

The image shows the McMath-Pierce Solar Telescope at night. The telescope is a large, dark, cylindrical structure with a prominent horizontal section. It is illuminated from below, creating a strong orange glow. The background is a dark night sky filled with numerous bright, diagonal streaks of light, representing star trails. The overall scene is framed by a dark border.

McMath-Pierce Active & Adaptive Optics

**Christoph Keller, Claude Plymate, Mark Ammons
National Solar Observatory, Tucson**

The World's Largest Solar Telescope

Infrared Instruments

- 1 to 5 μm imager and polarimeter (1 to 2.3 μm)
- 1.56 μm imaging vector polarimeter
- 0.3 to 12 μm grating spectrograph
- 0.3 to 20 μm FTS
- 6 to 15 μm imager (NASA)
- 12 μm vector polarimeter (NASA)



Adaptive Optics is by far the most important improvement that can be made to infrared observations at the McMath-Pierce

New IR Instruments and AO

2000

2001

2002

2003

2004

Aladdin Infrared Array Camera System

▲ *initial system*

▲ *final system*

Infrared Adaptive Optics

▲ *spot, limb, correlation tracker*

▲ *slow AO*

▲ *fast AO*

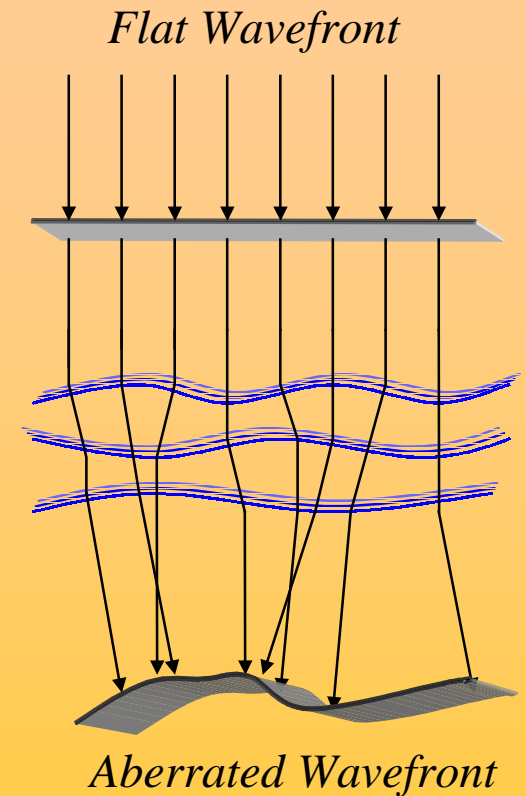
NSO/CSUN IR Polarimeter

Terminology

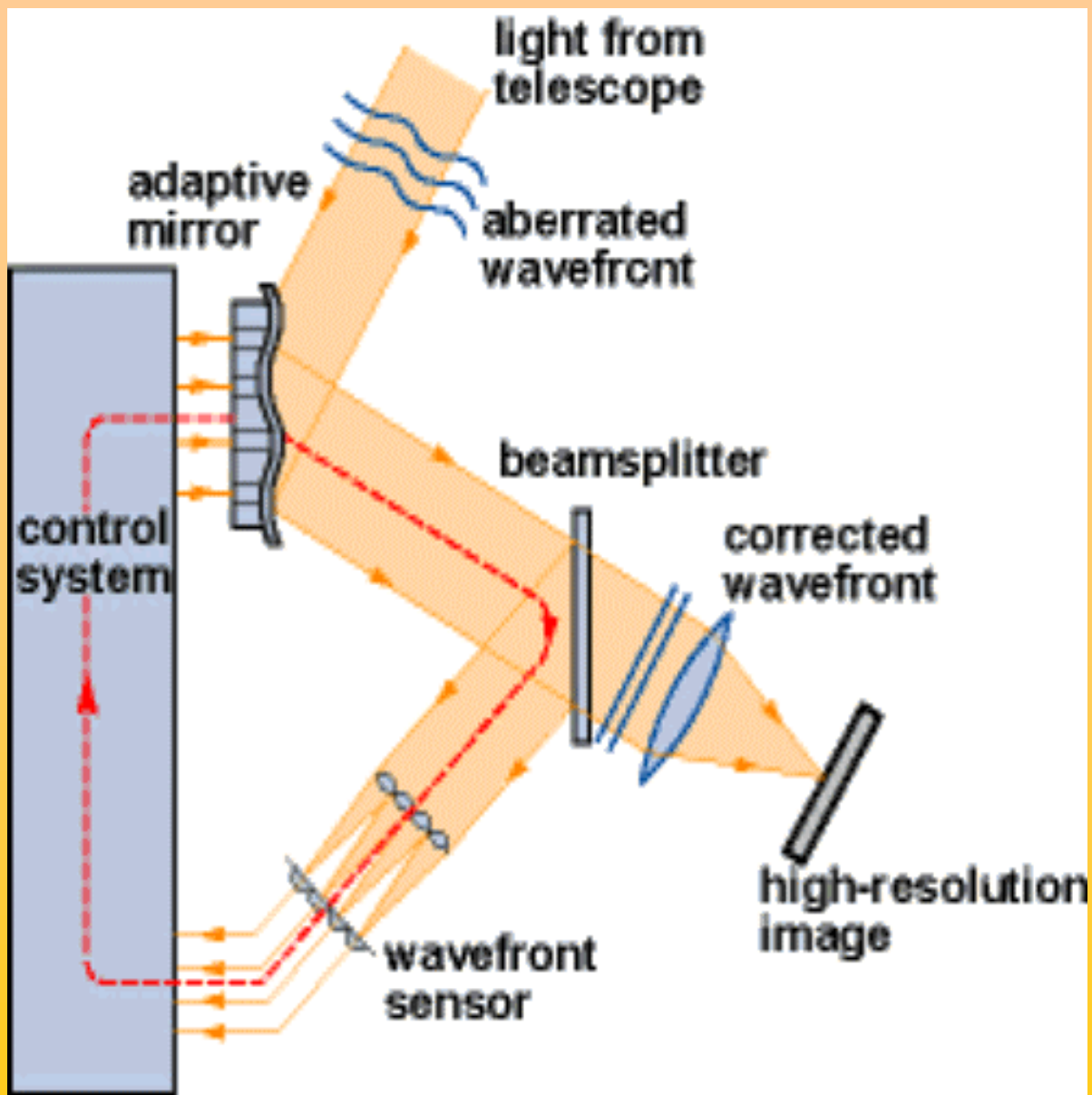
- *Active Optics* = image motion compensation, correlation tracking
- *Adaptive Optics* = focus, astigmatism etc. correction
- r_0 = Fried parameter, diameter of telescope that would be diffraction limited (large = good seeing)
- *Wavefront Sensor* = measures the shape of the incoming wavefront
- *Deformable Mirror* = 'rubber' mirror (surface can be deformed)
- *Actuator* = device acting on mirror that provides one degree of freedom

Atmospheric Wavefront Aberrations

- Waves from distant sources travel in straight lines, providing flat wavefronts for space-based telescopes
- Nonuniform refractive index fluctuation - masses of warm or cold air refract light differently
- Wavefronts cannot be focused into sharp images



General Adaptive Optics Setup



AO Requirements for 1.5-m Telescope

wavelength (μm)	r_0 (cm)	actuators	bandwidth (Hz)
0.5	4	1100	200
1.5	15	78	50
2.3	25	28	30
10.2	150	2	5

Assumes:

- Kolmogorov statistics
- Single seeing layer with constant wind speed

Tip-tilt is sufficient!

Index of Refraction of Air

- Wavelength dependence of index of refraction given by

$$n(\lambda) = 1 + (287.5 + \frac{1.34}{\lambda^2 [\mu m]}) 10^{-6}$$

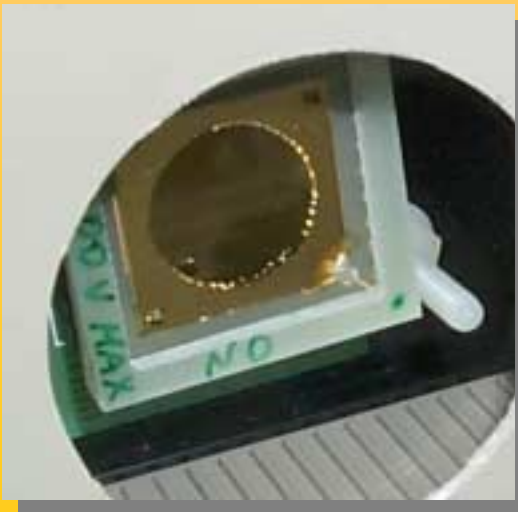
- 1 K temperature difference changes n by $1 \cdot 10^{-6}$
- Air is 'achromatic'
- Wavefront aberrations are independent of wavelength
- Measure wavefront in the visible and correct in the infrared
- Use cheap cameras in the visible for wavefront sensing instead of expensive infrared cameras

Low-Cost Approach in the Infrared

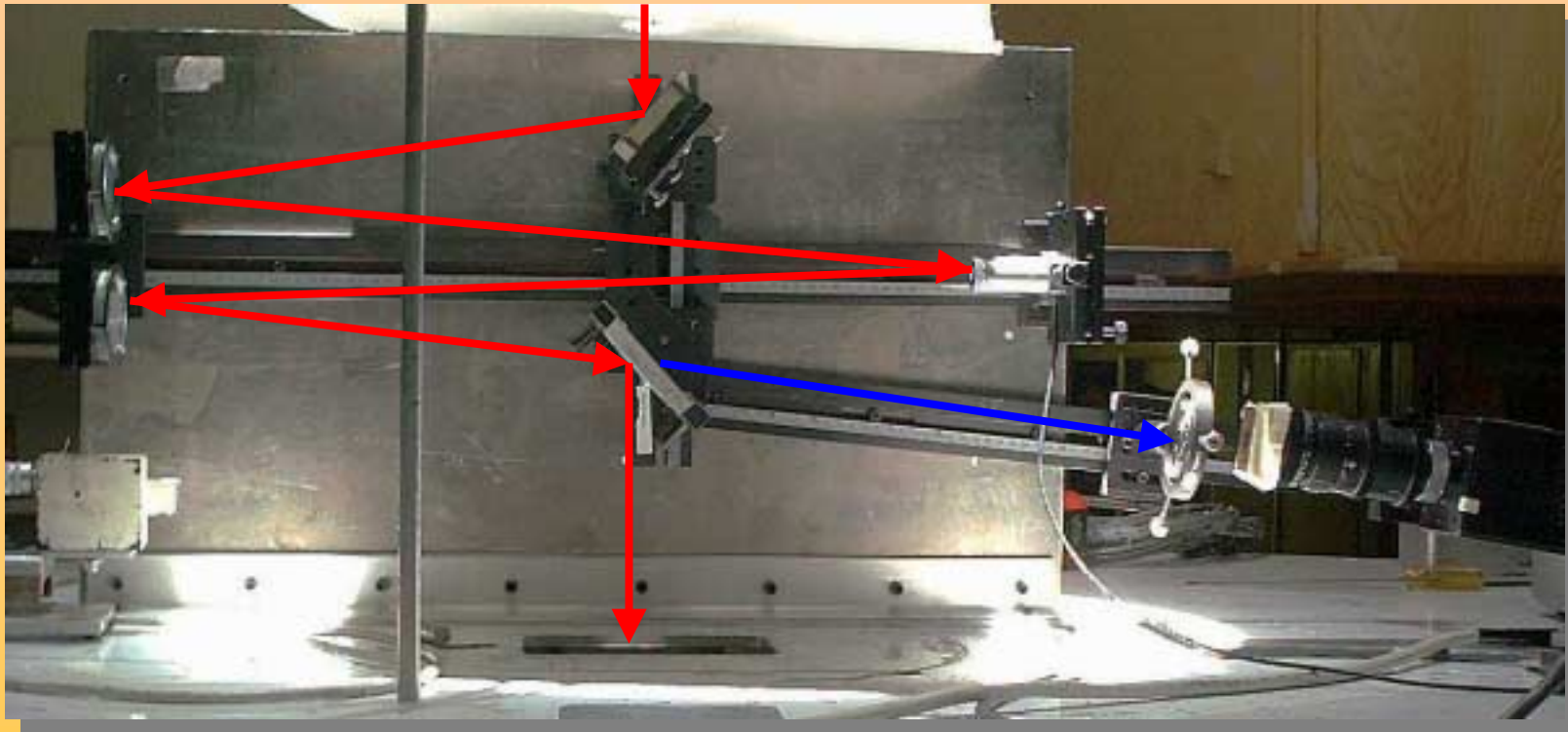
Low-cost, commercial off-the-shelf parts for a complete AO system have been purchased for less than \$25k and require minimal software effort:

- all-reflective, gold-coated off-the-shelf optics
- PiezoJena fast tip-tilt stage with large angular range
- Flexible Optics micromachined deformable mirror with 37 actuators
- DALSA 1kHz frame rate 256 by 256 CCD camera
- Industrial PC with 1 GHz Pentium III processor and Coreco PC-Dig digital frame grabber running Linux RedHat 7.1

Provide a flexible system for science, not a research and development system

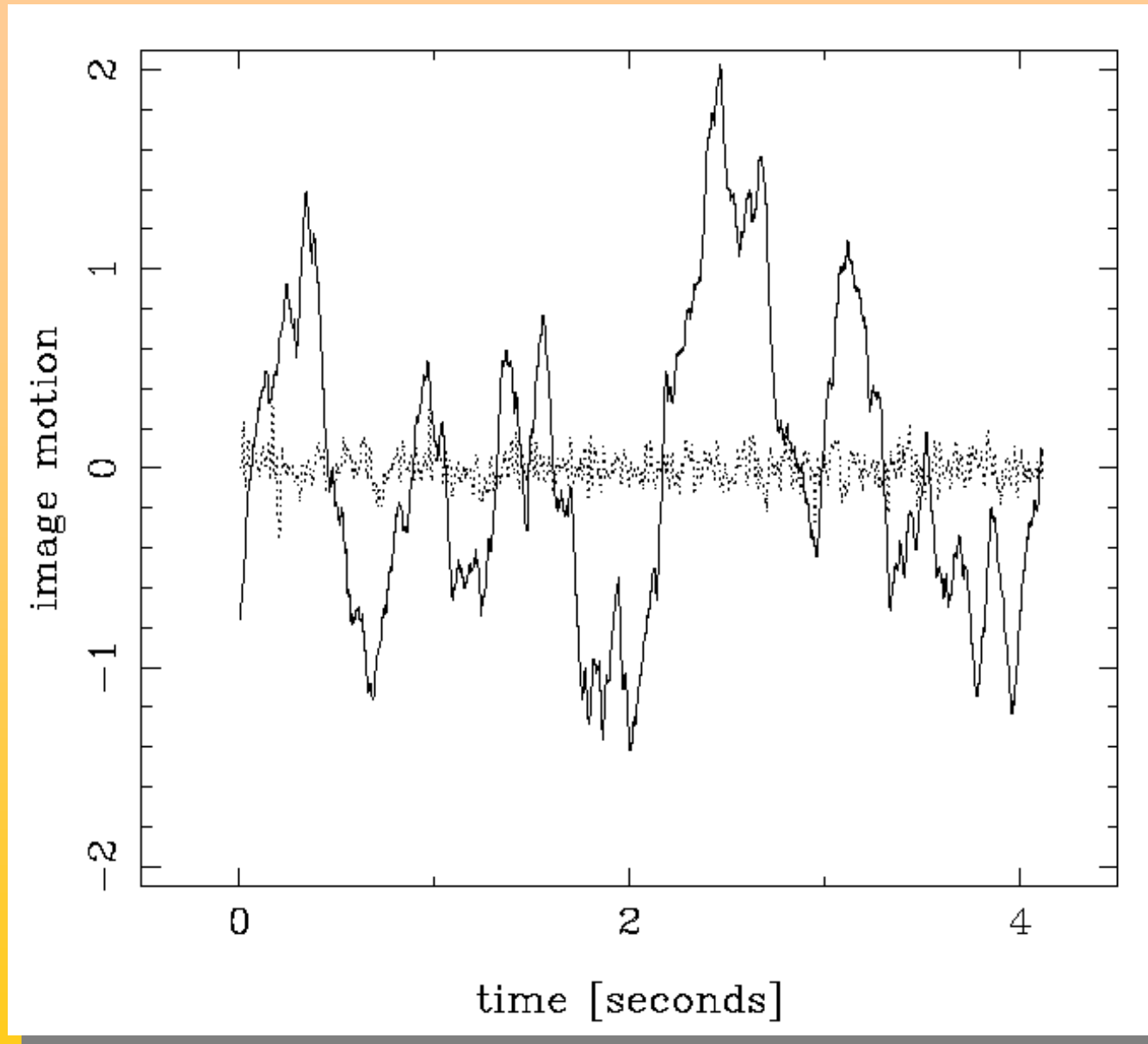


Tip-Tilt Correction: Universal Tracker

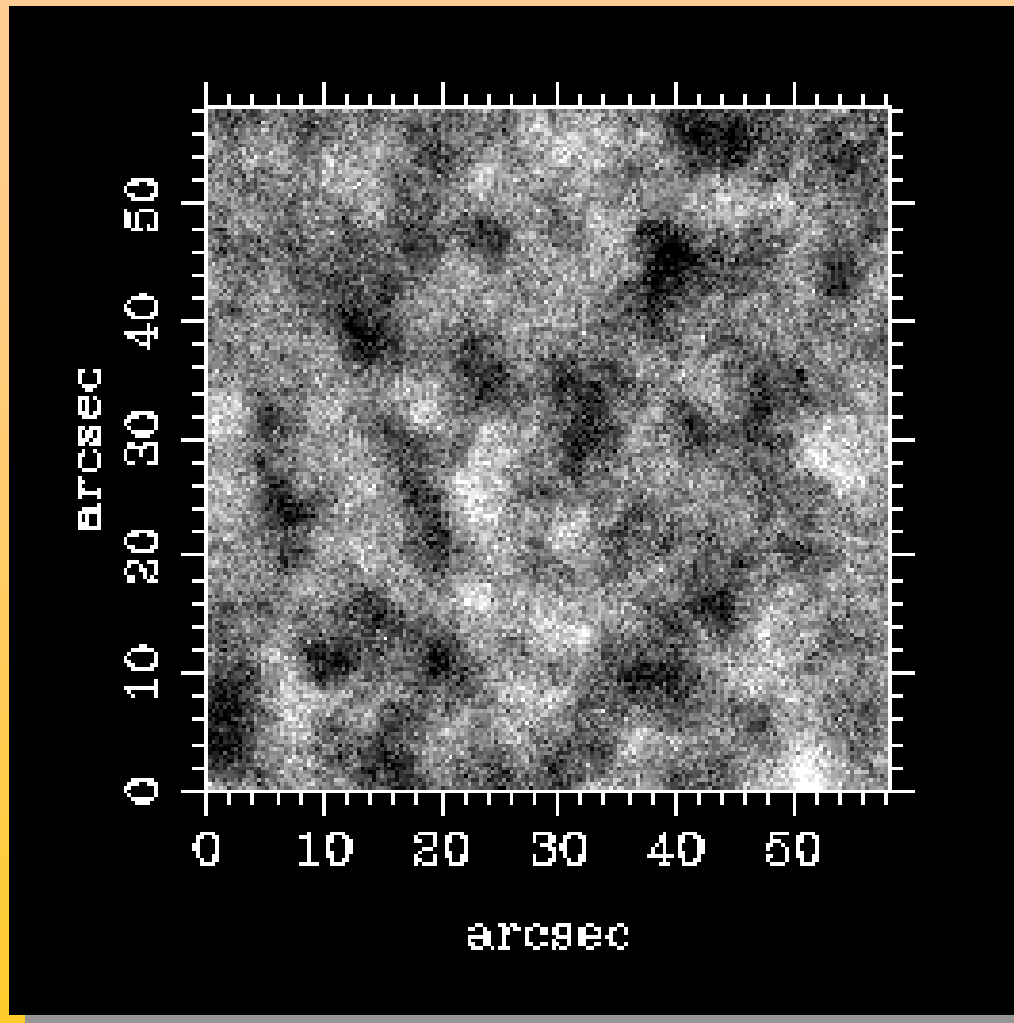


- General-purpose tip-tilt correction with three modes:
 - Digital quad-cell for sunspots
 - Digital limb tracker for various limb position
 - Correlation tracker
- Reference can be moved digitally to scan image across slit
- Current update rate is 500 Hz, corrects to about 50 Hz
- Used for scientific observations by users since April 1, 2002

Limb-Tracking Performance

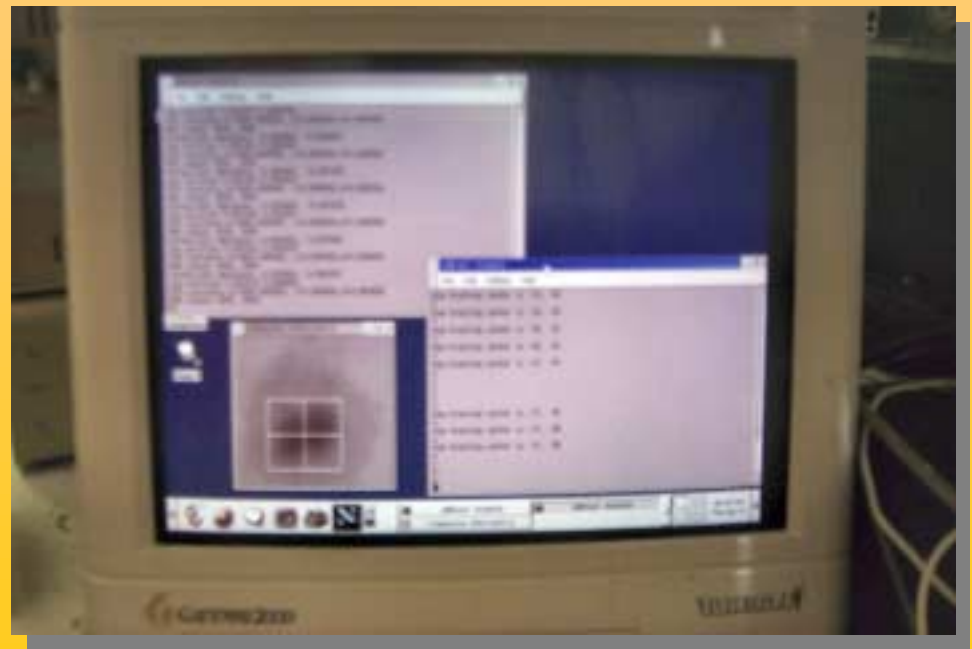


Correlation Tracking



- 256 by 256 pixel 950 frames/s CCD camera
- Sequence spans less than 1 second
- Telescope was moved quickly during this sequence
- Pattern with an rms contrast of about 1% with a scale larger than granulation
- Motion of pattern is easily seen and can be tracked on

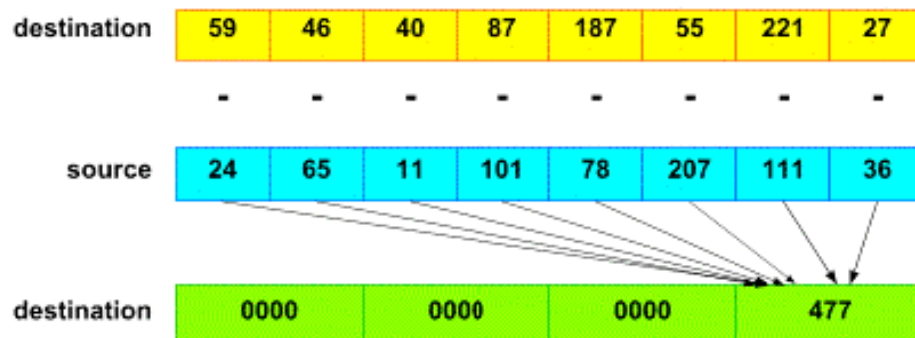
- Linux, RedHat 7.1 on 1GHz Pentium III industrial PC
- Soft realtime scheduling uses standard Linux kernel, no change in software needed
- GCC with inline assembler code for time-critical areas
- Open-source driver for PC-Dig frame grabber
- Pentium III MMX and SSE instructions provide parallel processing on 8 pixels for dark and flat corrections and correlation calculation



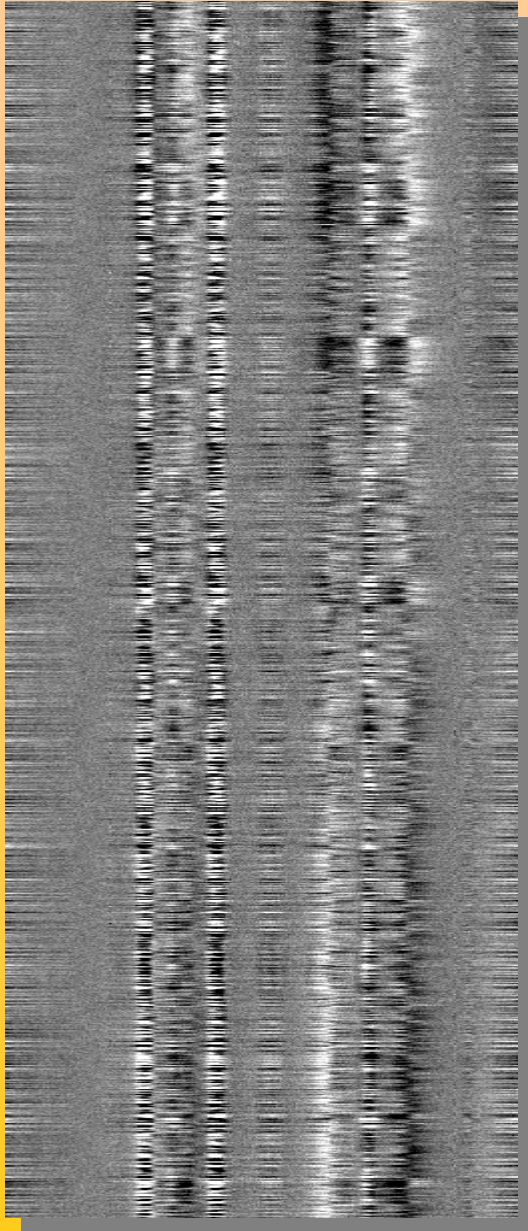
Code Snippet

```
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 instruction calculates sum of absolute differences of 8 pixels with 8 pixels of reference
- psadbw instruction can be scheduled every 2.5 clock cycles (1 ns for 1GHz)
- But Pentium III can only load 1 byte per clock cycle (on average)
- Performance is limited by 1GByte/s I/O limit, not by processing power

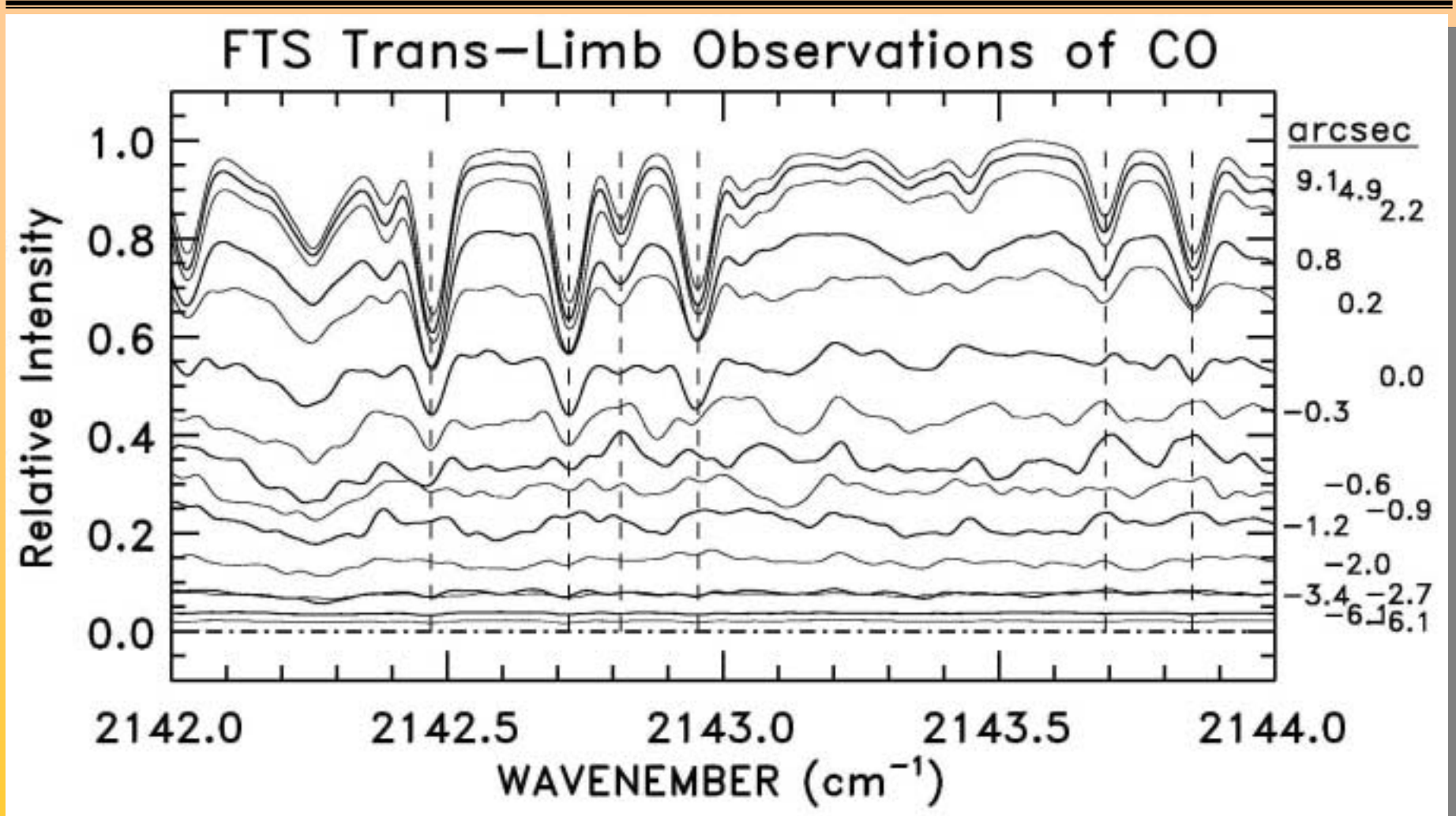


Science, Part 1



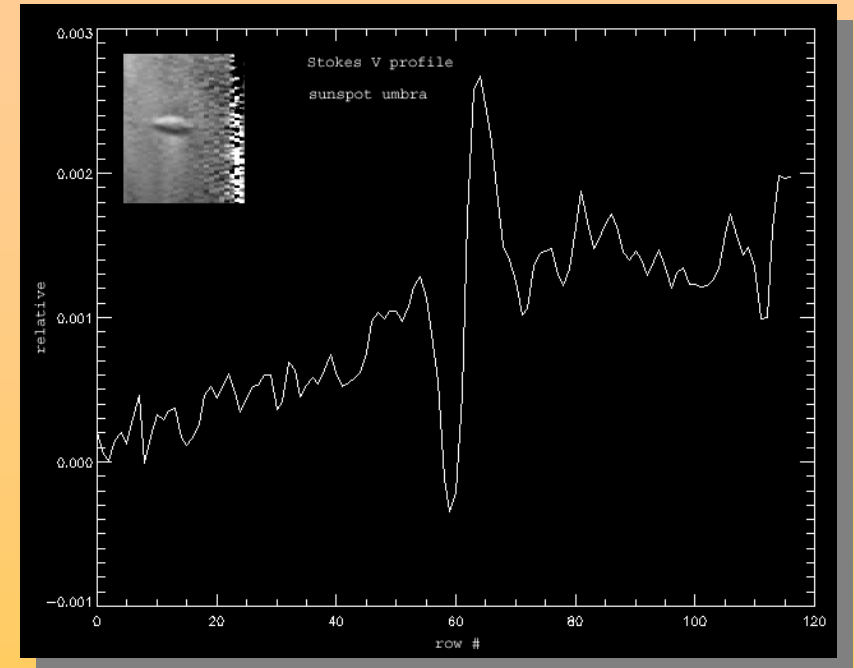
- Umbral oscillations in OH lines at 1.56 μm
- CSUN/NSO IR Camera
- Observations and image courtesy Matt Penn

Science, Part 2



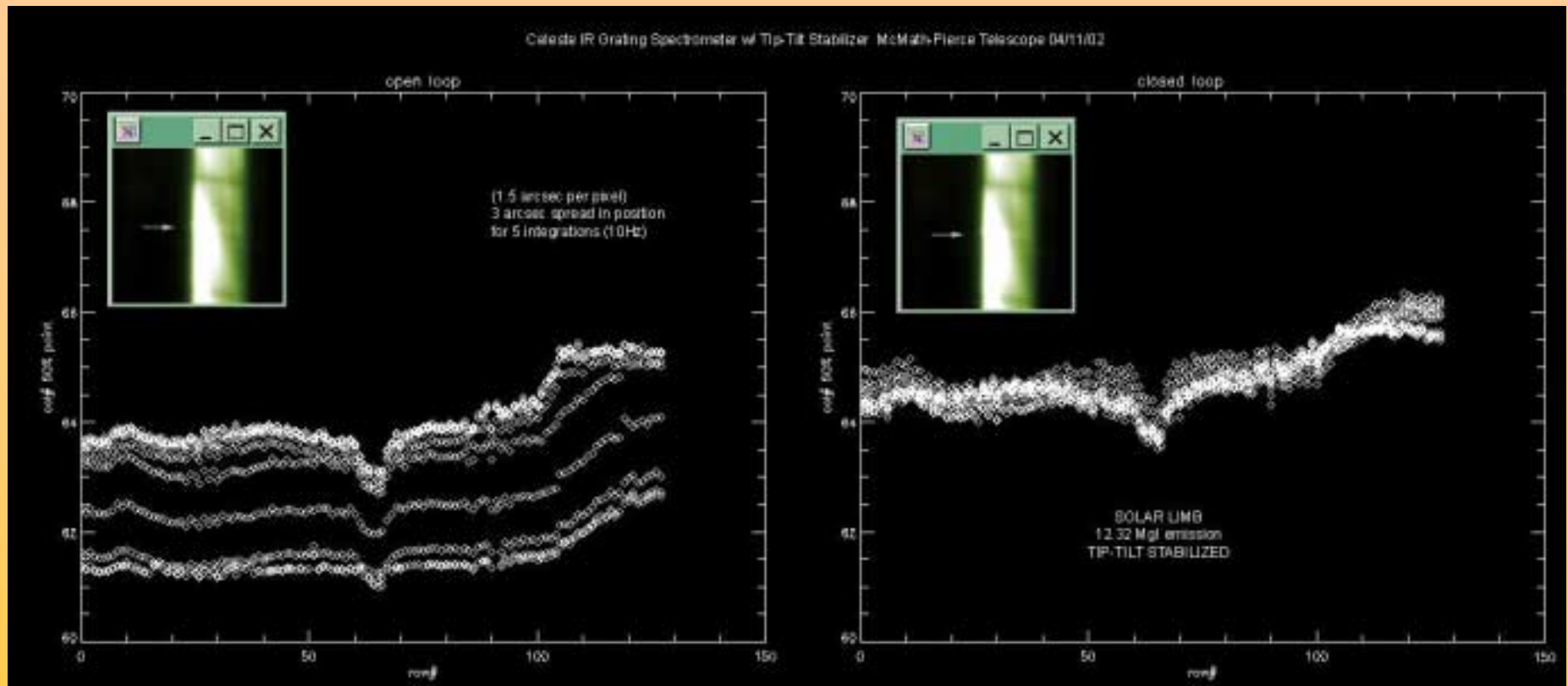
- First FTS observations of CO limb emission at $4.8 \mu\text{m}$
- Observations and figure courtesy Tom Ayres

Science, Part 3a



- NASA Goddard thermal infrared spectrograph and polarimeter (Celeste) combined with tip-tilt system
- Observations and pictures courtesy George McCabe

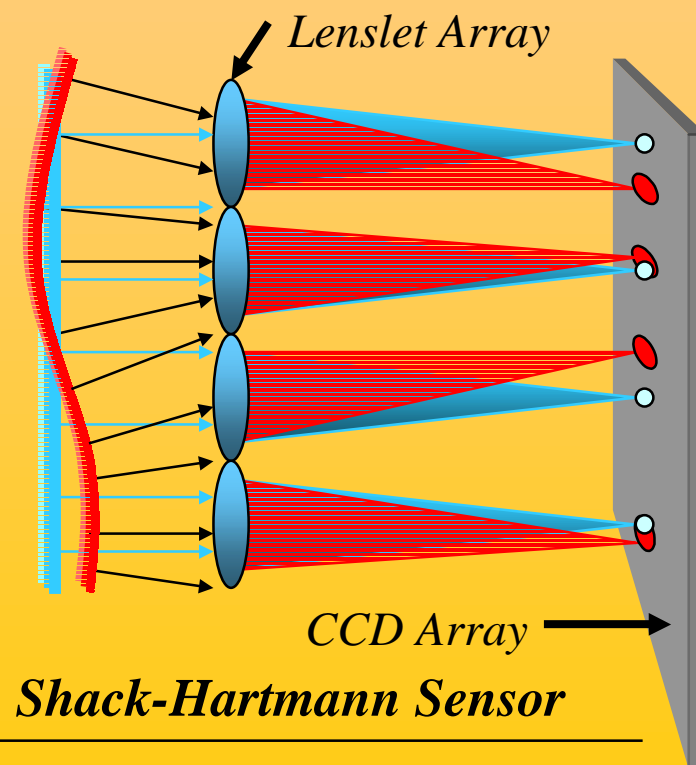
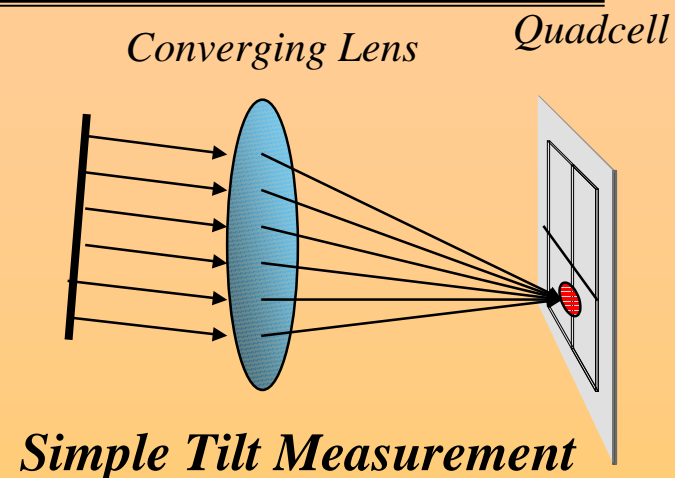
Science, Part 3b



- Limb extension of Mgl line at 10Hz with and without tip-tilt stabilization
- Graph shows position of limb as a function of wavelength
- Smaller numbers mean further away from sun center
- Observations and picture courtesy George McCabe

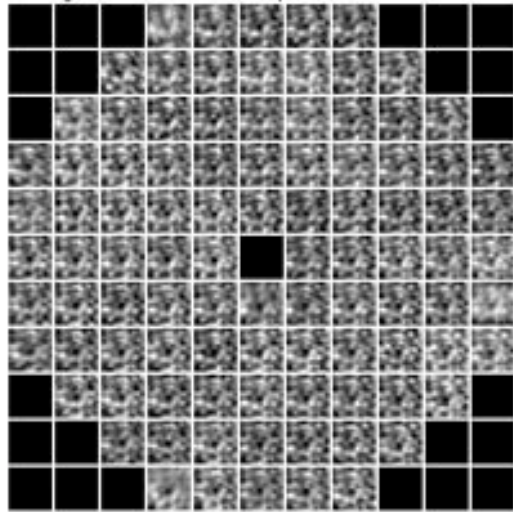
Shack-Hartmann Wavefront Sensor

- 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
- Use numerical techniques to find the wavefront that would produce the set of derivatives

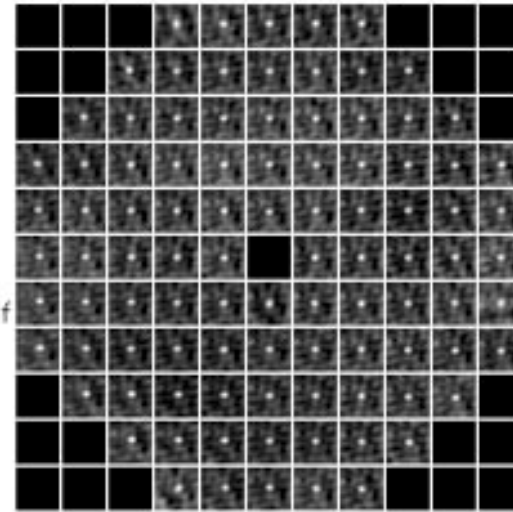


Correlating Shack-Hartmann

Array of subaperture images



2-d Crosscorrelations



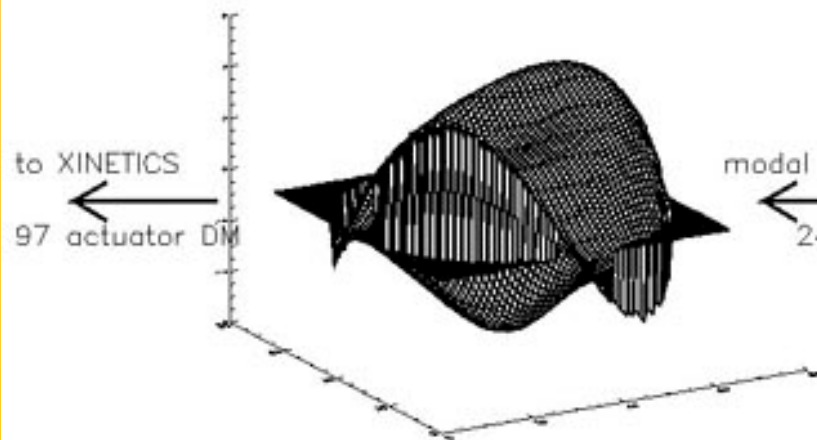
compute cross-

correlations
using off-the-shelf
DSP processors

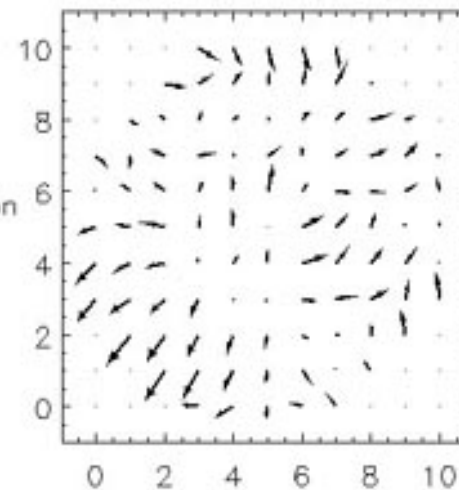


Wavefront

Slope Vectors

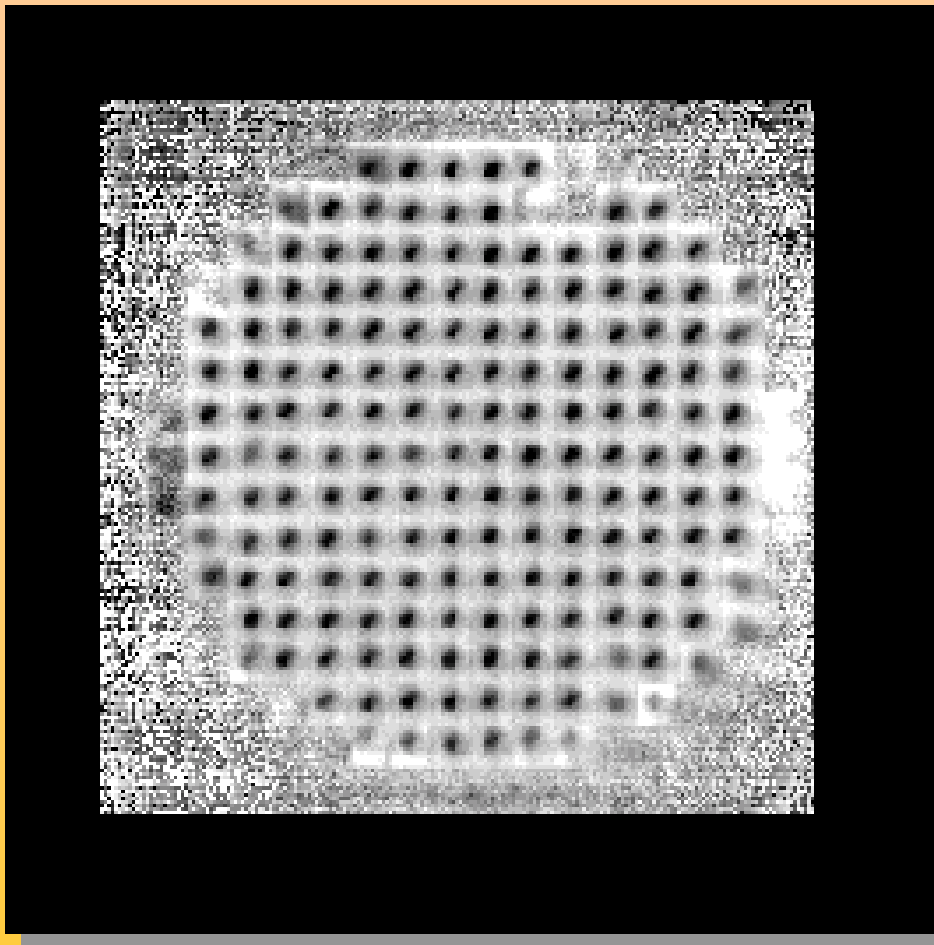


modal reconstruction
24 modes



Courtesy
Thomas
Rimmele

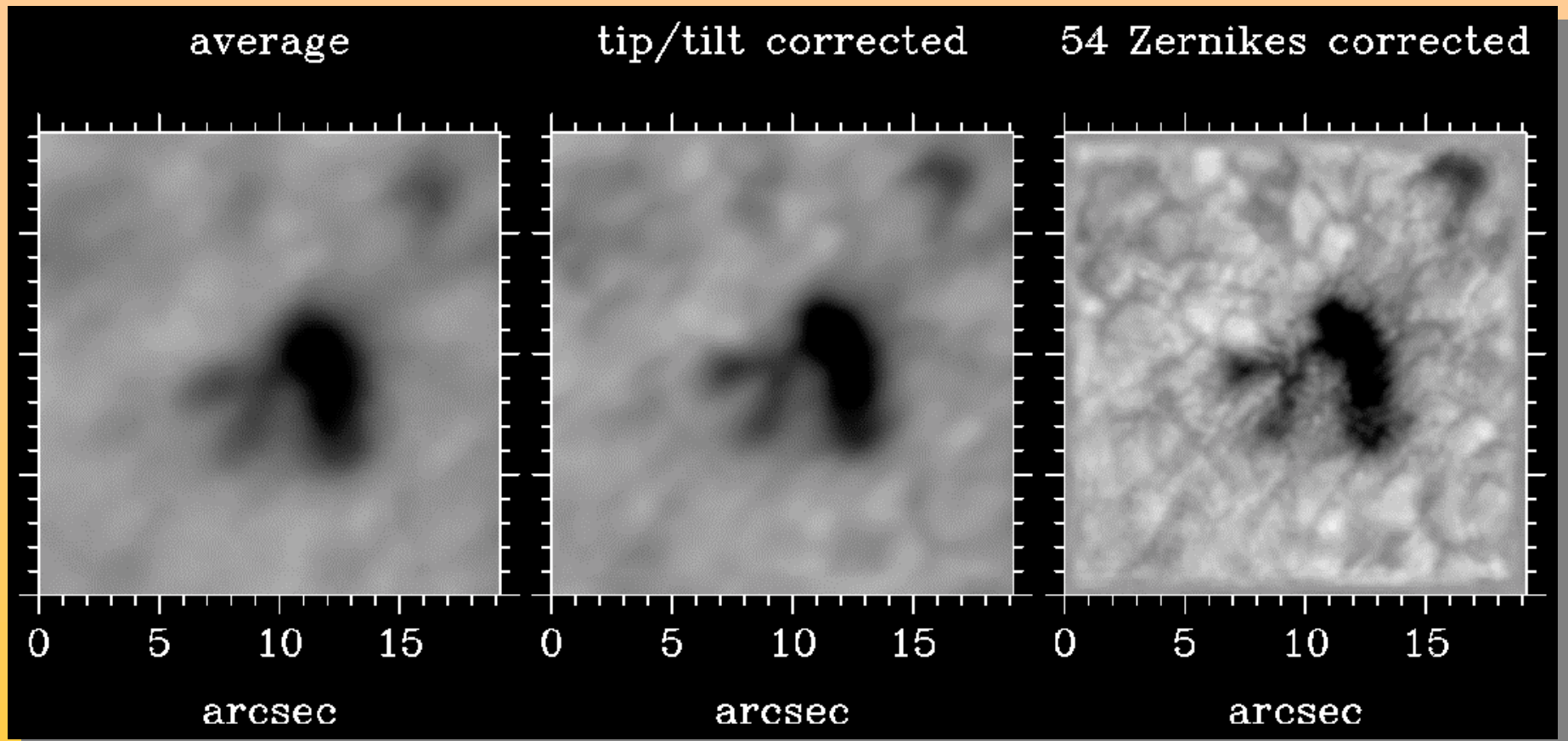
Shack-Hartmann Wavefront Sensing



Prototype wavefront sensor data of sunspot recorded at 500 Hz

- High-order wavefront sensing at $0.9 \mu\text{m}$ to use 'cheap', fast CCD camera instead of expensive IR camera
- Requires about 200 subapertures to adequately determine wavefront
- This is about 10 times more than any other solar AO system
- Pentium III `psadbw` provides
 - 256 by 256 pixel correlation tracking at $>500 \text{ Hz}$
 - wavefront sensing at $> 1 \text{ kHz}$ with 200 8 by 8 pixel subapertures

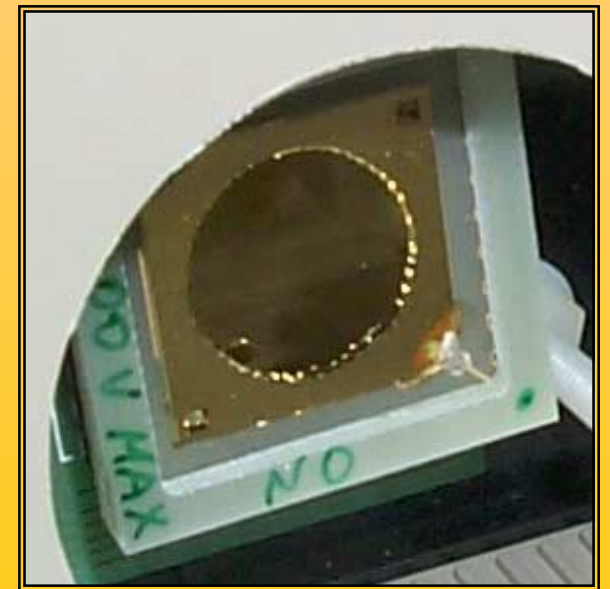
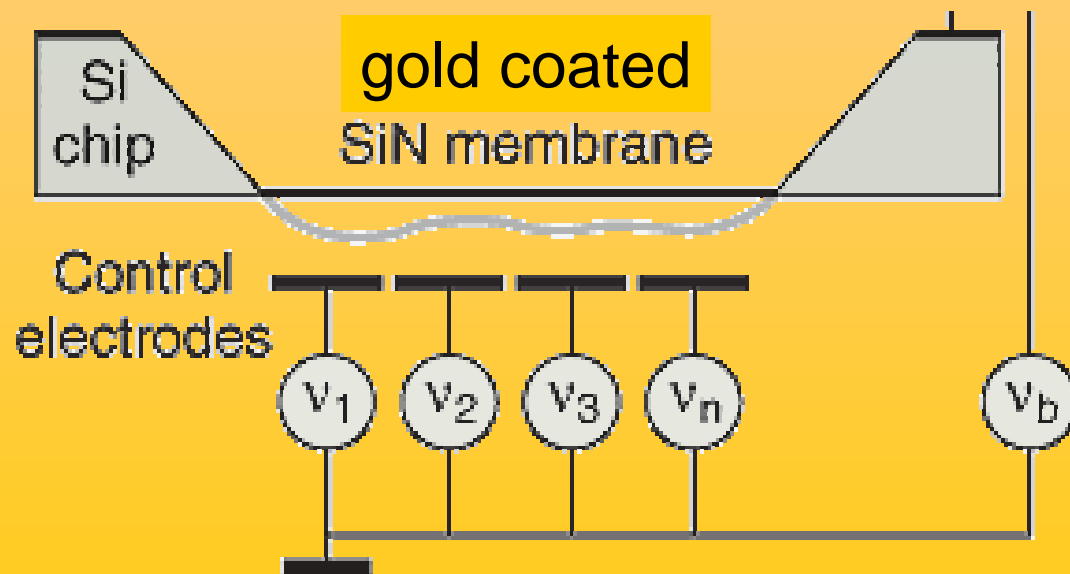
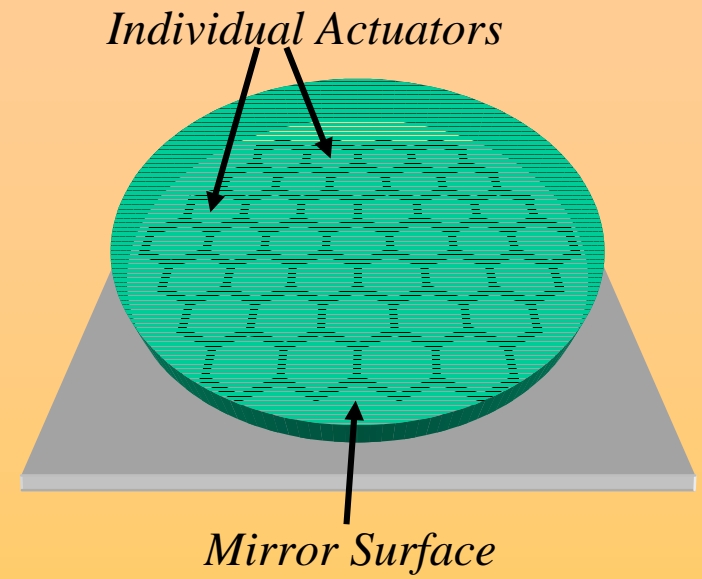
Deconvolution



- Deconvolution from wavefront sensing provides test of wavefront sensing accuracy, simulates AO results
- Example obtained with 106 subapertures over 1m aperture at 950 nm
- Dramatic improvement of spatial resolution as expected

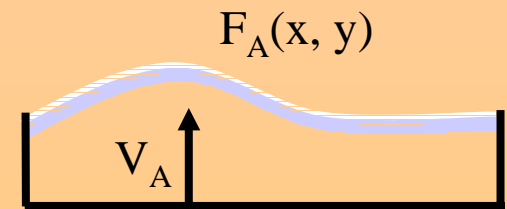
Deformable Mirror

- Micromachined deformable mirror (OKOtech) with 37 actuators
- 600-nm thick, 15-mm diameter silicon nitride membrane coated with gold
- Electrostatic actuators
- 6 μm maximum deflection
- 1 kHz frequency response
- Well matched to correct seeing

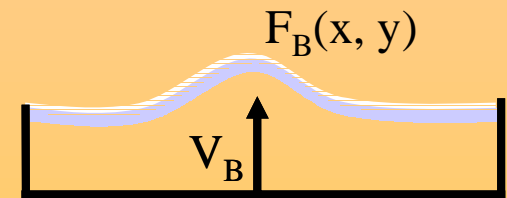


Summation Response

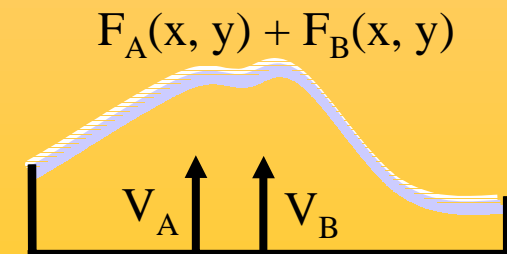
- Simple mirror response model — relates shape of mirror to voltage distribution
- Mirror shape formed by combination of actuator voltages is the sum of responses due to each individual actuator
- Assumption breaks down when mirror reaches elastic limit:
 - At combinations of large voltages
 - When voltages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



Actuator A = V_A



Actuator B = V_B



Actuator A = V_A ,

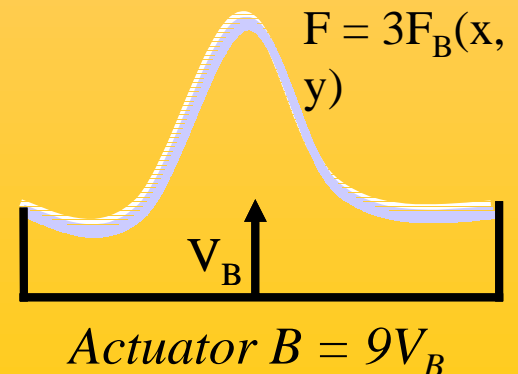
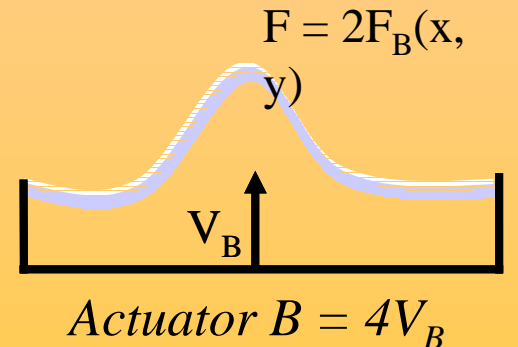
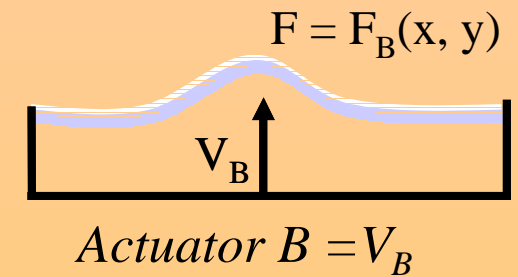
Actuator B = V_B

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:

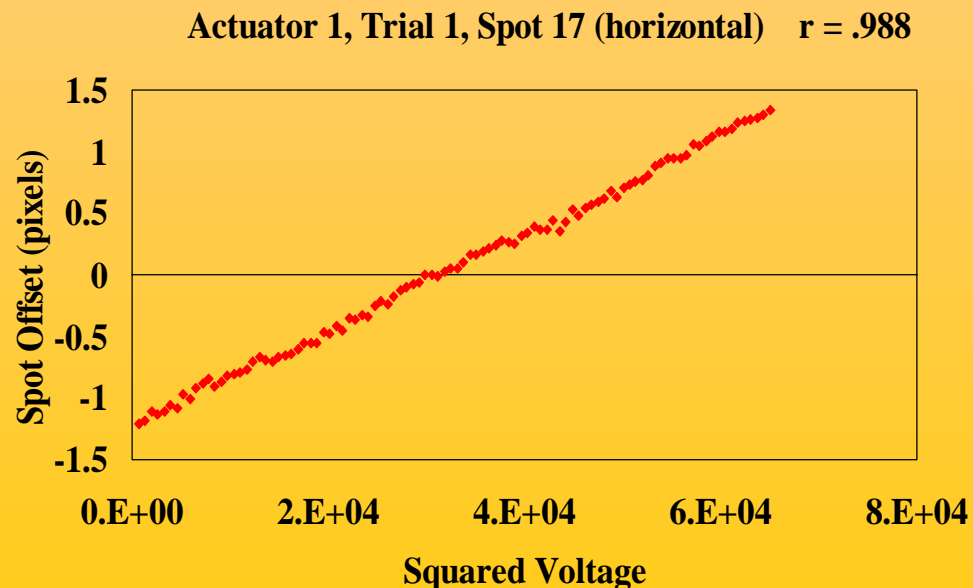
$$\varphi(x, y) = \sum_{k=1}^{37} a_k \varphi_k(x, y)$$

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

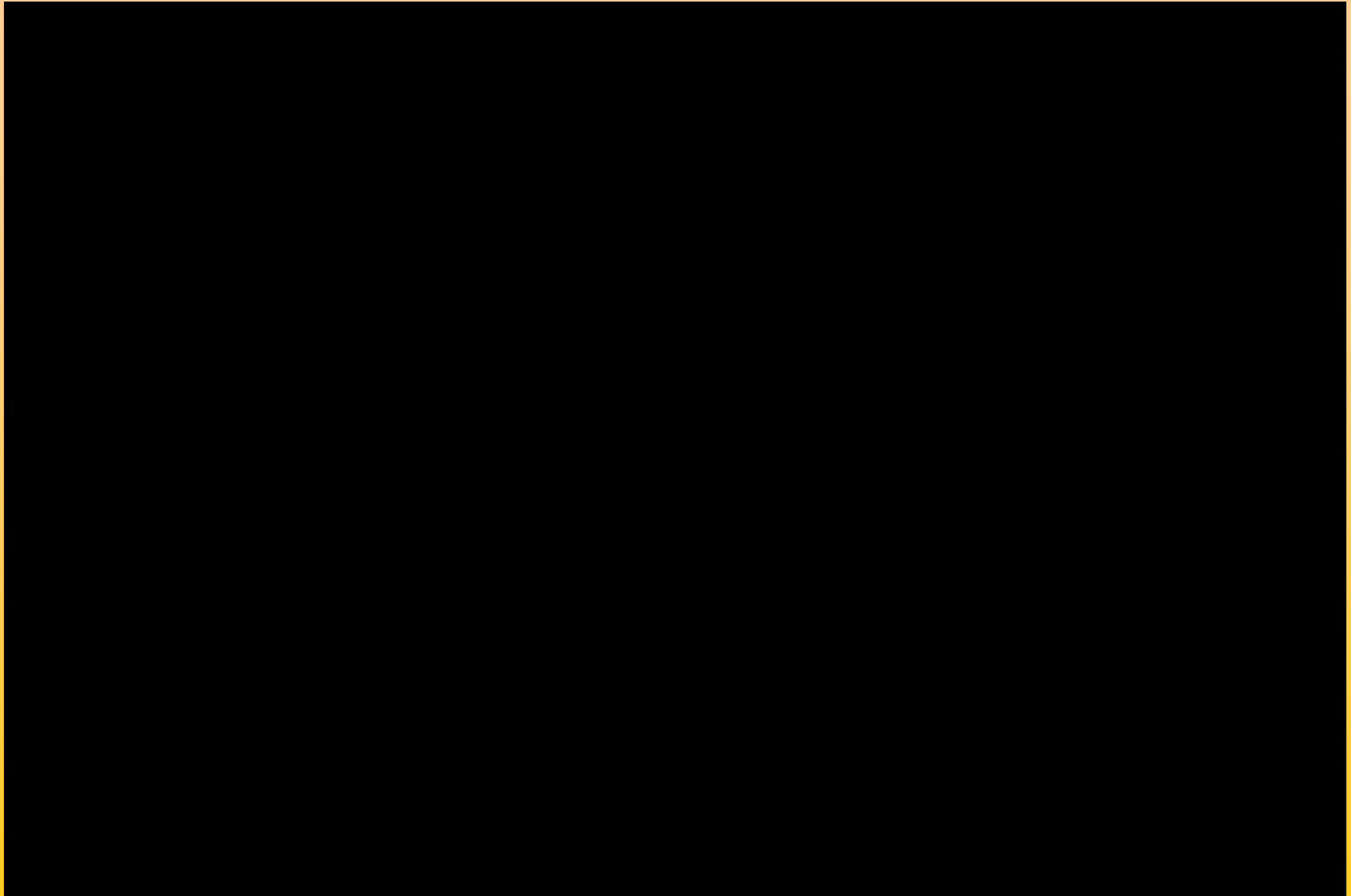


Measuring the Influence Matrix

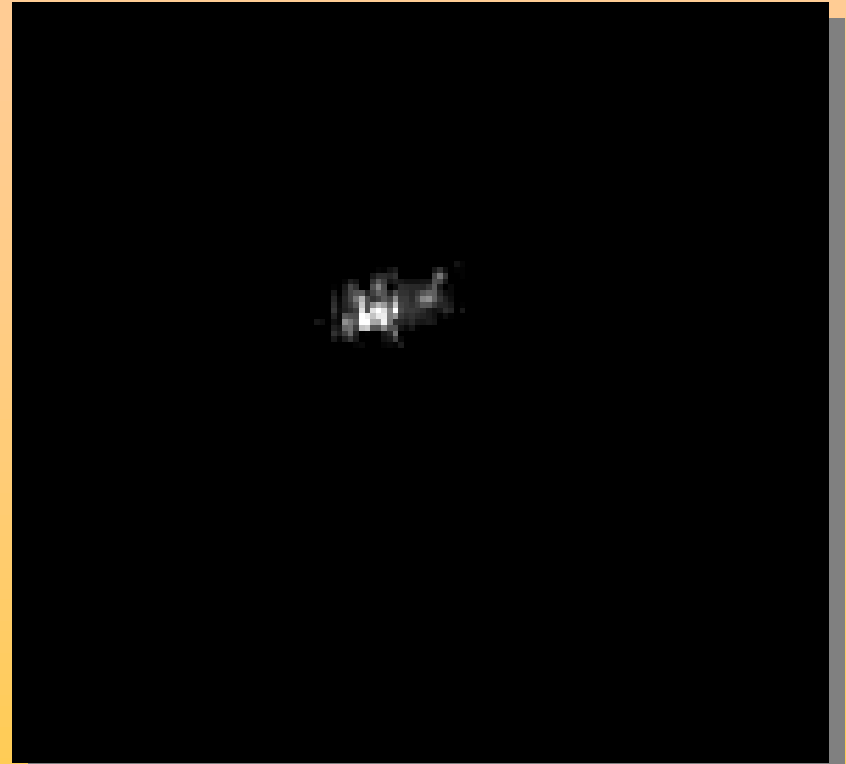
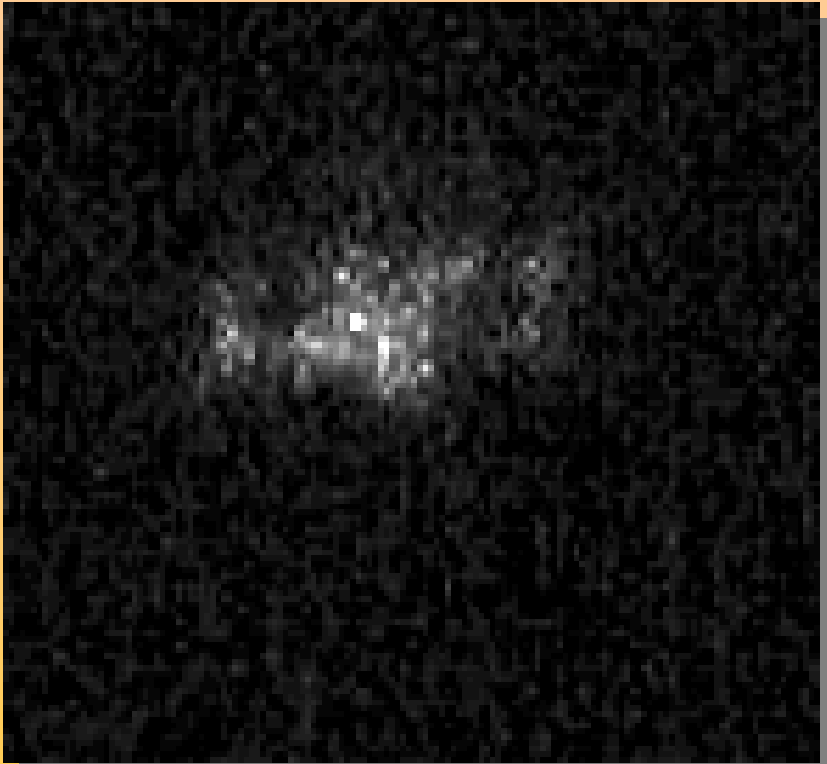
- Need to know voltages that will correct given wavefront sensor signals
- Measure mirror influence matrix by
 - Stepping each actuator k through the possible voltages and measure the wavefront sensor signal at each step
 - For the k th actuator and the n th subaperture, the slope of the best fit line is the element (n, k) of the influence matrix
- Inverse of influence matrix controls deformable mirror given a measured wavefront sensor signal



Closed-Loop Laboratory Tests

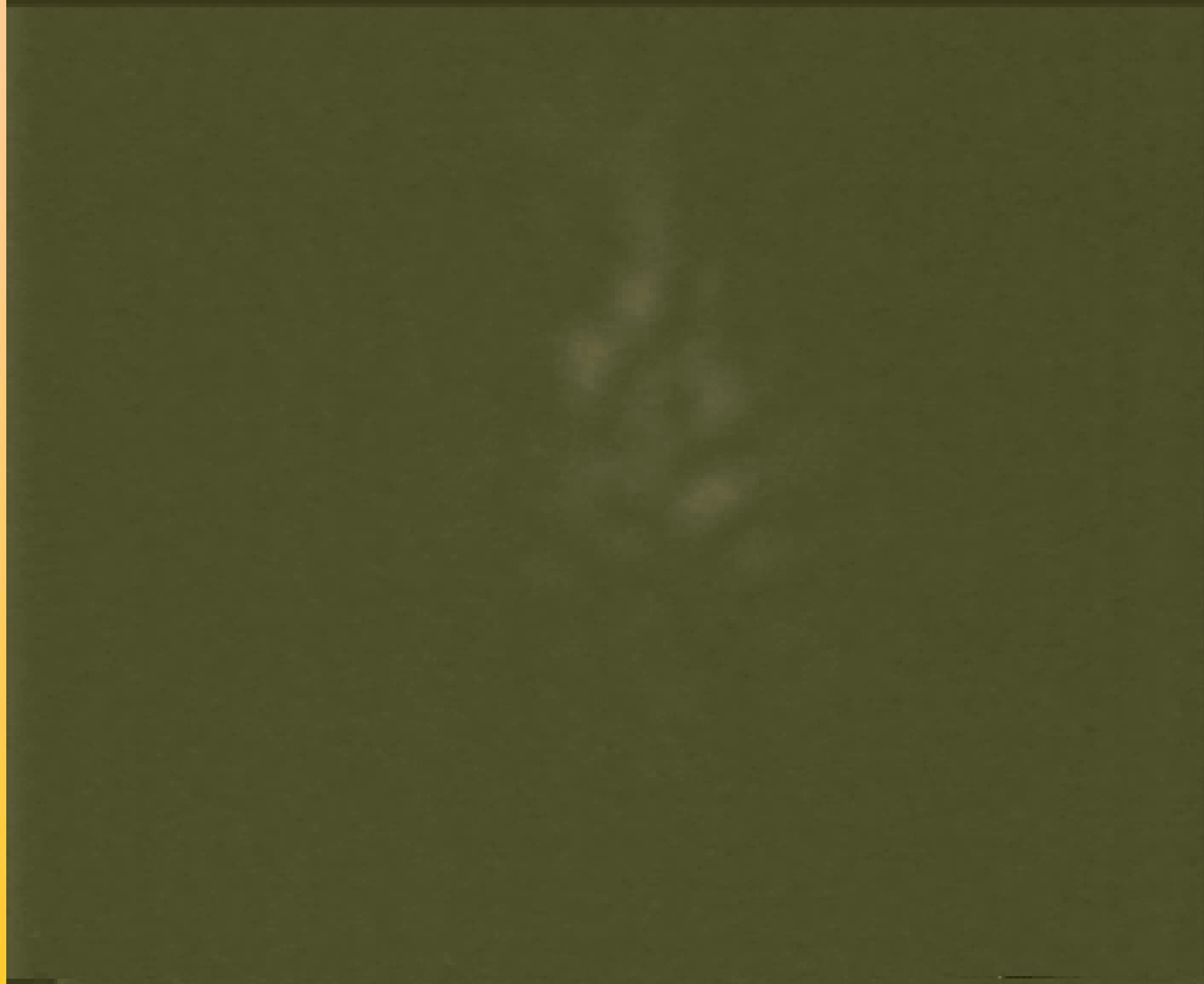


Laboratory Results



- Images of a laboratory point source through a bad piece of optics
- before (left) and (after) correction by the adaptive optics system
- Remaining aberrations are due to limited quality of point source itself

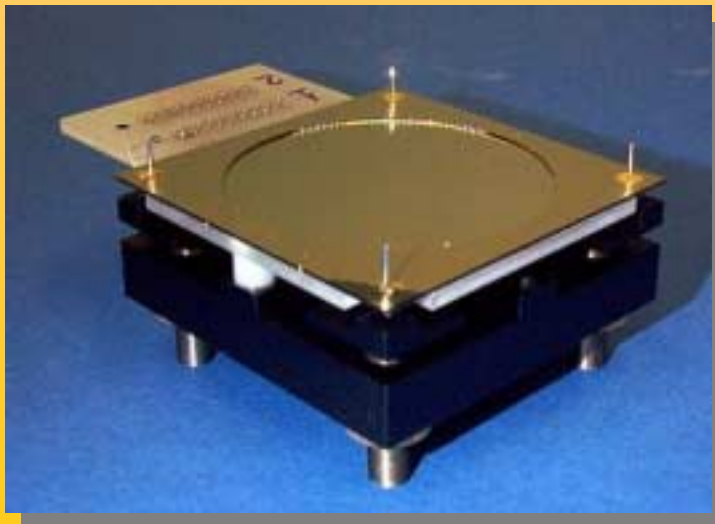
Fast Laboratory Tests



From Paterson et al. (2000)

- Universal Tracker (image motion correction only) is in scientific use since April 2002
- More than half of the observations since April 2002 requested the Universal Tracker
- Two scientific papers for refereed journals in draft form
- Slow closed-loop AO demonstrated in the lab with <\$7k hardware cost, 1 REU summer student (Mark Ammons, Summer 2001)
- Fast, stable closed-loop operation using 193 subapertures at 250 Hz demonstrated (June 2002)
- First corrected solar images and increase of update rate to 500 Hz within the next weeks
- Construction of user system during FY2003

- CSU Northridge expects to duplicate universal tracker
- New Swedish Solar Telescope wants to move to the same system
- Will reach up to 1kHz frame rate with existing system
- Linux 2.6 kernel will provide better real-time behavior
- Simple upgrade: Okotech mirrors available with up to 119 actuators
- Architecture scales well:
 - Pentium 4: 3.2 GByte/s, 16 pixels simultaneously!
 - CMOS Cameras with 1280 by 1024 at 485 frames/s (660MB/s)
 - 64-bit, 66MHz PCI bus frame grabbers-> 528 MB/s



wavelength (μm)	r_0 (cm)	actuators	bandwidth (Hz)
0.5	4	1100	200
1.5	15	78	50
2.3	25	28	30
10.2	150	2	5

Acknowledgements

- Rich Radick provided the lenselet array
- Thomas Rimmele and Kit Richards answered many questions