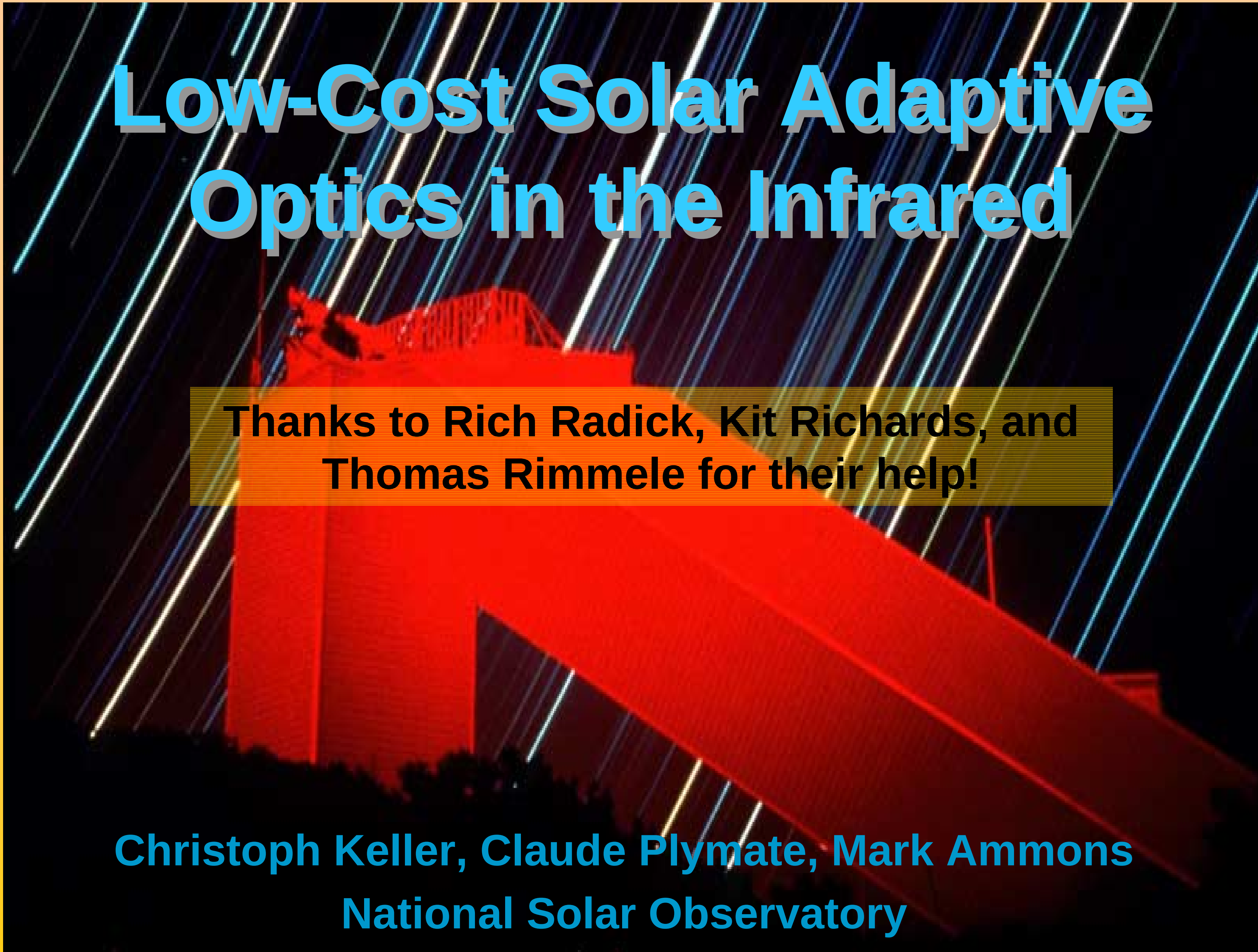


# Low-Cost Solar Adaptive Optics in the Infrared

Thanks to Rich Radick, Kit Richards, and Thomas Rimmele for their help!

Christoph Keller, Claude Plymate, Mark Ammons
National Solar Observatory

# *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.

# *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 |

Tip-tilt is sufficient!

Assumes:

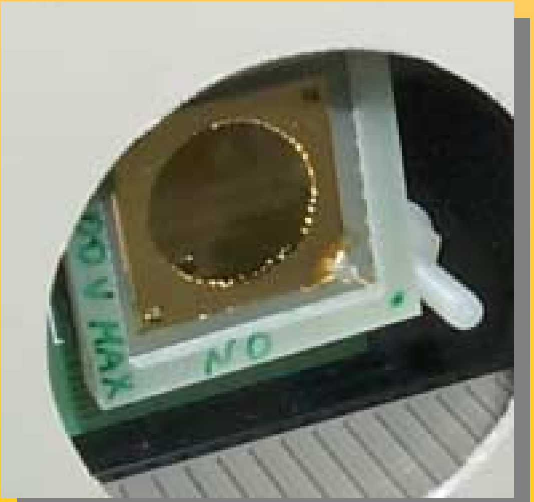
- Kolmogorov statistics
- Single seeing layer with constant wind speed

# *Low-Cost Approach in the Infrared*

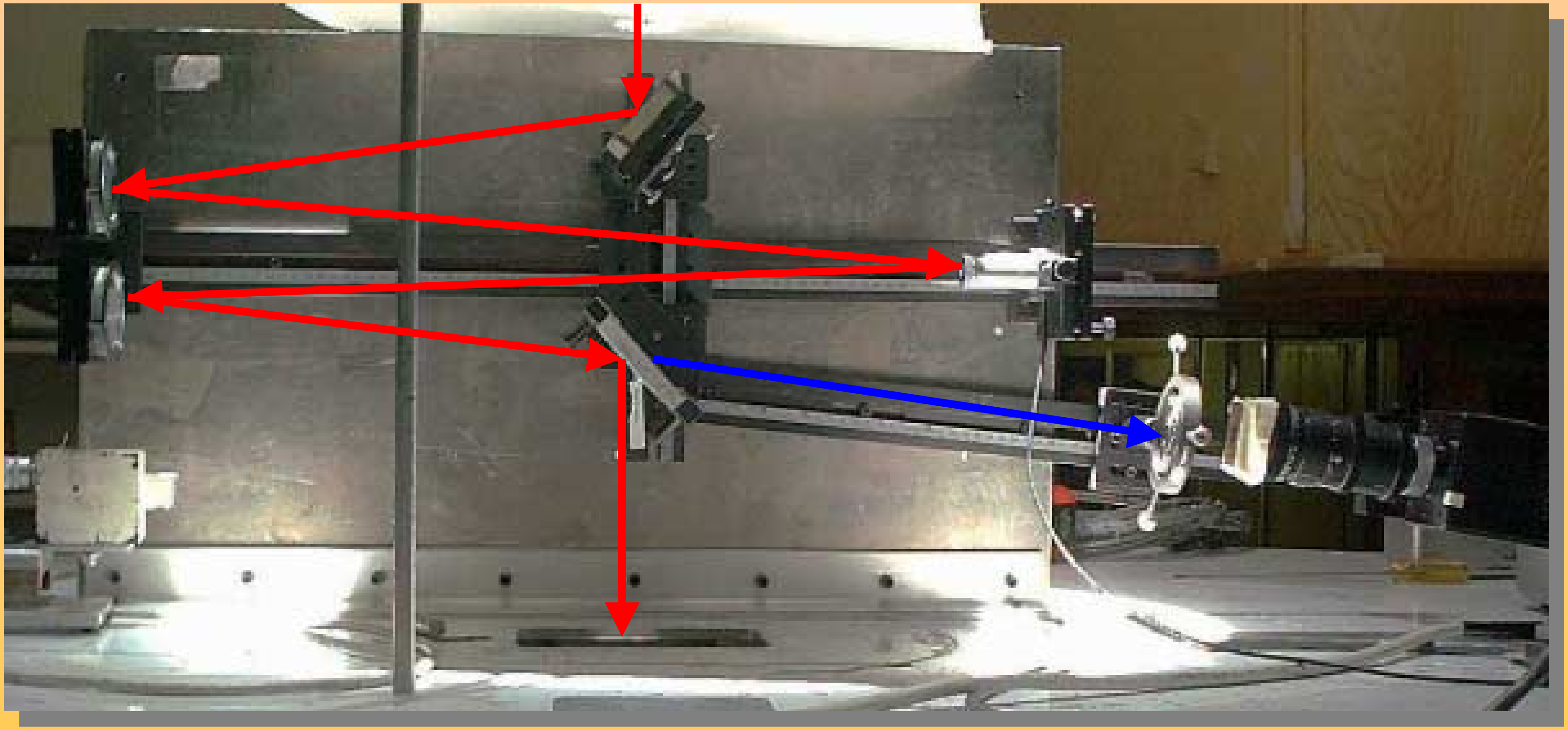
Low-cost, commercial off-the-shelf parts for a complete AO system have been purchased for less than $25k and require minimal software effort:

- all-reflective, gold-coated off-the-shelf optics (90% throughput)
- 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
- Available for all IR instruments, telescope focus is the only change

Goal of providing a flexible system for science, not an R&D system.

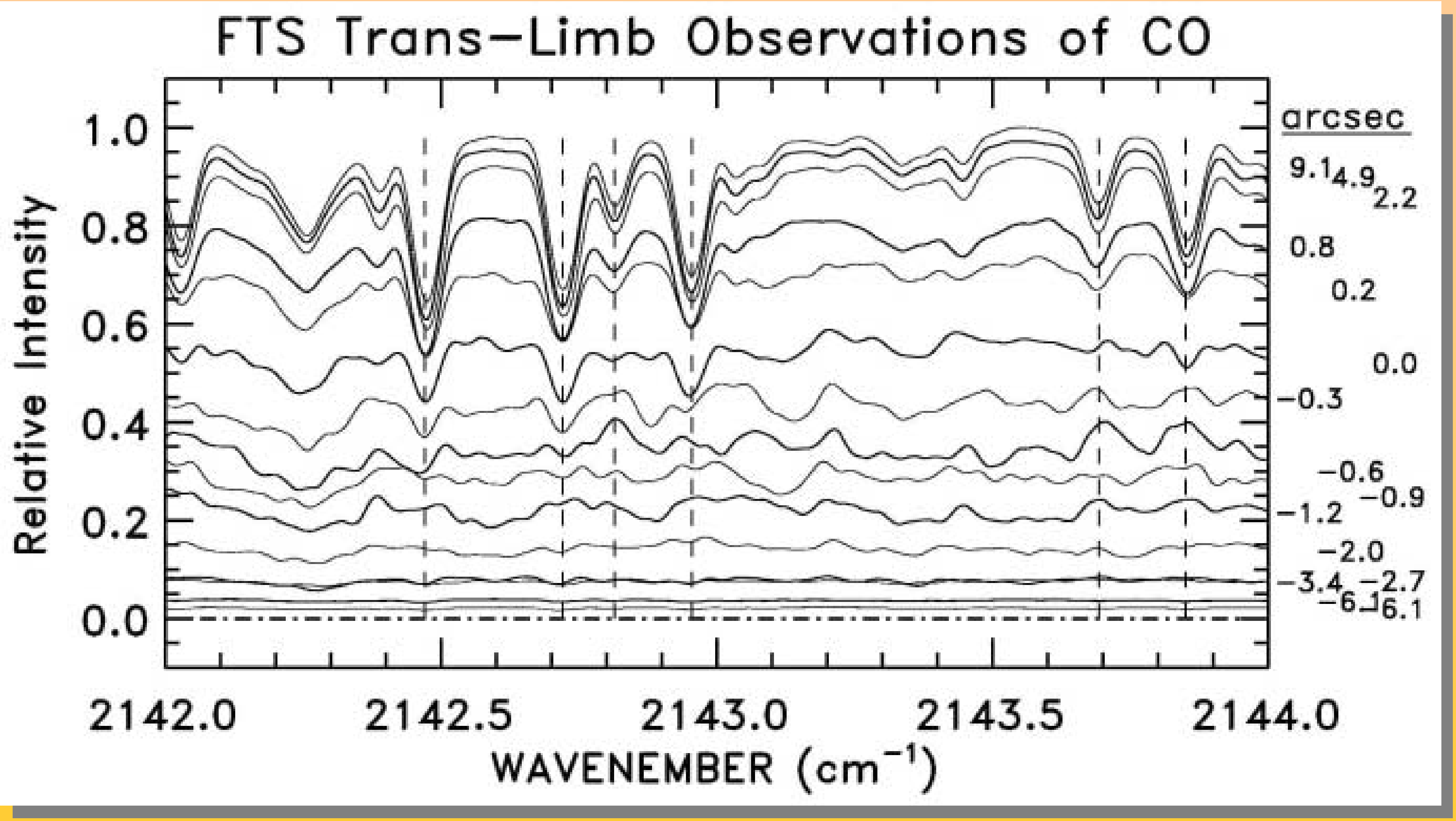


# *Tip-Tilt Correction: Universal Tracker*



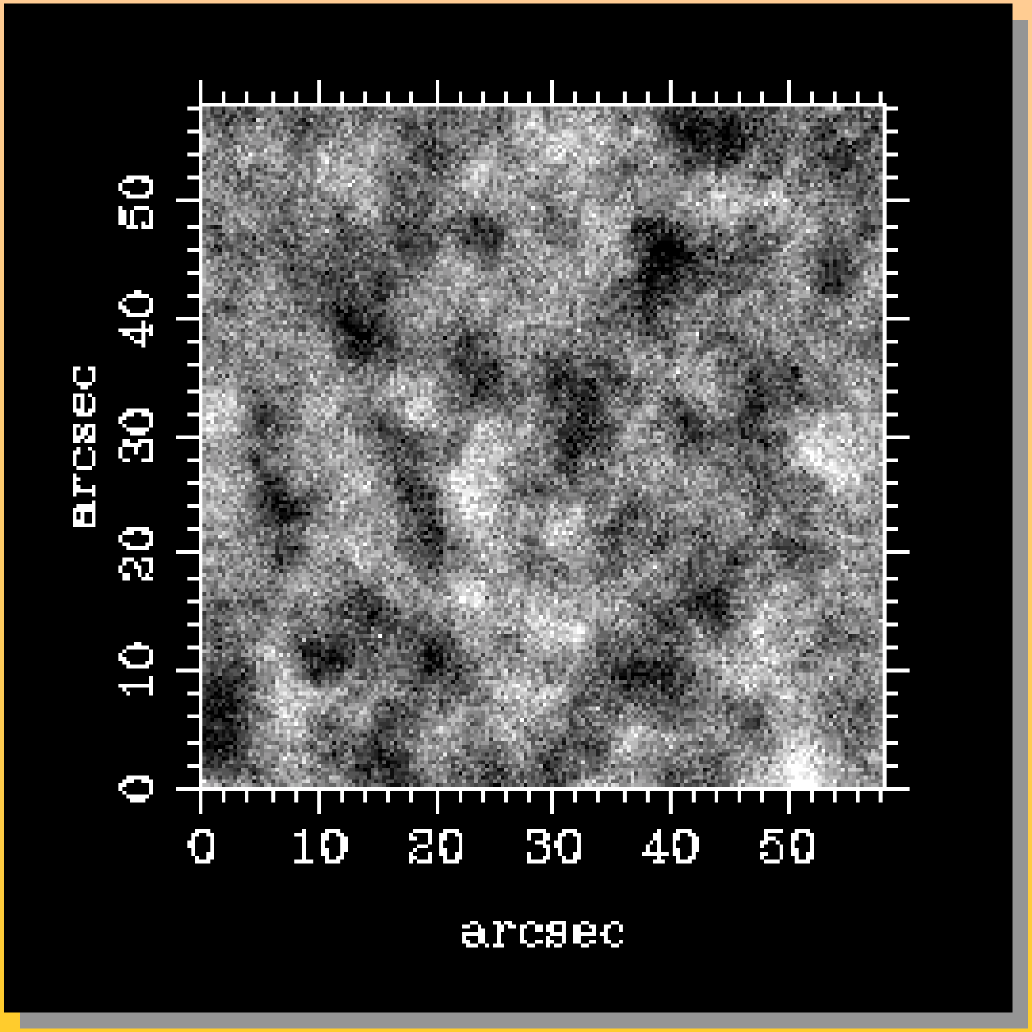
- General-purpose tip-tilt correction with three modes:
  - Digital quad-cell for sunspots
  - Digital limb tracker for various limb position
  - Correlation tracker
- Reference can be moved digitally to scan image across slit
- Current update rate is 500 Hz, corrects to about 50 Hz
- Used for scientific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

# *Science*




- First FTS observations of CO limb emission at 4.8 µm
- Observations and figure courtesy Tom Ayres

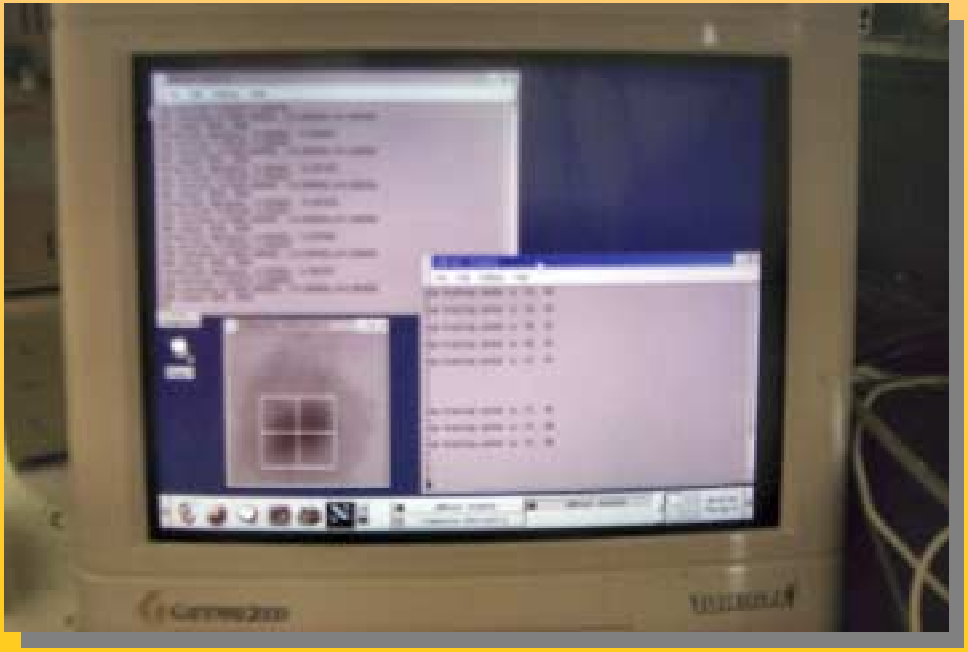
# *Correlation Tracking*




- 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

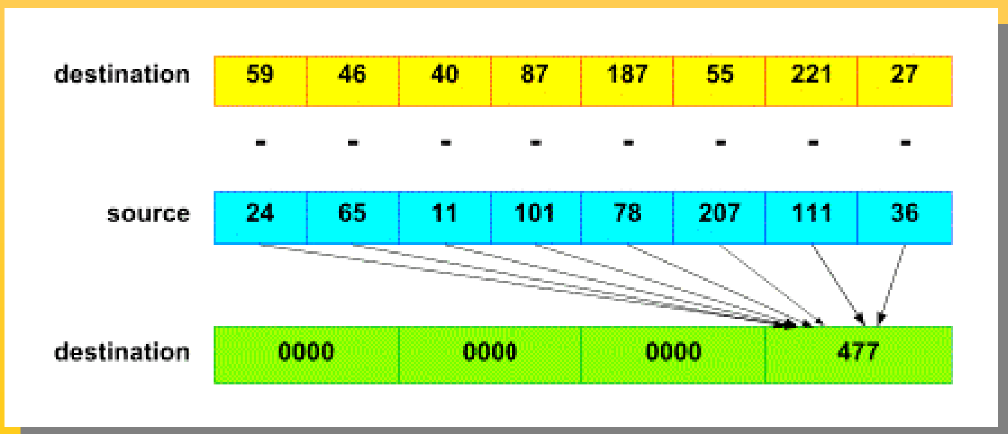
# Software

- 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



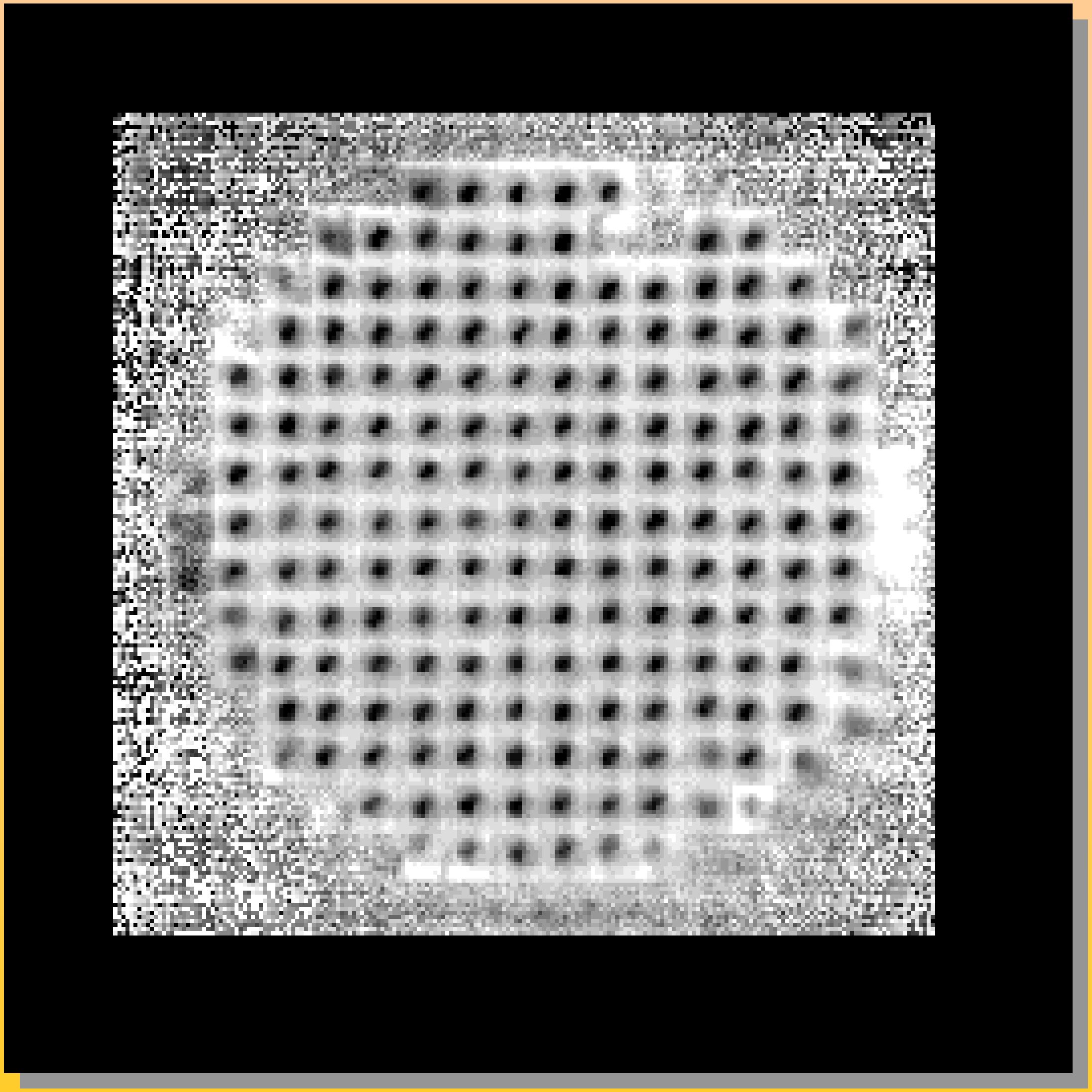
# Code Snippet

```
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:** 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 1GByte/s I/O limit, not by processing power!
- 256 by 256 pixel correlation tracking at >500 Hz
- wavefront sensing at > 1 kHz with 200 8 by 8 pixel subapertures

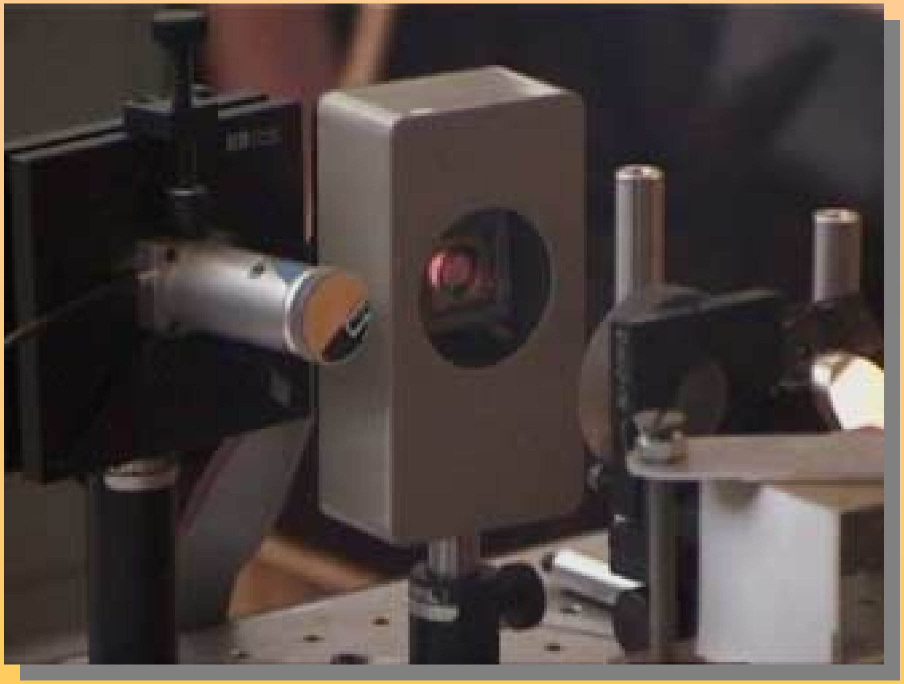
# *Shack-Hartmann Wavefront Sensing*



**Prototype wavefront sensor data of sunspot recorded at 500 Hz**

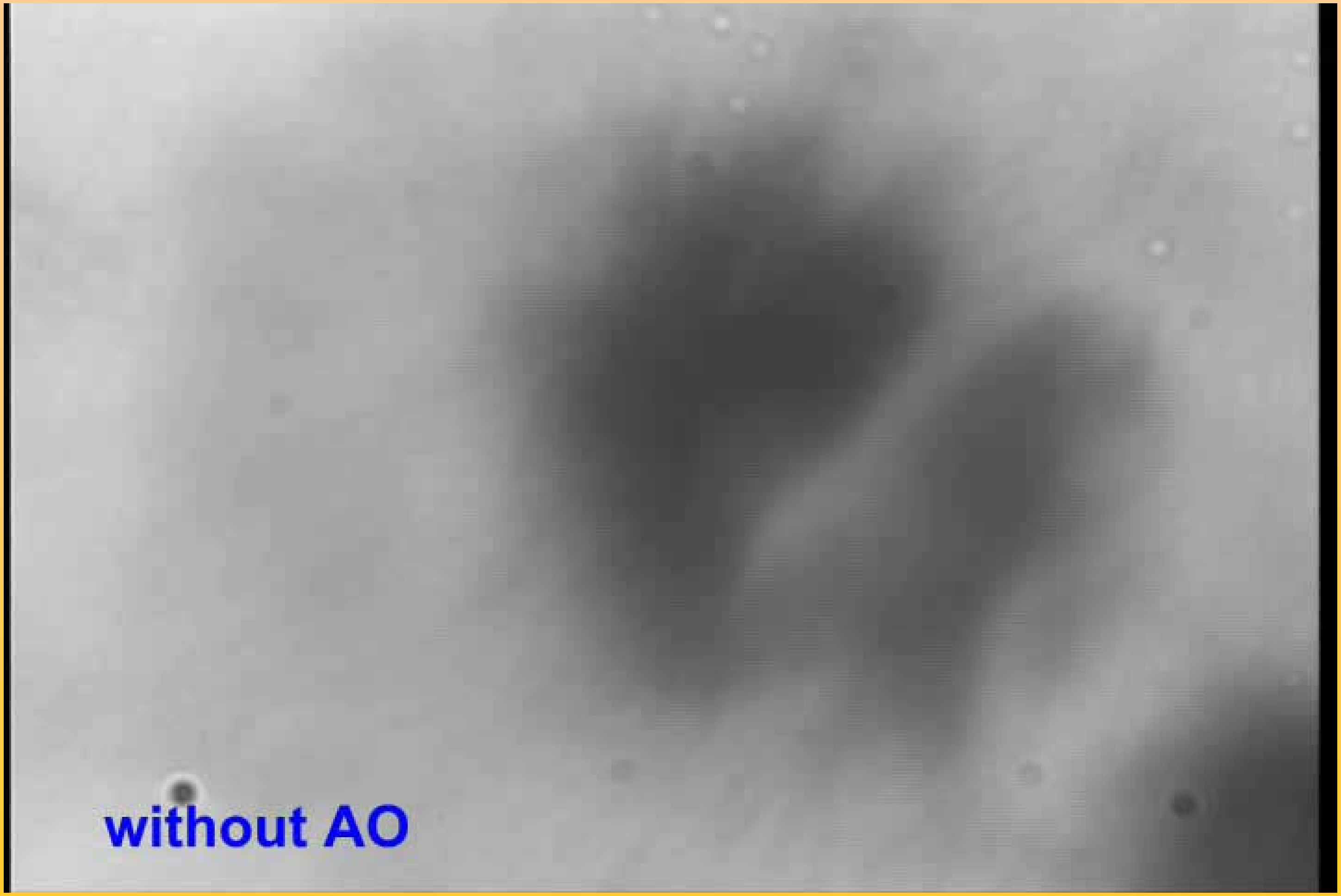
- High-order wavefront sensing at 0.9 µm to use 'cheap', fast CCD camera instead of expensive IR camera
- Requires about 200 subapertures to adequately determine wavefront
- This is about 10 times more than any other solar AO system

# Breadboard AO Setup



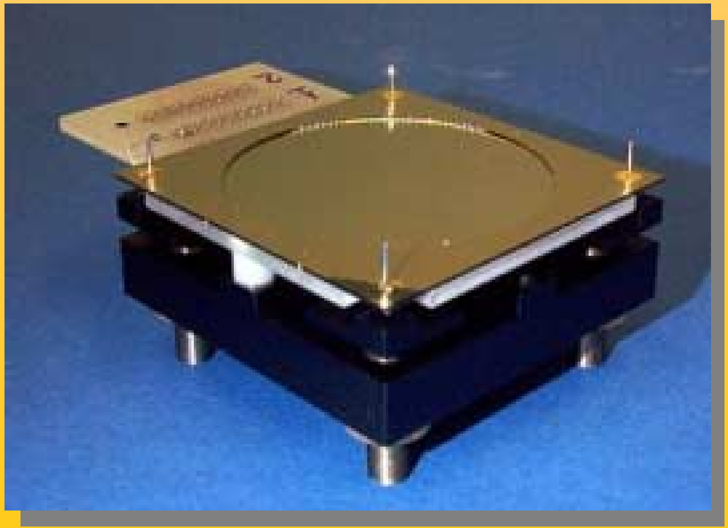
- Currently at West Auxiliary telescope, stopped down to 50 cm
- Wavefront sensor running at 830 nm
- Video ‘science’ camera at 990 nm
- 250 Hz closed-loop update rate
- 193 subapertures

# *July 2, 2002: First Light*



# Outlook

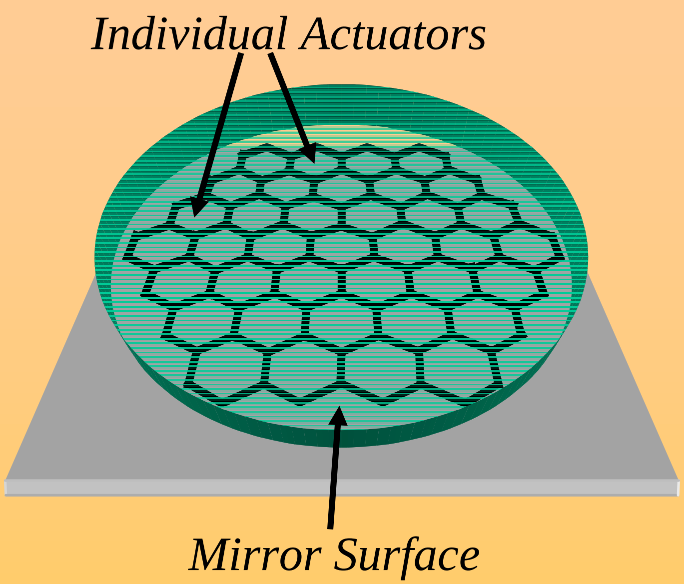
- Bread-board available on shared risk basis starting January 2003
- User system will be built during the next 12 months
- Will reach up to 1kHz frame rate with existing system
- Linux 2.6 kernel will provide even better real-time behavior
- Simple upgrade: Okotech mirrors available with up to 119 actuators
- Processing 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

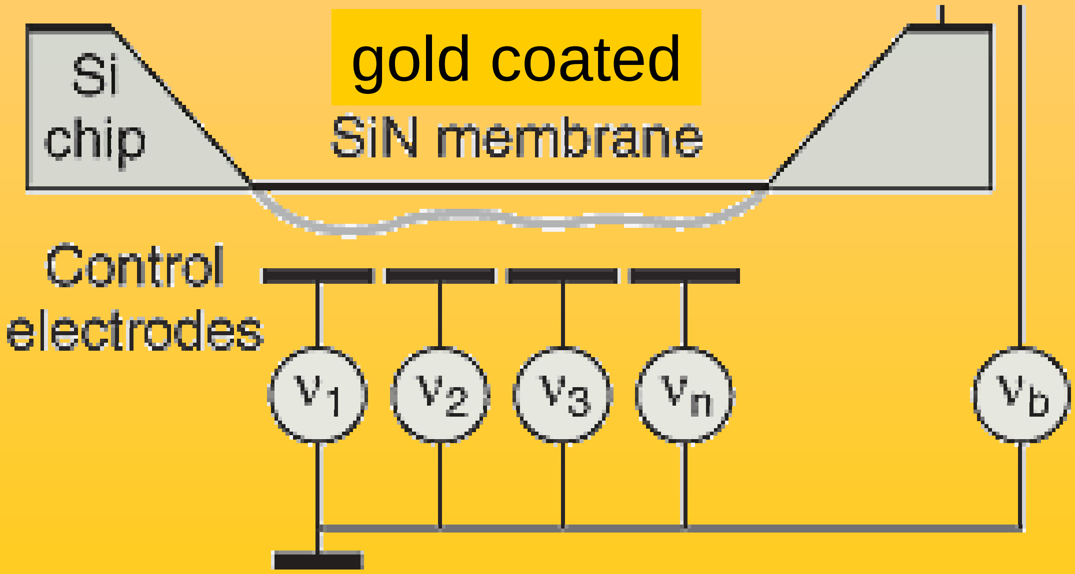


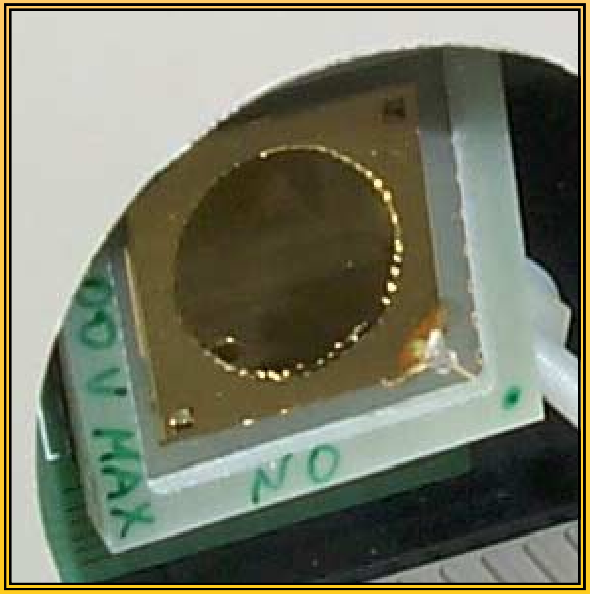
| wavelength (µm) | $r_0$ (cm) | actuators | bandwidth (Hz) |
|---|---|---|---|
| 0.5 | 4 | 1100 | 200 |
| 1.5 | 15 | 78 | 50 |
| 2.3 | 25 | 28 | 30 |
| 10.2 | 150 | 2 | 5 |

# 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

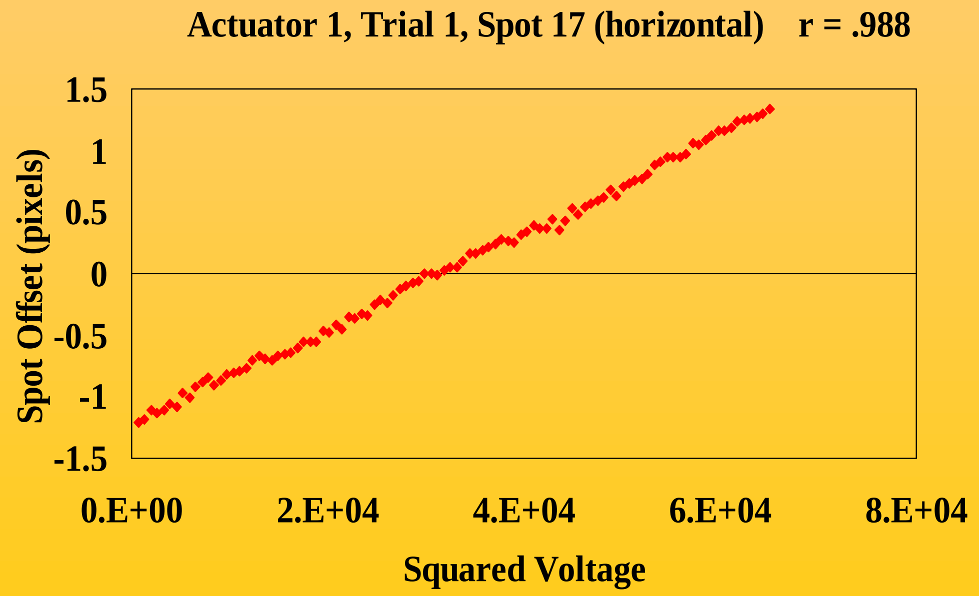


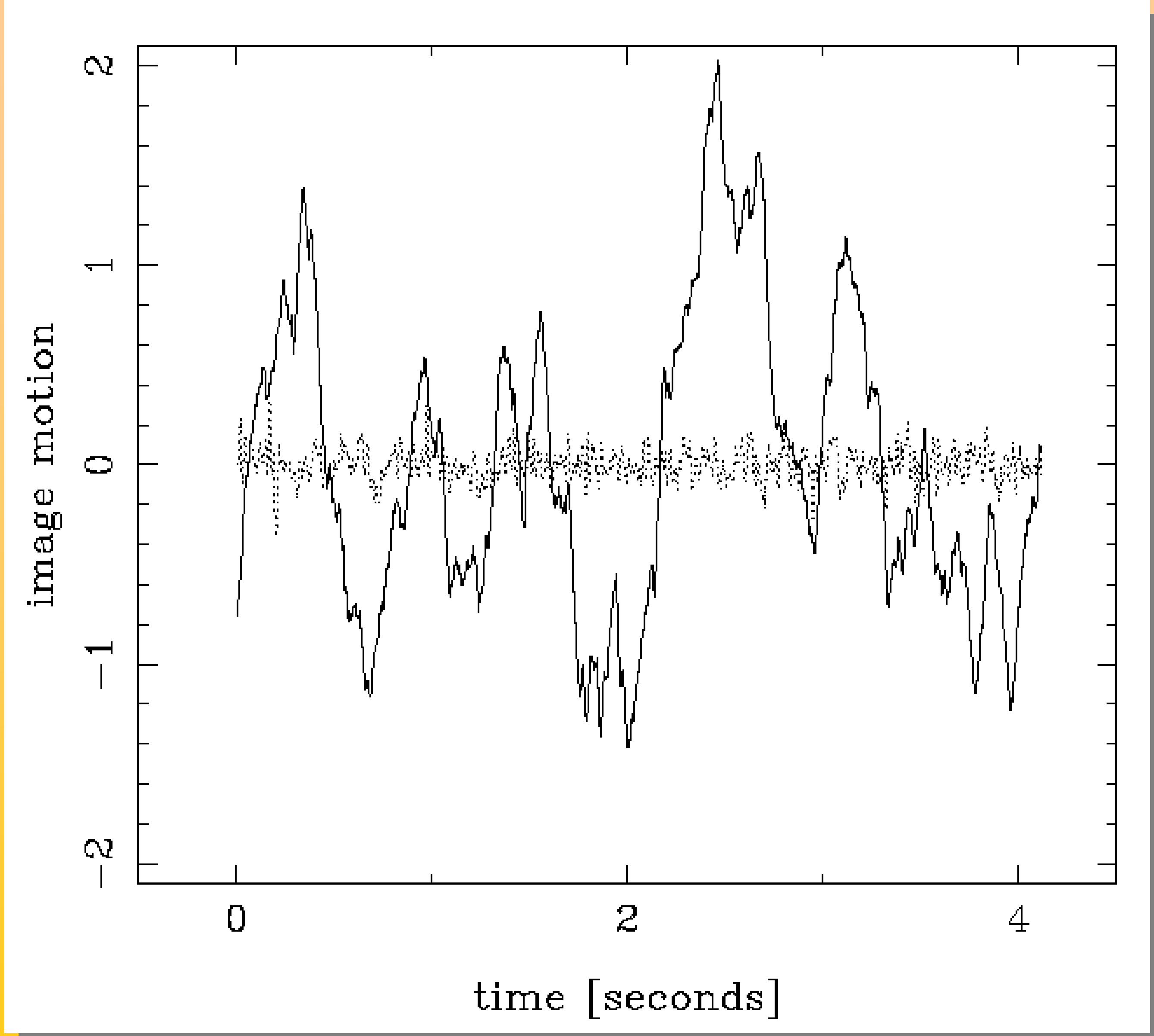



# *Measuring the Influence Matrix*

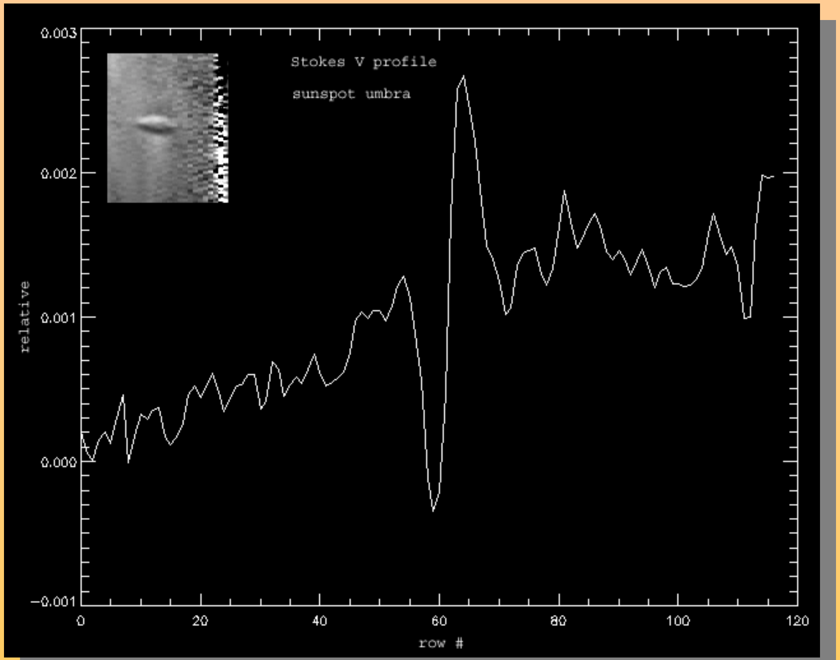
- Need to know voltages that will correct given wavefront sensor signals
- Measure mirror influence matrix by
  - Stepping each actuator k through the possible voltages and measure the wavefront sensor signal at each step
  - For the kth actuator and the nth subaperture, the slope of the best fit line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



# Limb-Tracking Performance



# *Science, Part 2*




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

# Status

- 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