum_{i=i_{\min}}^{i_{\max}} \sum_{j=j_{\min}}^{j_{\max}} I(i,j)}$$

- Program must know approximate spot location to avoid integrating over other spots - only include spots in fixed integration areas
- Threshold clipping:
    - Only pixels above intensity threshold are integrated
    - Threshold subtracted from intensities to reduce background noise



Finding Spot Offsets

Mathematical Representation for 37 Actuators and 36 subapertures

- Save computation time by ignoring wavefront shape
- Derivatives of mirror surface *and* individual spot offsets are proportional to squared voltage
- Consider each spot's relationship to each actuator:

$$c_n = \sum_{k=1}^{37} a_k b_{nk}$$

(For a single spot — x-offset or y-offset)

- Combine above equations for each spot offset n to form a matrix equation:

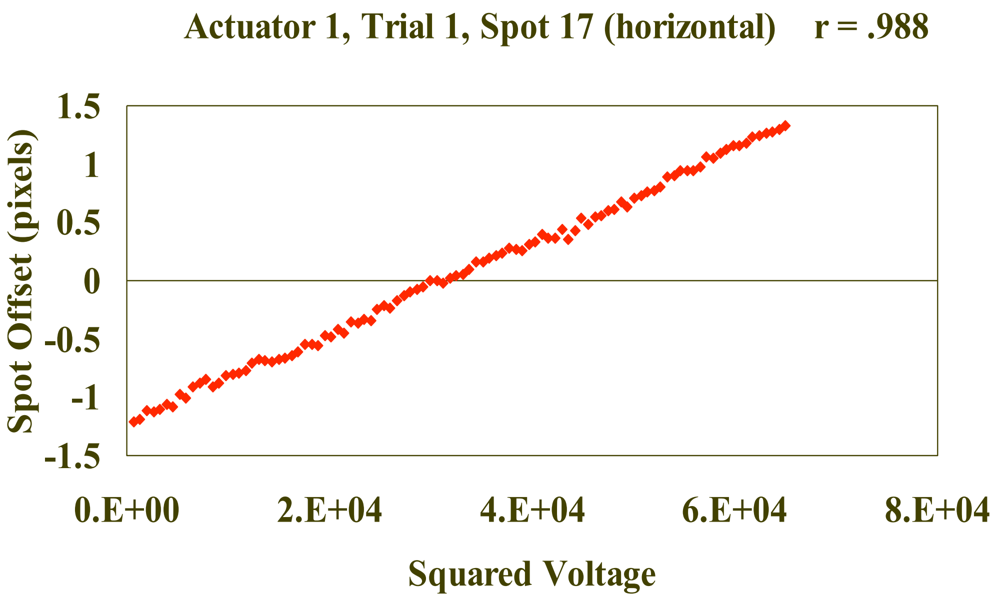
$$C = BA$$

- C = 72 element vector listing spot offsets
- A = Control Vector — 37 element vector listing the squared voltages)
- B = Influence matrix — 72 by 37 matrix describing the influence of specific actuator voltages on the spot offsets.

Measuring the Influence Matrix

- For AO, need to know voltages that will correct the given spot positions — must solve for A (control vector) given C (spot offsets)
- First find B (influence matrix), possible through direct measurement and experimentation:
    - Step each actuator k through the possible voltages and measure the spot locations at each step
    - For the kth actuator and the nth spot coordinate, the slope of the best fit line is the element (n, k) of the influence matrix B

- Influence matrix gives the resulting spot offsets when multiplied by a control vector (list of squared voltages)



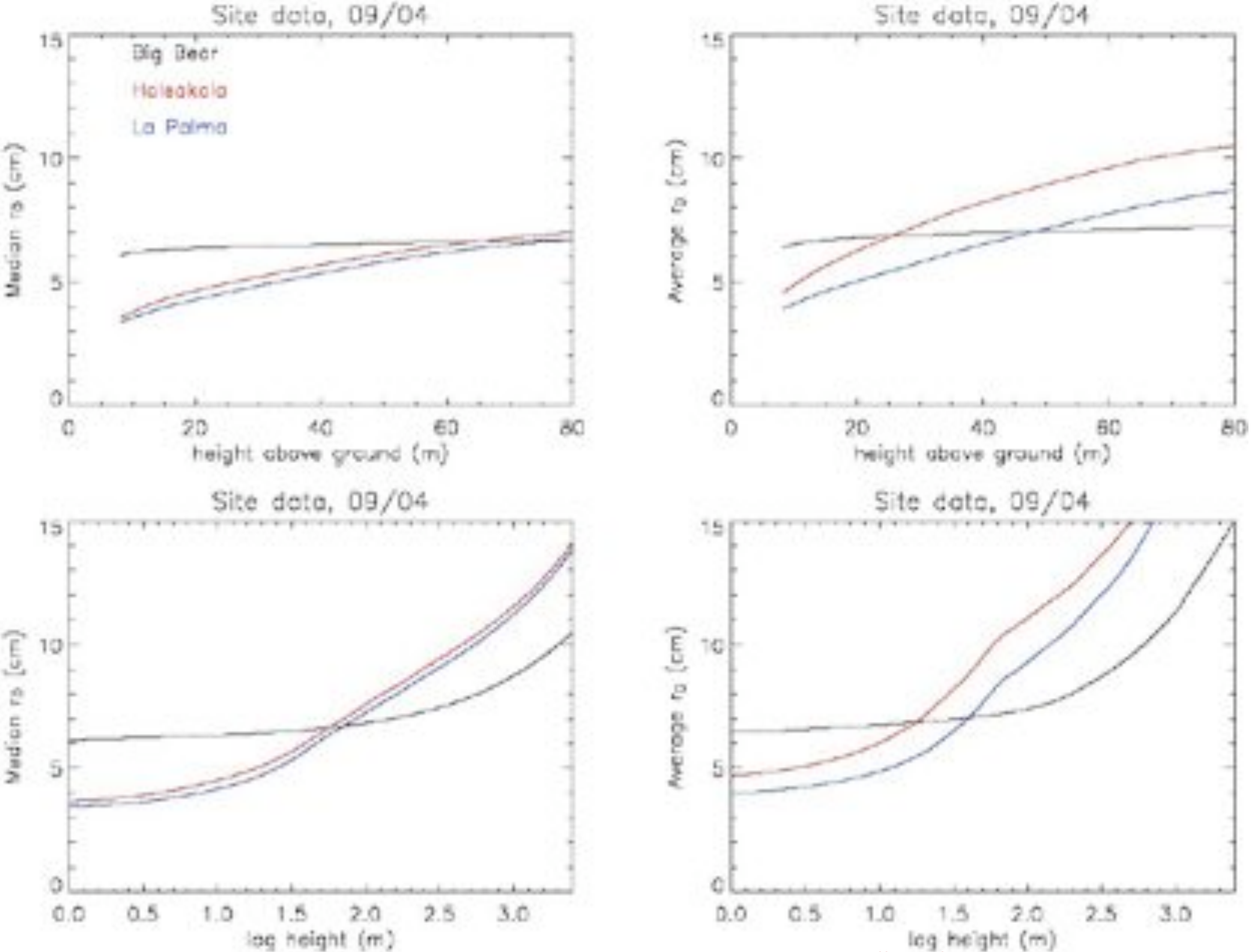
Solving for the Control Vector

- Influence matrix is known and C is given from wavefront sensor — need to find A (control vector) to correct for the error wavefront
- Need to invert equation C = BA as follows:

$$A = B^{-1}C$$

- Overdetermined system:
  - Need to map a 72 dimension space into a 37 dimension space
  - No exact solution A exists for any given set of spot offsets
  - No exact B^{-1} exists (B is rectangular)
- Singular Value Decomposition: Generates approximate B^{-1} that won't solve equation, but will represent best solution
- Permits well-behaved system

Solar AO = mostly GLAO

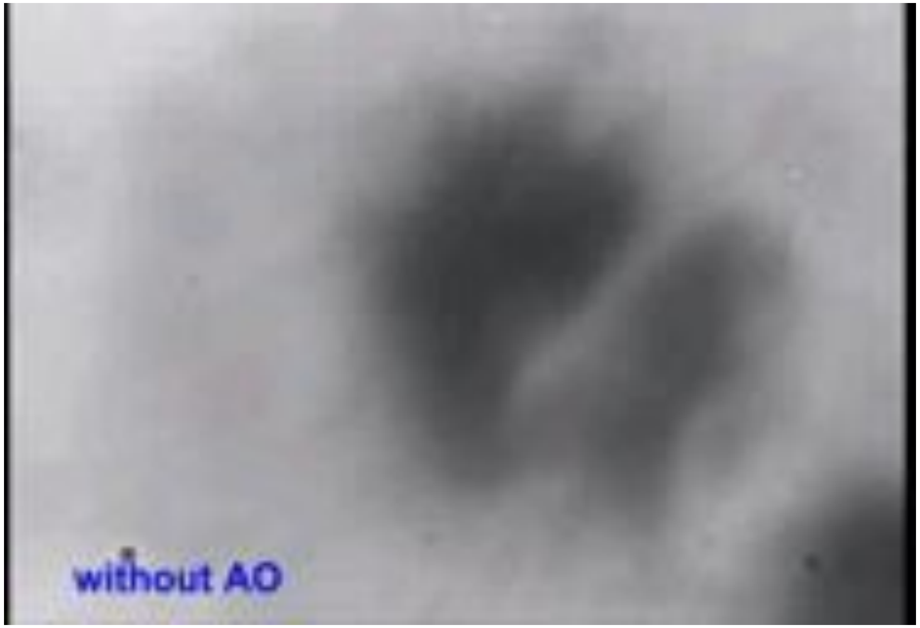


Hill et al. 2004

Solar Adaptive Optics Systems

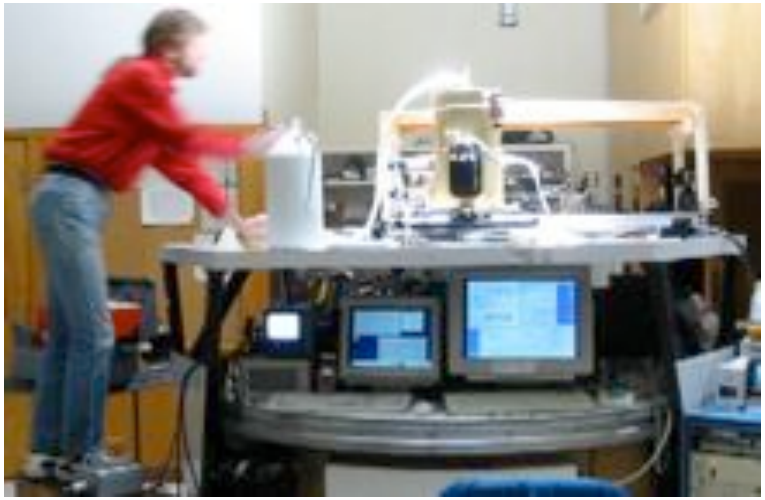
Telescope / AO System	Subap.	Act.	Frequ.	Reconstructor	First light
76-cm DST / Lockheed	19	57	-	Analog	1989
76-cm DST / Low-Order AO	24	97	< 1.6 kHz	24 DSPs	1998
76-cm DST / AO76	76	97	2.5 kHz	40 DSPs	2002
70-cm VTT / KAOS	36	35	955 Hz	8x900MHz Sun	2002
48-cm SVST La Palma	19	19	955 Hz	566 MHz Alpha	1999
1.5-m McMath-Pierce	120-200	37	955 Hz	1 GHz PIII	2002
97-cm SST La Palma	37	37	955 Hz	1.4 GHz Athlon	2003
60-cm BBSO	76	97	2.5 kHz	40 DSPs	2005

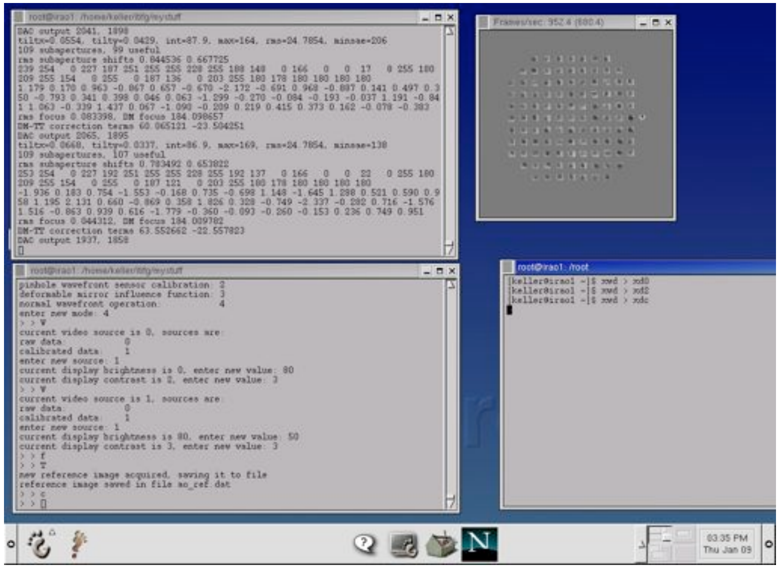
$25,000 AO at 1.5-m McMath-Pierce



- ❑ Low-cost system for infrared 1-20 µm at world's largest solar telescope
- ❑ 110-150 subapertures
- ❑ 37 actuator Okotech mirror
- ❑ PC/Linux based control system

Simple AO Setup





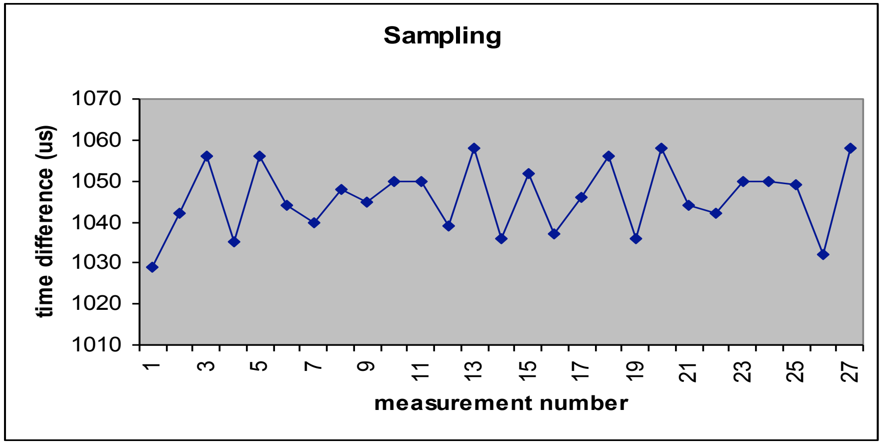
```
DAC output 2041, 1898
tiltx=0.0554, tilty=0.0429, int=87.9, max=164, rms=24.7854, minsae=206
109 subapertures, 99 useful
rms subaperture shifts 0.844536 0.667725
239 254   0 227 187 251 255 255 228 255 188 148   0 166   0   0  17   0 255 180
209 255 154   0 255   0 187 136   0 203 255 180 178 180 180 180 180
1.179 0.170 0.963 -0.867 0.657 -0.670 -2.172 -0.691 0.968 -0.887 0.141 0.497 0.3
50 -0.793 0.341 0.398 0.046 0.063 -1.299 -0.270 -0.084 -0.193 -0.037 1.191 -0.84
1 1.063 -0.339 1.437 0.067 -1.090 -0.209 0.219 0.415 0.373 0.162 -0.078 -0.383
rms focus 0.083398, DM focus 184.098657
DM-TT correction terms 60.065121 -23.504251
DAC output 2065, 1895
tiltx=0.0668, tilty=0.0337, int=86.9, max=169, rms=24.7854, minsae=138
109 subapertures, 107 useful
rms subaperture shifts 0.783492 0.653822
253 254   0 227 192 251 255 255 228 255 192 137   0 166   0   0  22   0 255 180
209 255 154   0 255   0 187 121   0 203 255 180 178 180 180 180 180
-1.936 0.183 0.754 -1.553 -0.168 0.735 -0.698 1.148 -1.645 1.288 0.521 0.590 0.9
58 1.195 2.131 0.660 -0.869 0.358 1.826 0.328 -0.749 -2.337 -0.282 0.716 -1.576
1.516 -0.863 0.939 0.616 -1.779 -0.360 -0.093 -0.260 -0.153 0.236 0.749 0.951
rms focus 0.044312, DM focus 184.009782
DM-TT correction terms 63.552662 -22.557823
DAC output 1937, 1858
```

```
pinhole wavefront sensor calibration: 2
deformable mirror influence function: 3
normal wavefront operation:           4
enter new mode: 4
> > V
current video source is 0, sources are:
raw data:           0
calibrated data:    1
enter new source: 1
current display brightness is 0, enter new value: 80
current display contrast is 2, enter new value: 3
> > V
current video source is 1, sources are:
raw data:           0
calibrated data:    1
enter new source: 1
current display brightness is 80, enter new value: 50
current display contrast is 3, enter new value: 3
> > f
> > T
new reference image acquired, saving it to file
reference image saved in file ao_ref.dat
> > c
> >
```

```
[keller@irao1 ~]$ xwd > xd0
[keller@irao1 ~]$ xwd > xd2
[keller@irao1 ~]$ xwd > xdc
```

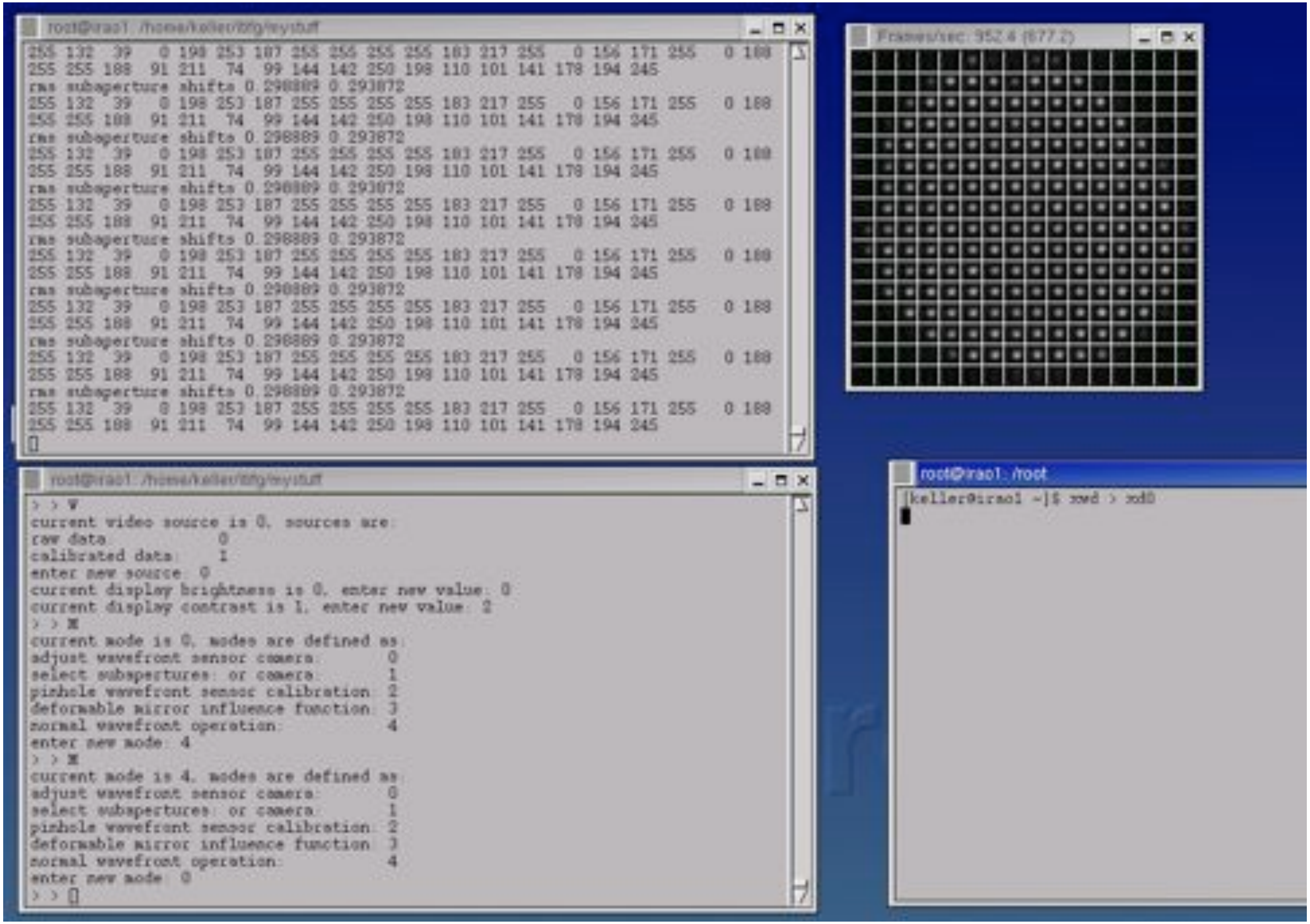
Operating System Considerations

- Regular Linux is good enough if soft-realtime scheduling is used



```
#include <sched.h> /* for sched_setscheduler soft-realtime behavior */
...
// variable for soft realtime scheduling
 struct sched_param *p;
...
 /* set soft real-time scheduling */
 sched_getparam(0,p);
 p->sched_priority = 50;
 if (sched_setscheduler(0,SCHED_FIFO,p))
  fprintf(stderr,"Could not change scheduler settings\n");
```

Wavefront Sensor Adjustment

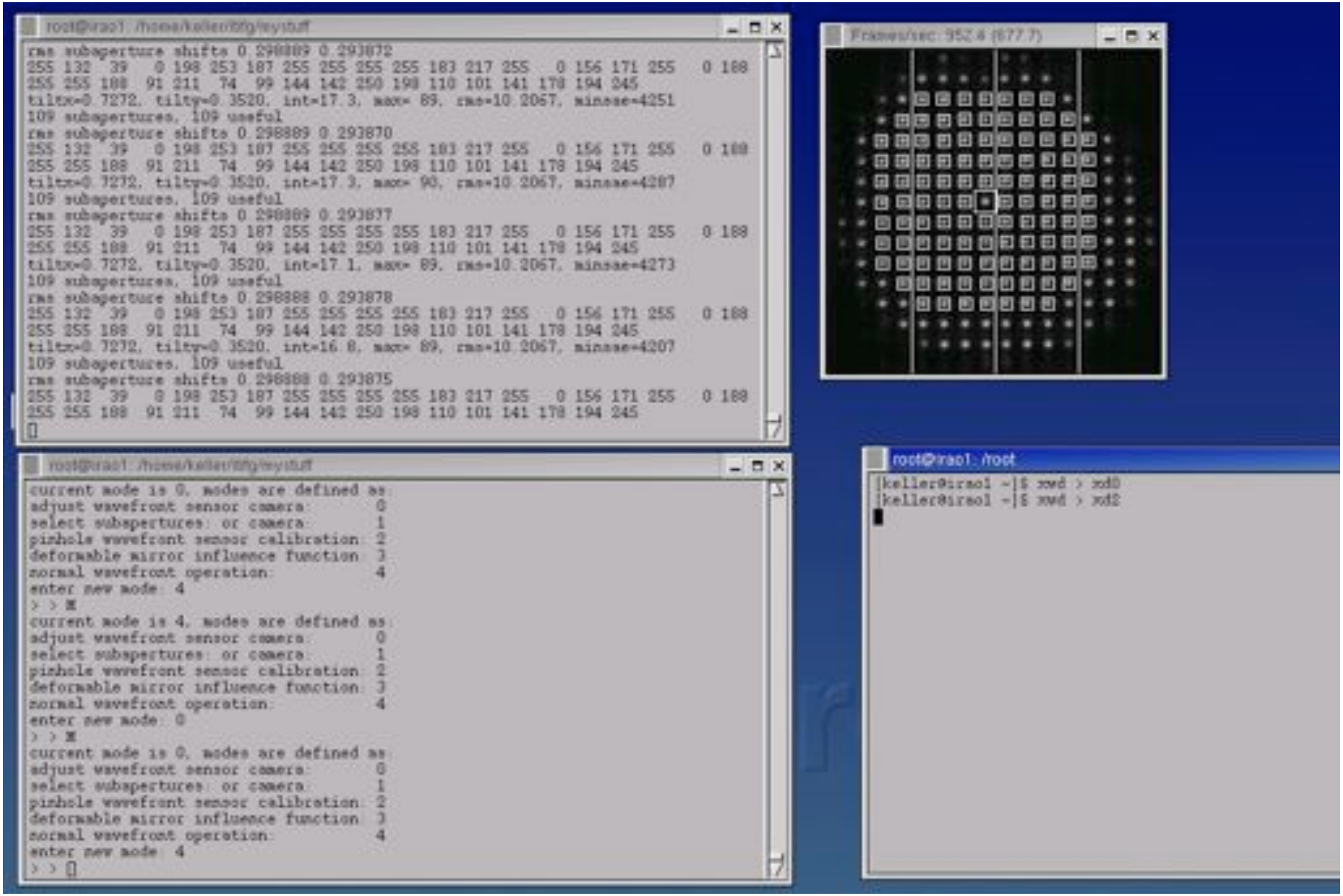


```
255 132  39   0 198 253 187 255 255 255 255 183 217 255   0 156 171 255   0 188
255 255 188  91 211  74  99 144 142 250 198 110 101 141 178 194 245
rms subaperture shifts 0.298889 0.293872
255 132  39   0 198 253 187 255 255 255 255 183 217 255   0 156 171 255   0 188
255 255 188  91 211  74  99 144 142 250 198 110 101 141 178 194 245
rms subaperture shifts 0.298889 0.293872
255 132  39   0 198 253 187 255 255 255 255 183 217 255   0 156 171 255   0 188
255 255 188  91 211  74  99 144 142 250 198 110 101 141 178 194 245
rms subaperture shifts 0.298889 0.293872
255 132  39   0 198 253 187 255 255 255 255 183 217 255   0 156 171 255   0 188
255 255 188  91 211  74  99 144 142 250 198 110 101 141 178 194 245
rms subaperture shifts 0.298889 0.293872
255 132  39   0 198 253 187 255 255 255 255 183 217 255   0 156 171 255   0 188
255 255 188  91 211  74  99 144 142 250 198 110 101 141 178 194 245
rms subaperture shifts 0.298889 0.293872
255 132  39   0 198 253 187 255 255 255 255 183 217 255   0 156 171 255   0 188
255 255 188  91 211  74  99 144 142 250 198 110 101 141 178 194 245
rms subaperture shifts 0.298889 0.293872
255 132  39   0 198 253 187 255 255 255 255 183 217 255   0 156 171 255   0 188
255 255 188  91 211  74  99 144 142 250 198 110 101 141 178 194 245
rms subaperture shifts 0.298889 0.293872
255 132  39   0 198 253 187 255 255 255 255 183 217 255   0 156 171 255   0 188
255 255 188  91 211  74  99 144 142 250 198 110 101 141 178 194 245
```

```
> > V
current video source is 0. sources are:
raw data:           0
calibrated data:    1
enter new source: 0
current display brightness is 0. enter new value: 0
current display contrast is 1. enter new value: 2
> > M
current mode is 0. modes are defined as:
adjust wavefront sensor camera:       0
select subapertures: or camera:       1
pinhole wavefront sensor calibration: 2
deformable mirror influence function: 3
normal wavefront operation:           4
enter new mode: 4
> > M
current mode is 4. modes are defined as:
adjust wavefront sensor camera:       0
select subapertures: or camera:       1
pinhole wavefront sensor calibration: 2
deformable mirror influence function: 3
normal wavefront operation:           4
enter new mode: 0
> >
```

```
[keller@irao1 ~]$ xwd > xd0
```

Subaperture Selection

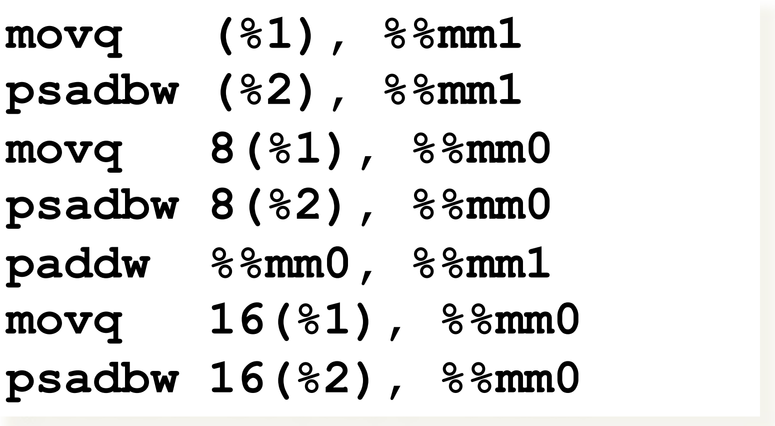


```
rms subaperture shifts 0.298889 0.293872
255 132  39   0 198 253 187 255 255 255 255 183 217 255   0 156 171 255   0 188
255 255 188  91 211  74  99 144 142 250 198 110 101 141 178 194 245
tiltx=0.7272, tilty=0.3520, int=17.3, max= 89, rms=10.2067, minsse=4251
109 subapertures, 109 useful
rms subaperture shifts 0.298889 0.293870
255 132  39   0 198 253 187 255 255 255 255 183 217 255   0 156 171 255   0 188
255 255 188  91 211  74  99 144 142 250 198 110 101 141 178 194 245
tiltx=0.7272, tilty=0.3520, int=17.3, max= 90, rms=10.2067, minsse=4287
109 subapertures, 109 useful
rms subaperture shifts 0.298889 0.293877
255 132  39   0 198 253 187 255 255 255 255 183 217 255   0 156 171 255   0 188
255 255 188  91 211  74  99 144 142 250 198 110 101 141 178 194 245
tiltx=0.7272, tilty=0.3520, int=17.1, max= 89, rms=10.2067, minsse=4273
109 subapertures, 109 useful
rms subaperture shifts 0.298888 0.293878
255 132  39   0 198 253 187 255 255 255 255 183 217 255   0 156 171 255   0 188
255 255 188  91 211  74  99 144 142 250 198 110 101 141 178 194 245
tiltx=0.7272, tilty=0.3520, int=16.8, max= 89, rms=10.2067, minsse=4207
109 subapertures, 109 useful
rms subaperture shifts 0.298888 0.293875
255 132  39   0 198 253 187 255 255 255 255 183 217 255   0 156 171 255   0 188
255 255 188  91 211  74  99 144 142 250 198 110 101 141 178 194 245
```

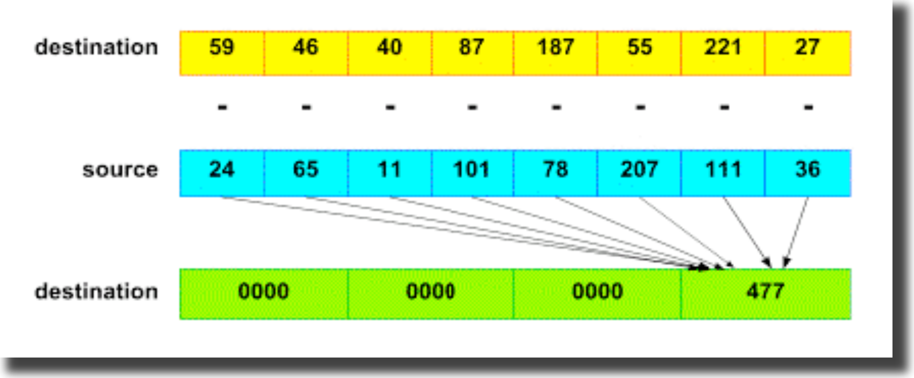
```
current mode is 0, modes are defined as:
adjust wavefront sensor camera:          0
select subapertures: or camera:          1
pinhole wavefront sensor calibration:    2
deformable mirror influence function:    3
normal wavefront operation:              4
enter new mode: 4
> >
current mode is 4, modes are defined as:
adjust wavefront sensor camera:          0
select subapertures: or camera:          1
pinhole wavefront sensor calibration:    2
deformable mirror influence function:    3
normal wavefront operation:              4
enter new mode: 0
> >
current mode is 0, modes are defined as:
adjust wavefront sensor camera:          0
select subapertures: or camera:          1
pinhole wavefront sensor calibration:    2
deformable mirror influence function:    3
normal wavefront operation:              4
enter new mode: 4
> >
```

```
[keller@irao1 ~]$ xwd > xd0
[keller@irao1 ~]$ xwd > xd2
```

Code Snippet

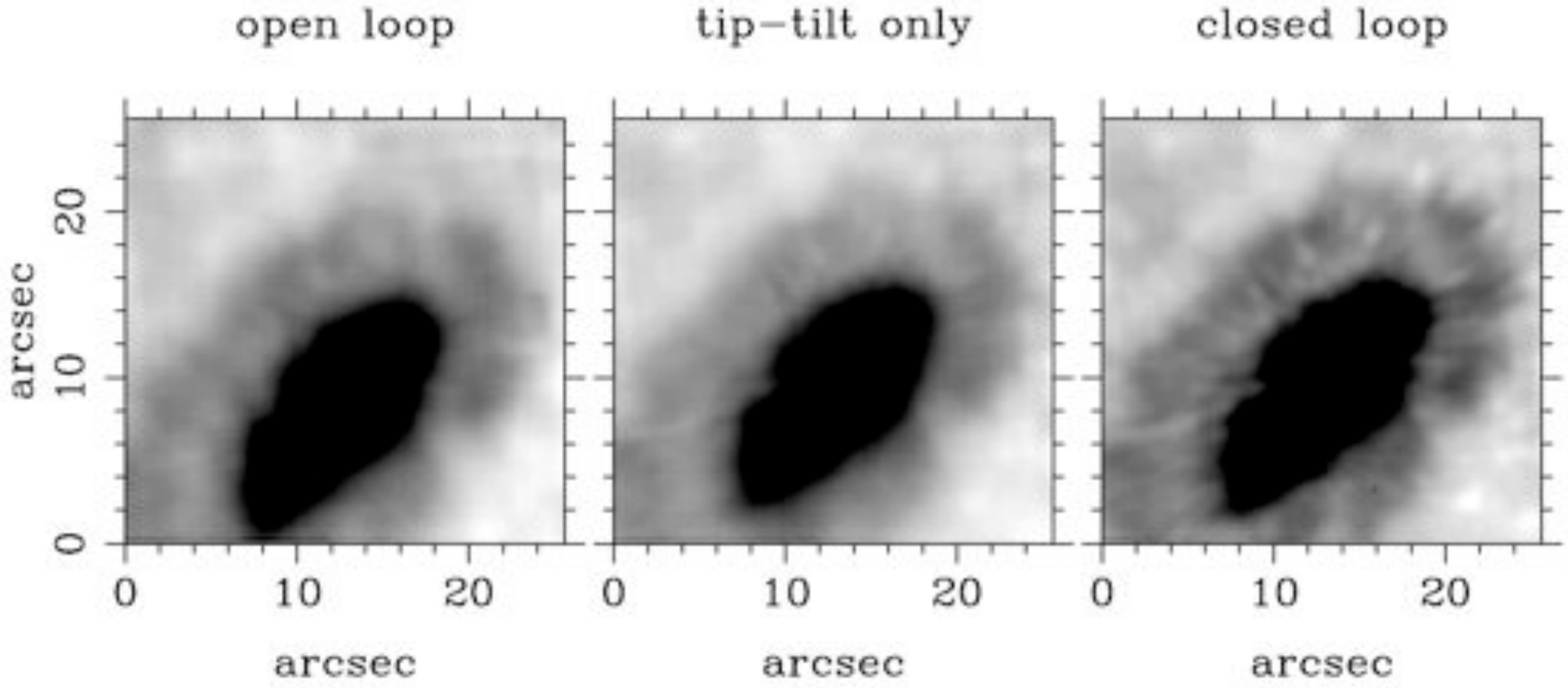


```
movq    (%1), %%mm1
psadbw (%2), %%mm1
movq    8(%1), %%mm0
psadbw 8(%2), %%mm0
paddw   %%mm0, %%mm1
movq    16(%1), %%mm0
psadbw 16(%2), %%mm0
```



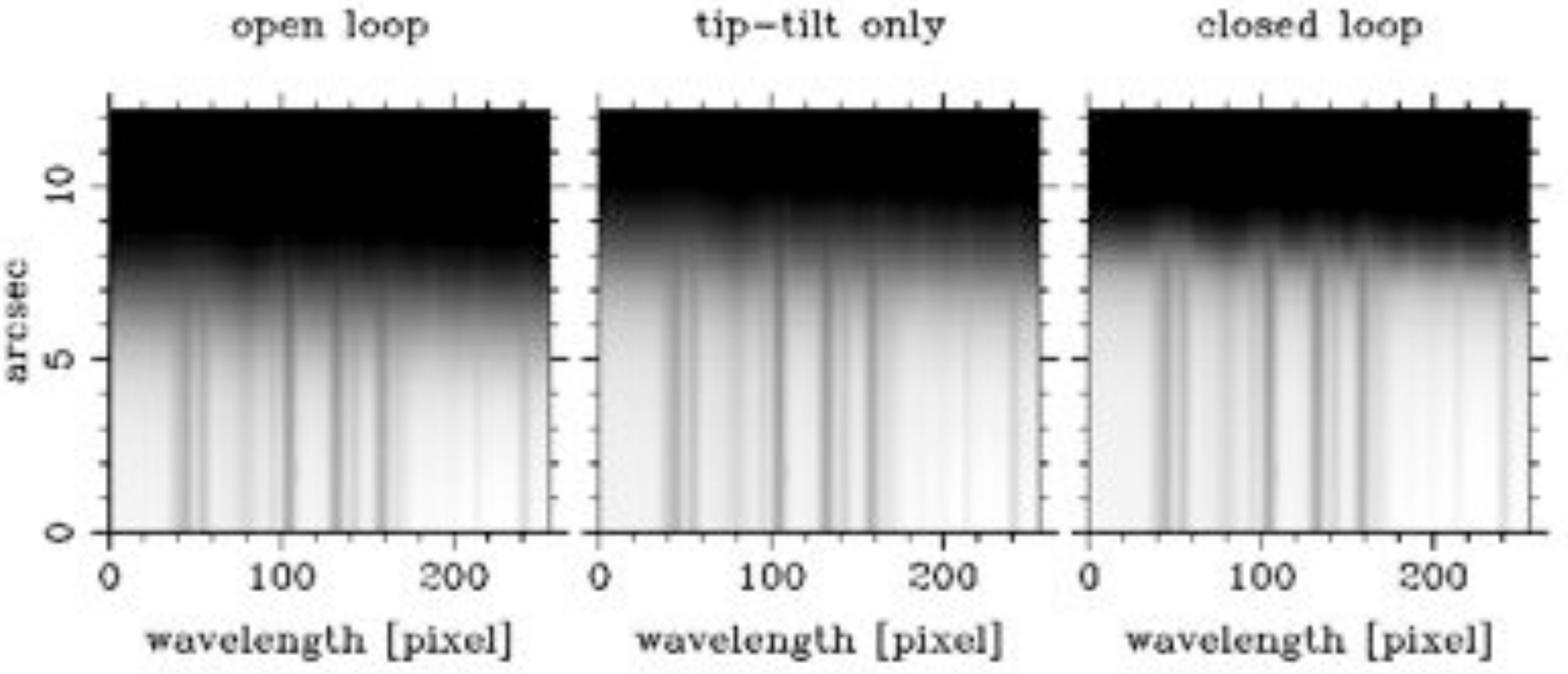
- **`movq`** instruction moves 8 pixels simultaneously into MMX register
- **`psadbw`**: sum of absolute differences of 8 pixels with 8 pixels of reference, every 2.5 clock cycles
- But Pentium III can only load 1 byte per clock cycle (on average)
- Performance is limited by I/O limit, not by processing power!

Jan. 22, 2003, First Thermal IR Light



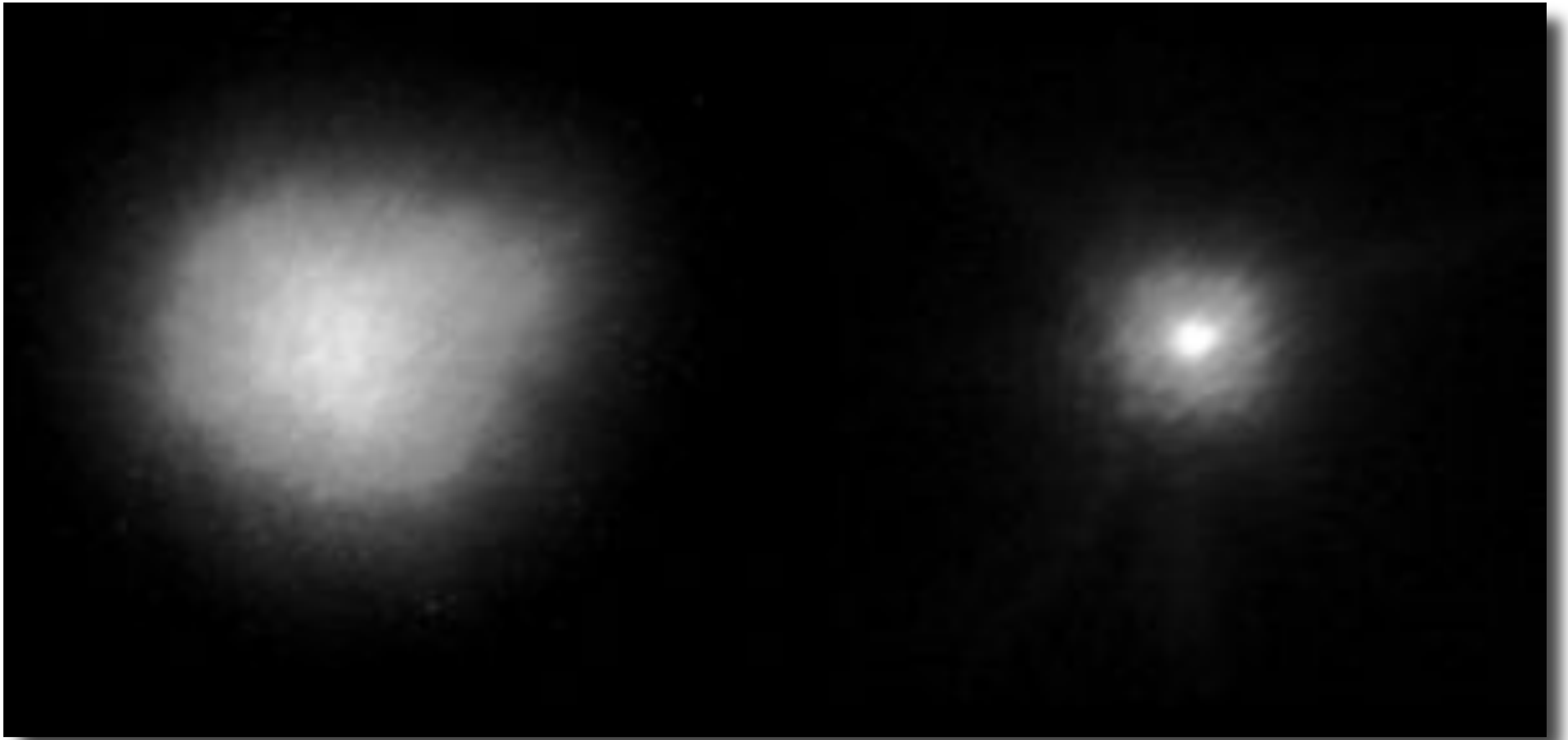
- Median seeing conditions
- 4.8 µm imaging of sunspot close to limb, 0.8 arcsec diffraction limit
- Wavefront sensing at 900 nm
- 955 Hz update rate, 107 subapertures

Average CO Limb Emission



- Below median seeing conditions
- 4.8 μm spectra of CO emission at limb, 0.8 arcsec diffraction limit
- Wavefront sensing at 900 nm
- 955 Hz update rate, 100 subapertures
- Integrated over 30 frames, about 20 seconds in time

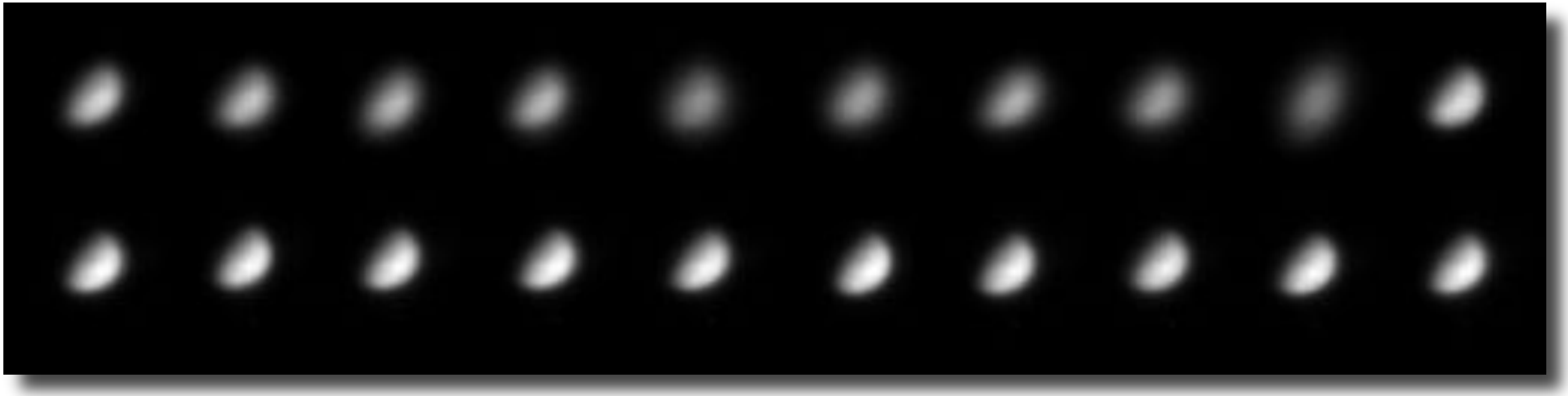
Solar AO Used at Night: Vega



Keller and Plymate, 2 March 2005

- FWHM reduced from 0.7 to 0.17 arcsec

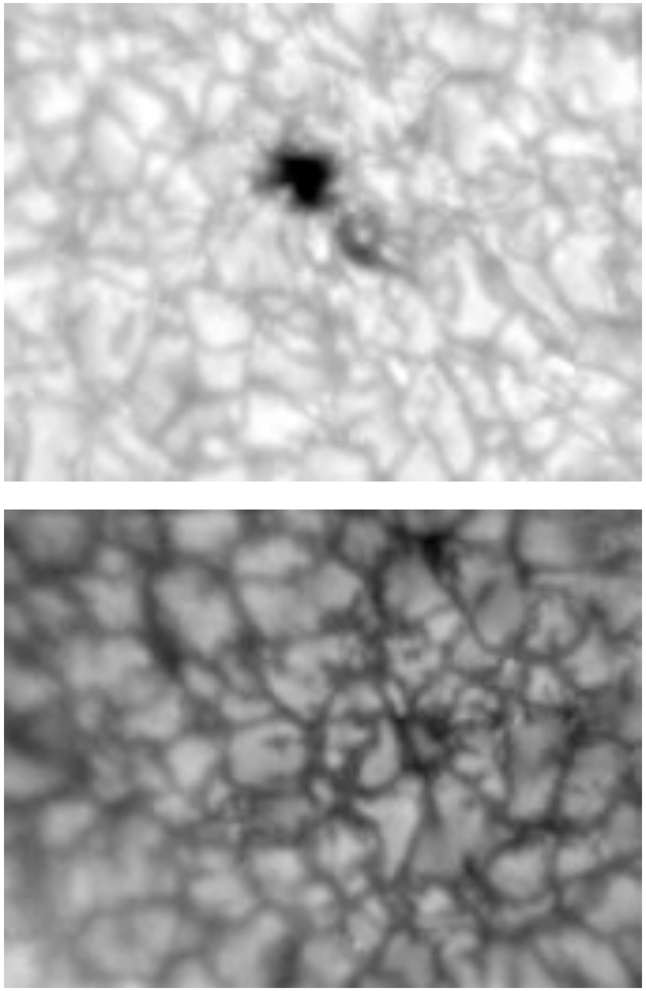
Mercury During the Day



Keller and Plymate, 9 March 2005

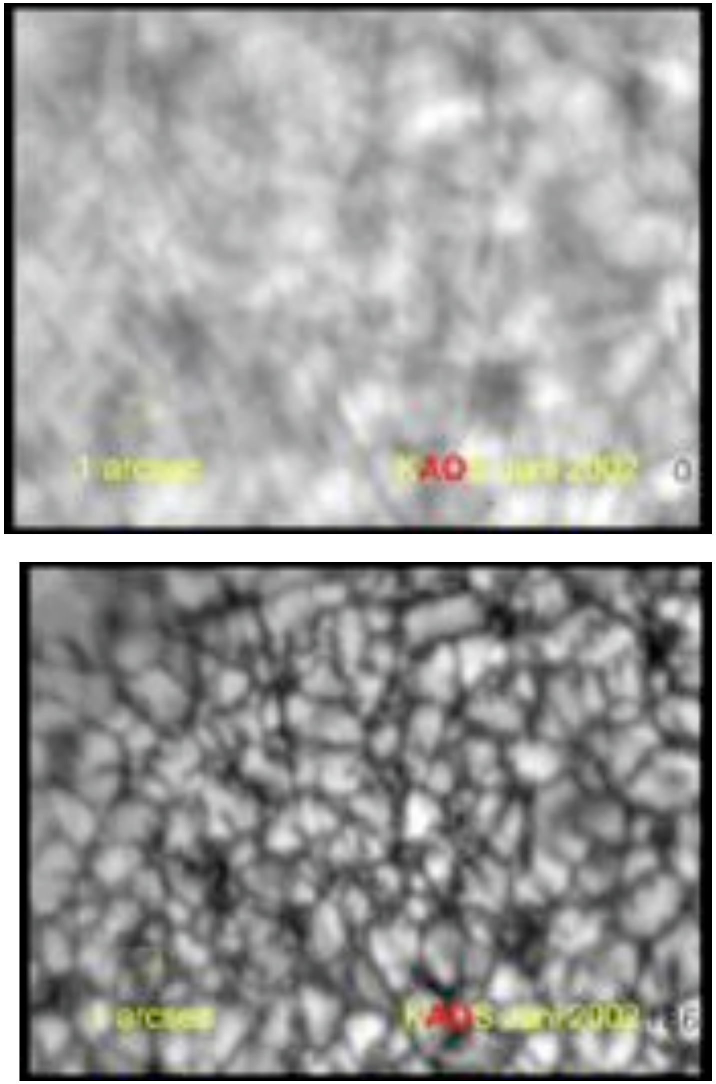
- requires sky background subtraction
- consistent high resolution, ideal for integral field spectroscopy
- two Mercury space missions

AO76 at Dunn Solar Telescope

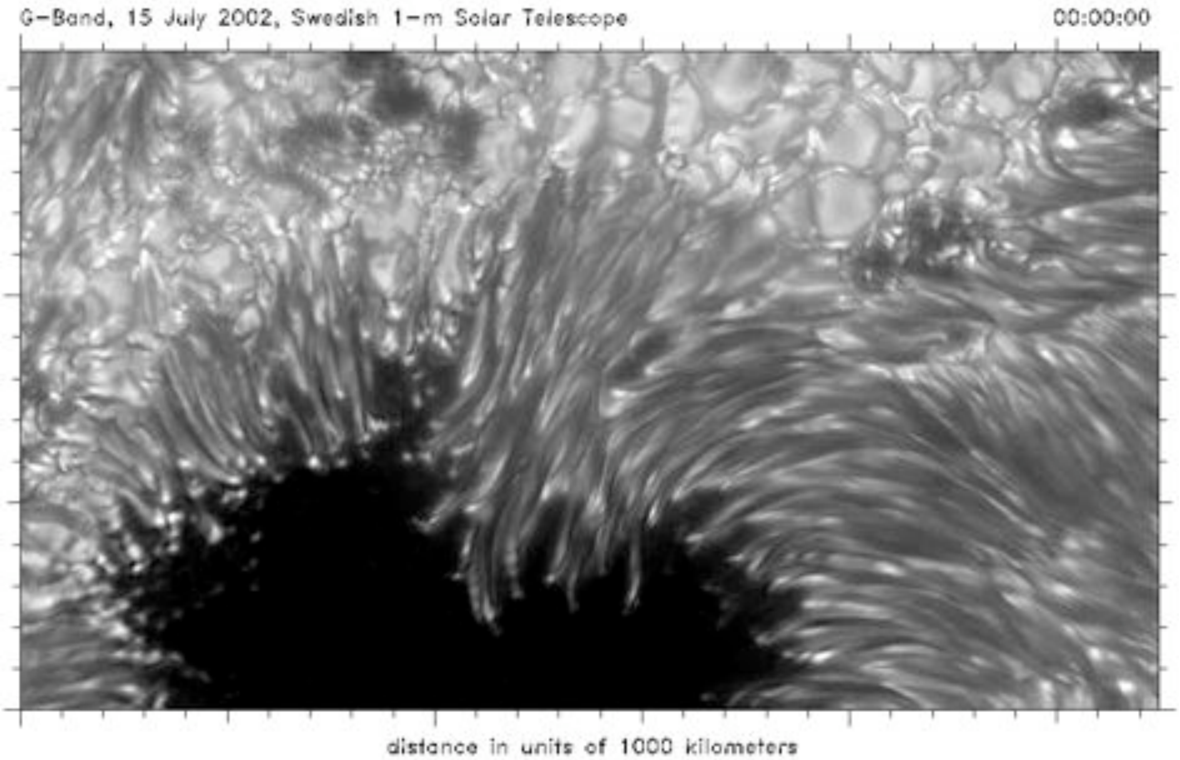


Rimmele and
Richards

KAOS at 70-cm VTT in Tenerife



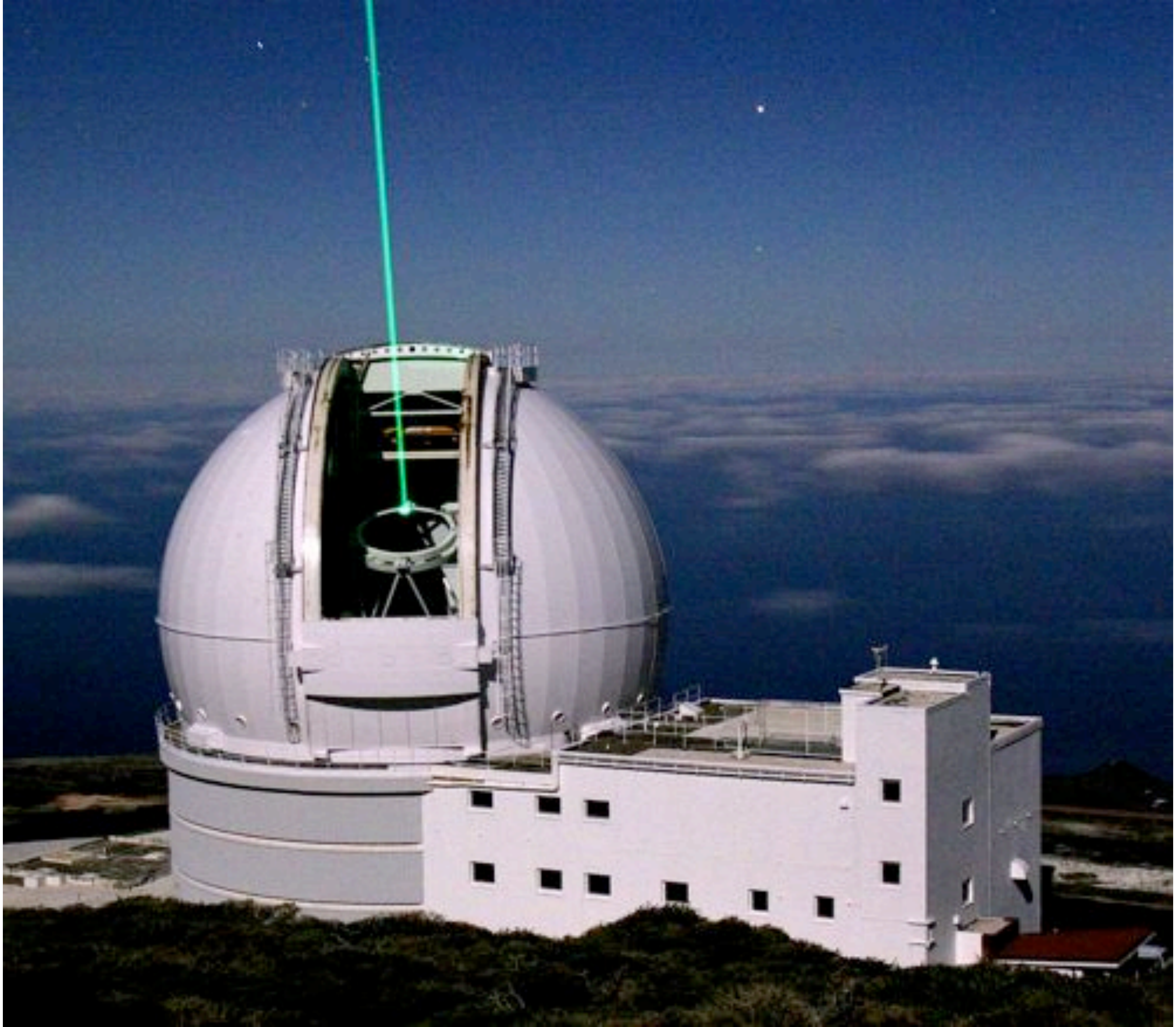
1-m Swedish Solar Telescope



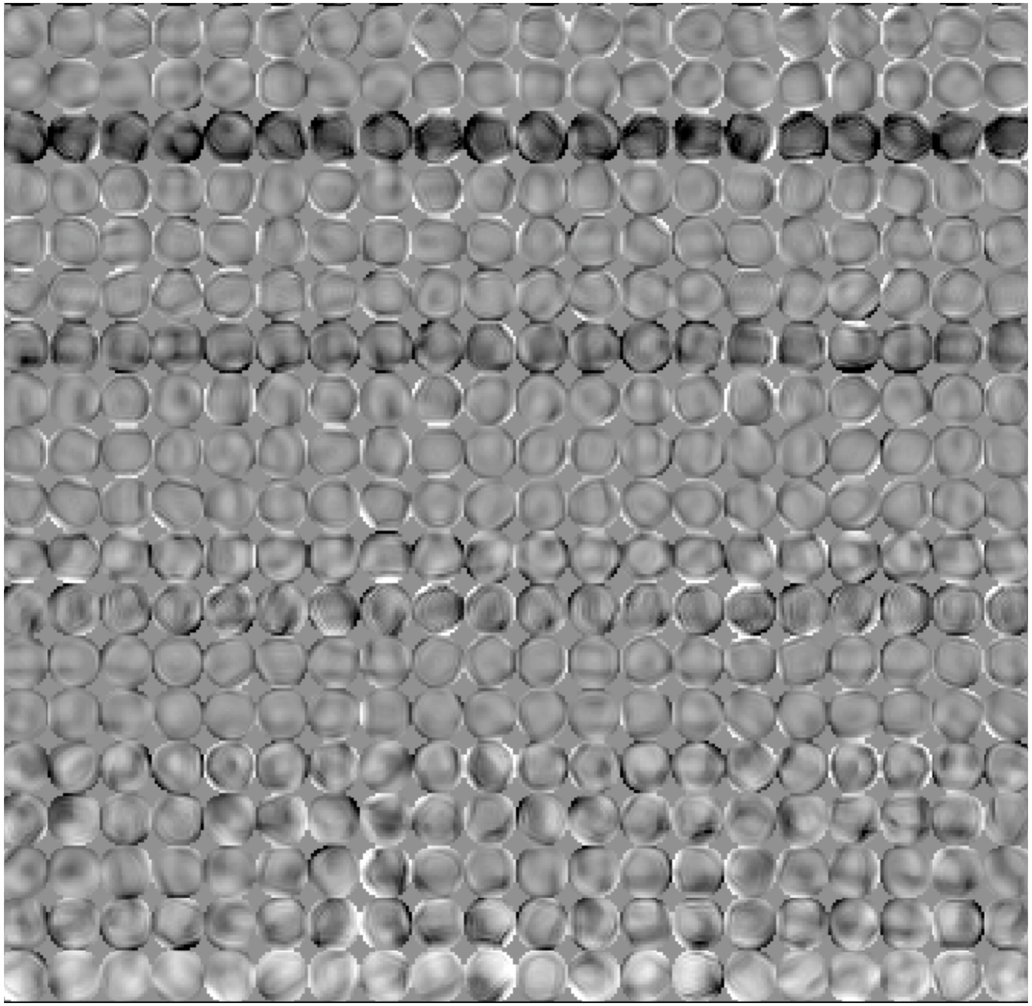
Scharmer, Gudiksen, Kiselman, Löfdahl, Rouppe van der Voort

Laser Guide Star

- Isoplanatic patch is relatively small (~10 arcsec)
- Most areas on the sky do not have adequately bright guide star within isoplanatic patch
- Artificial stars:
  - Excite sodium layer at about 90 km
  - Rayleigh scattering in first few km

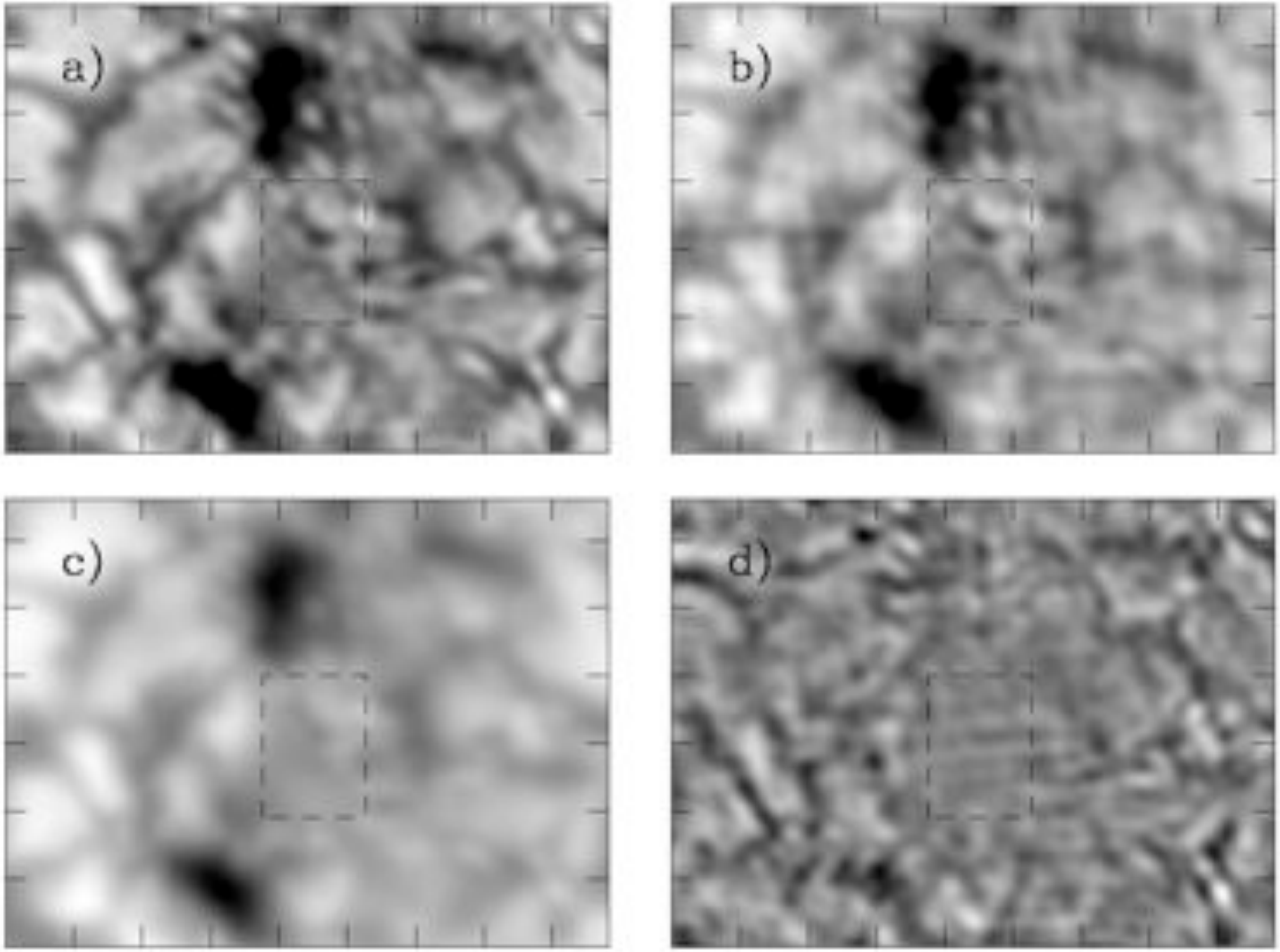


Wavefront Estimates



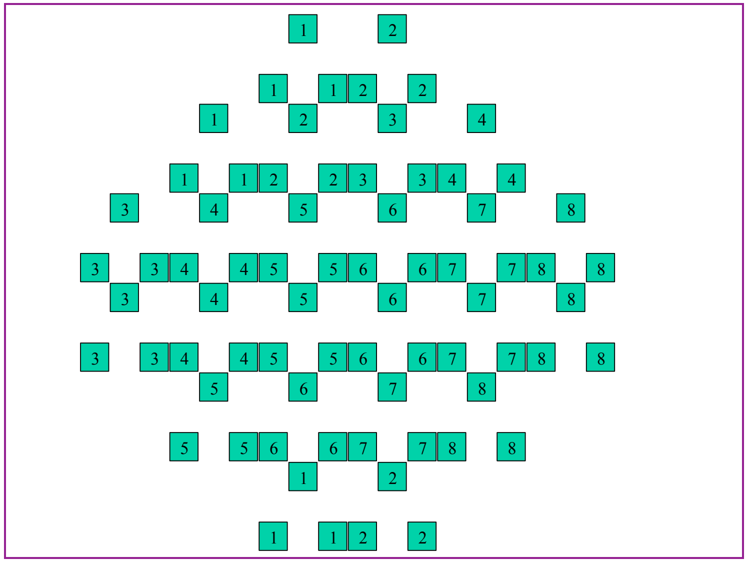
- Reconstruction occurs on small segments
- Segment size comparable to isoplanatic patch
- Wavefront is estimated for each segment
- Object estimates of segment are combined into a single image

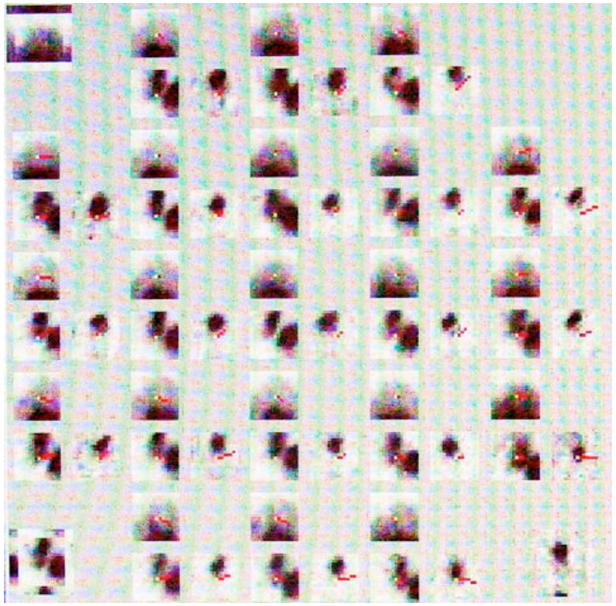
Isoplanatic Patch Size



MCAO at the National Solar Observatory

- Proof of concept experiment in 2004
- 3 guide structures, tomographic approach
- Uses existing AO76 hardware (97 actuator Xinetics mirror, 76 subapertures)
  - 2 DMs at 0 km, 2 km
  - Flexible WFS camera accommodates multiple fields per subaperture (fewer subapertures, 24 MCAO vs. 76 conv. AO)

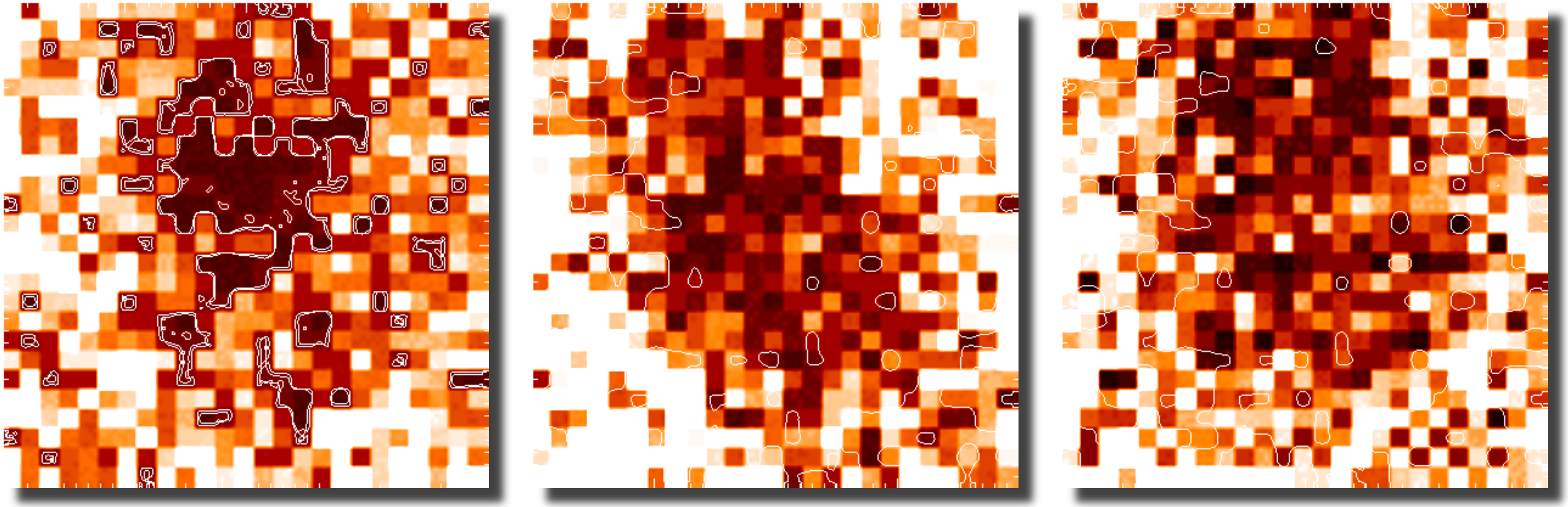




Rimmele et al.

Results of NSO/DST Tests

Residual image motion roughly measures AO correction in FOV (~90”)



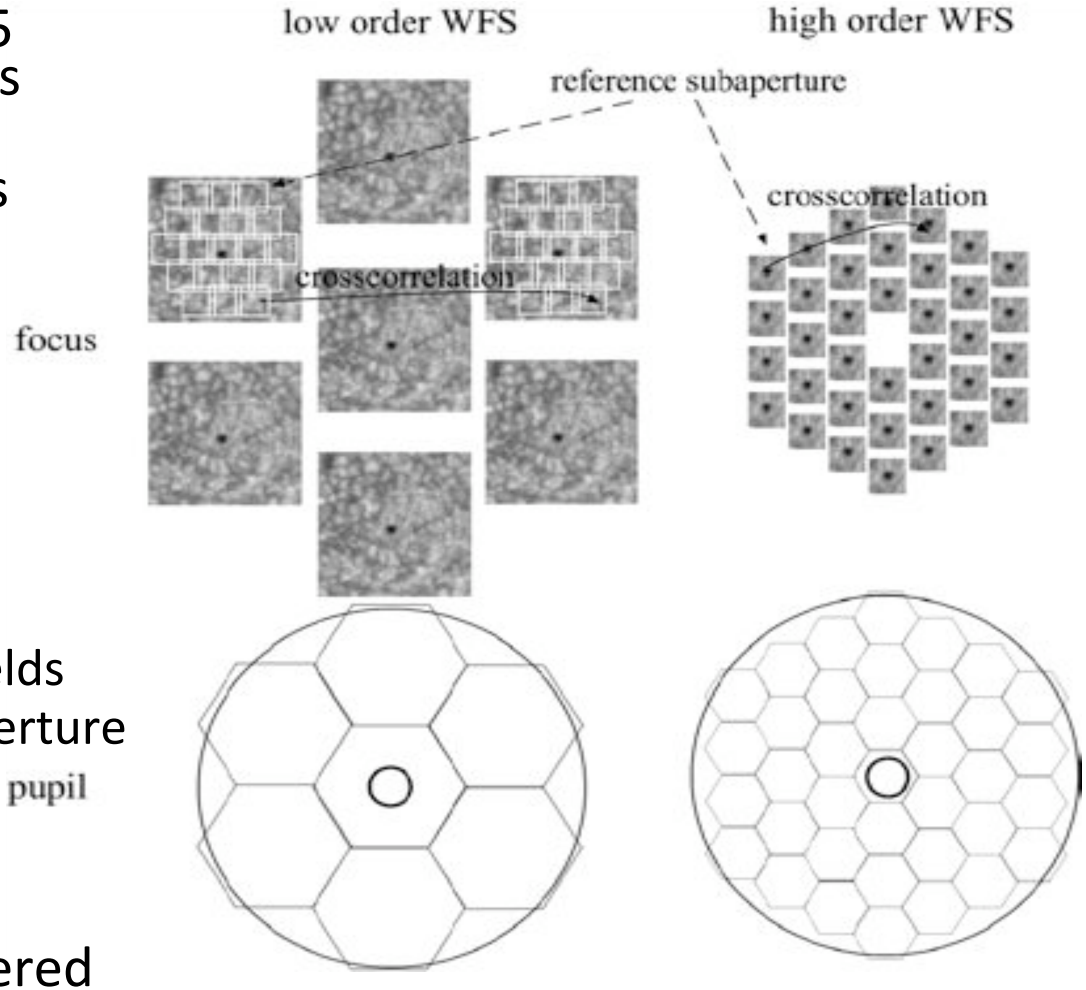
Conventional AO MCAO GLAO

Rimmele et al.

- MCAO control loop needs work – far from optimal
- 2nd DM at a higher conjugate (>10km) – re-work optical setup
- More detailed performance analysis – comparison to model predictions
- Excellent test-bed for MCAO development

Kiepenheuer Institute for Solar Physics MCAO

- Conventional AO with 35 actuator LaPlacian Optics
- Permanent MCAO setup in Optics Lab with 2 DMs
- 0, 12 km conjugate
- High Order WFS:
  - 36 subapertures
  - single 12“ field
  - 35 cross correlations
  - 70 shift values
- Low Order WFS:
  - 7 subapertures, 20“ fields
  - 19 subfields per subaperture
  - 133 cross correlations
  - 266 shift values
- Loop closed in 2003
- Moving shadows discovered

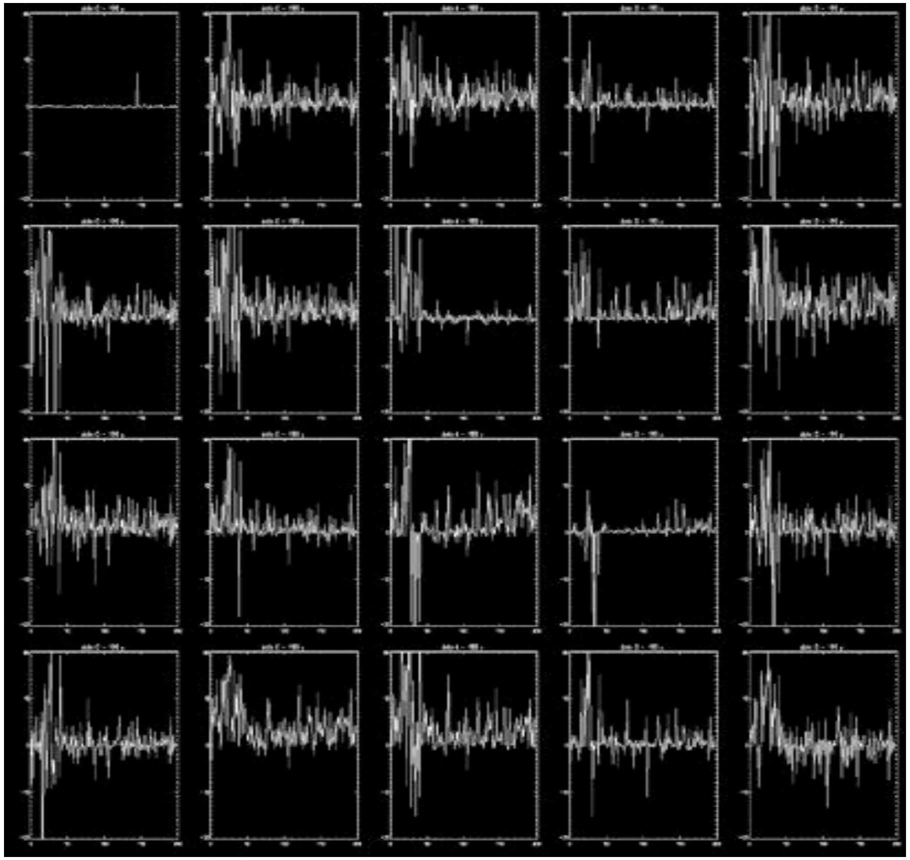


Berkefeld et al.

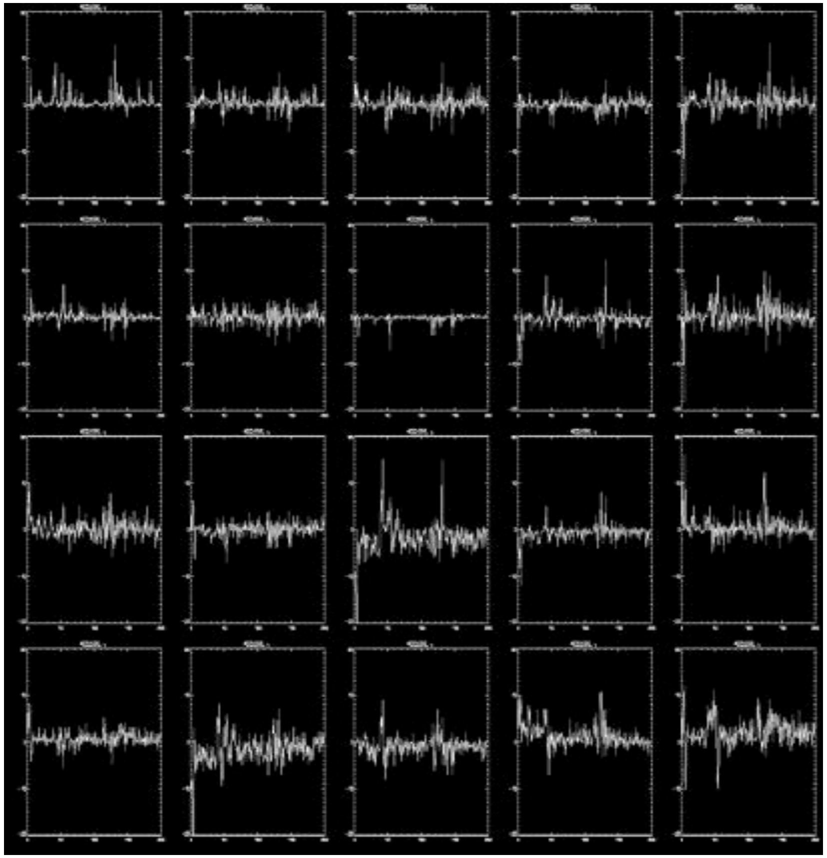
KIS MCAO Performance

Subfield image jitter

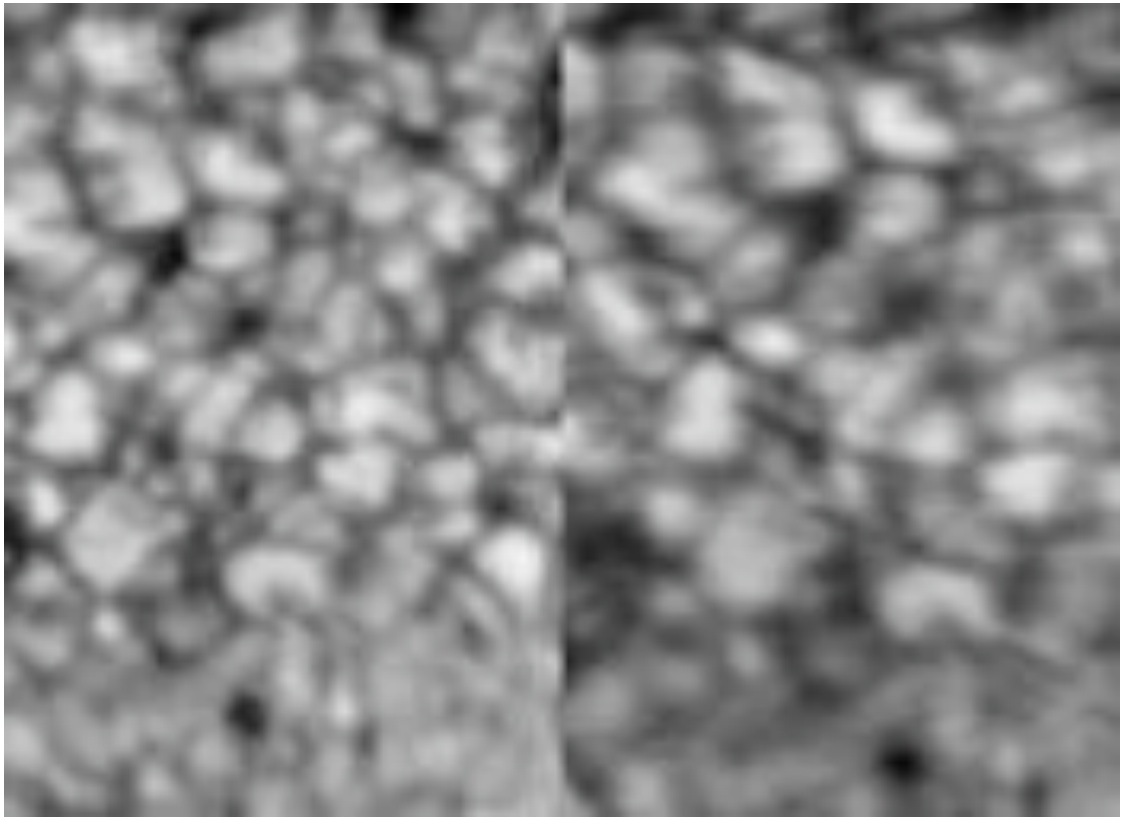
MCAO off : rms = 0.2 arcsec



MCAO on : rms = 0.09 arcsec



Low-order AO Properties



With AO

Without AO

- 76-cm telescope aperture
- median seeing: 7 cm at 600 nm
- 24 subaperture Shack-Hartmann
- 80 by 80 PixelVision camera
- 1600 Hz frame/update rate
- 97-element Xinetics mirror