Low-cost solar adaptive optics in the infrared

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ABSTRACT

We have developed a low-cost adaptive optics system for solar observations in the infrared between 1 and 28 µm with the 1.5-m McMath-Pierce solar telescope. The 37-actuator membrane mirror and a fast tip-tilt mirror are controlled by a PC running Linux RedHat 7.1 that analyzes images from a 256 by 256 pixel, 1 kHz frame rate CCD camera. The total hardware cost is less than $25,000, and the system provides diffraction-limited performance under median seeing conditions above 2.3 µm. The single Pentium III processor provides enough computing power to analyze the 200 subapertures of the Shack-Hartmann wavefront sensor in real time. We describe the hardware and software implementations and show results from the first tests at the telescope.

Keywords: adaptive optics, infrared, Sun

1. INTRODUCTION

The McMath-Pierce Solar telescope (see Fig. 1), with an aperture of 1.5 m is the world's largest solar telescope, provides unique observing opportunities in the infrared because of its all-reflective design. No other solar telescope of reasonable aperture provides access to the infrared beyond 2.3 µm. Instruments that are currently used at the telescope include a 256 by 256 InSb camera that is used between 1 and 5 µm behind filters, spectrographs, and polarization analyzers, a Fourier Transform Spectrometer (FTS) that operates from 0.3 to 20 µm, and more or less permanently installed visitor instruments such as a 6 to 15 µm spectrometer and polarimeter and a 12-µm imaging vector polarimeter. A new 1024 by 1024 InSb infrared camera for the 1 to 5 µm range is currently under construction.

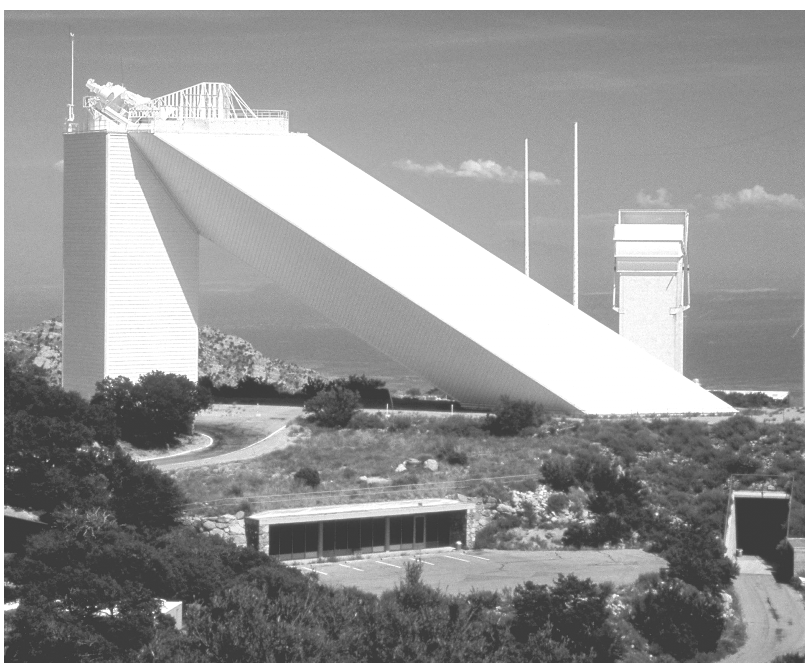

Fig. 1: The 1.5-m McMath-Pierce Solar telescope as seen from the West. There is a 1.5-m main telescope and two 0.9-m auxiliary telescopes.

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These instruments are used to study the solar atmosphere from the photosphere to the corona. Major advantages of the infrared include larger Zeeman splitting of spectral lines and the direct connection between brightness and temperature. For instance, recent observations of the mysterious chromospheric carbon-monoxide clouds at 4.6 μm revealed a connection with granulation[1], which requires sub-arcsecond spatial resolution.

The single most important improvement to these infrared observations at the McMath-Pierce is the implementation of active and adaptive optics to correct for aberrations induced by the atmosphere and, to a smaller amount, by the telescope. It is well known that the implementation of adaptive optics in the infrared is significantly easier than in the visible. Table 1 summarizes the average seeing properties at the McMath-Pierce and the required adaptive optics properties as a function of wavelength.

Table 1: Seeing as measured with Fried's parameter r_0, the required number of actuators to reach the diffraction limit of the 1.5-m McMath-Pierce telescope, and the required bandwidth for an adaptive optics system as a function of wavelength. The calculations assume Kolmogorov statistics and a single seeing layer with a constant wind speed.

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

Since fast infrared cameras for wavefront sensing in the infrared are currently prohibitively expensive, the wavefront sensing must occur in a wavelength range that is accessible with silicon-based imagers such as CCDs and CMOS devices. Fortunately, the Earth's atmosphere is nearly achromatic, which makes wavefront determination in the visible and correction in the infrared feasible. However, this approach provides additional challenges as compared with existing AO systems that both sense and correct in the visible such as those at the Dunn Solar Telescope[2] in New Mexico and at the Swedish Solar Telescope in La Palma, Canary Islands[3]. The main challenge is the great increase in sub-aperture number required for the wavefront sensing (several hundred at 1μm). On the other hand, the correction bandwidth may be much slower (see Table 1).

2. LOW-COST APPROACH

A low-cost AO system using almost exclusively commercial off-the-shelf components is nothing new. Paterson et al.[4] described a system that has many hardware components in common with the system outlined here. Our approach differs in that it must handle the additional challenges posed by the low-contrast surface of the extended solar surface. Indeed, the main difference between the Paterson et al. system and ours consists in our low-cost approach to the data processing and the associated software. Furthermore, Paterson et al. only used their system in the laboratory using artificial sources and turbulence, while our system has been successfully tested at a telescope.

As Paterson et al. have already shown, the advent of low-cost deformable mirrors (DMs) with a significant number of actuators and fast, relatively large format CCD cameras has opened the door for night-time, low-cost AO. However, solar AO systems require special wavefront sensors that can work on low-contrast extended-source solar features. Traditionally, correlation-based algorithms are used[2,3], which require massive computing power. The use of Digital Signal Processors (DSPs) to provide this computing power led to high hardware and software costs. Substantial increases in computer speed has allowed for designs with decreased reliance on external processors. Scharmer et al.[3] built a solar AO system around a single Compaq workstation with a 600-MHz Alpha 21164 processor. However, they still needed a custom-built interface to pipe the data into the processor at a high enough speed.

DSPs have several disadvantages over general-purpose processors that lead to early obsolescence with no upgrade path to new technology[5]. General-purpose processors are as efficient per clock cycle as DSPs, but the clock-speed improvement of general-purpose processors has consistently outpaced DSPs for over a decade[5]. Furthermore, general-purpose processors now include multi-media instructions that allow for highly parallel processing of pixels. In particular, MPEG compression requires the calculation of subaperture shifts similar to what is needed in a correlating Shack-Hartmann wavefront sensor. As a result, most general-purpose processors now include instructions to calculate the sum of absolute differences. Finally, DSP-based solutions require a careful design that depends on the relation between subapertures and DSPs, which makes flexible wavefront sensor (WFS) geometries almost impossible. This is crucial for the McMath-Pierce system since the aperture of these telescopes changes its shape during the course of the year.

Large software costs often destroy the advantage of AO systems that are designed around low cost hardware. We have tried to avoid this pitfall by selecting hardware elements that implied minimal software efforts. This included the use of an industrial PC with Linux RedHat 7.1 out of the box and the selection of interface cards with supported Linux drivers.

3. HARDWARE APPROACH

The optics for the tip-tilt and AO systems are currently based on optical breadboard tables (see Fig. 2 for the AO setup). Once sufficient experience has been gained with these arrangements, a dedicated user instrument will be assembled. All optical elements are off-the-shelf. Mirrors are gold-coated to minimize the loss in reflectivity in the infrared.

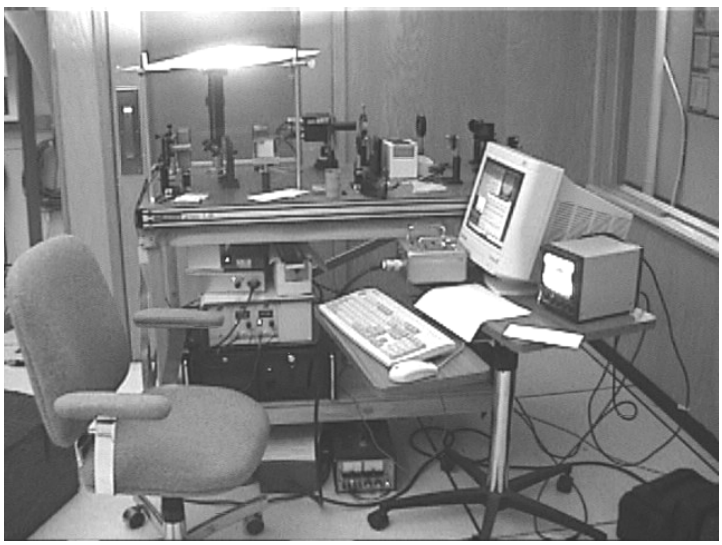

Fig. 2: Overview of the complete breadboard AO setup under the West Auxiliary telescope of the McMath-Pierce facility. Much of the space is occupied by the flexible Shack-Hartmann wavefront sensor setup.

The tip-tilt mirror is mounted on a PSH-8 piezo-driven platform from PiezoJena, which has a large tilt range of 8 mrad. This large tilt range is necessary because of the large demagnification of the pupil from 1.5 m to about 10 mm.

The DM is a gold-coated 37-actuator electrostatic membrane mirror from Okotech in the Netherlands. It has been well characterized in numerous laboratory experiments (see list of publications at http://www.okotech.com). This 15-mm diameter mirror has sufficient range for use in astronomical adaptive optics, as the mirror mode amplitudes are well matched to the atmospheric seeing modes. The mirror actuators show no hysteresis and are almost completely linear with the applied voltage squared (see Fig. 3). The achievable surface shape can be well controlled at up to 1 kHz, which is sufficient for infrared AO at the McMath-Pierce telescope. Okotech provides the necessary ISA computer interface and high-voltage driver cards. High-voltage converters step a 12-volt laboratory power source supply up to the 300-volts required by the high-voltage mirror driver cards.

The wavefront sensor is based on an orthogonal lenslet array and a Dalsa CA-D6-256 CCD camera. The camera has 256 by 256 pixels and reads out at nearly 1kHz with 8-bit internal digitization. This camera is connected to a PC-Dig LVDS digital frame grabber from Coreco Imaging Technologies. The latter can keep up with the 1-kHz full frame rate provided by the camera and can transfer the digital data at the required rate over the PCI bus to the main memory. The industrial PC from Kontron USA is based on a combined PCI/ISA passive back-plane and a 1GHz Pentium III single-board computer that uses the Intel 815E chipset. Figure 4 shows an example of the wavefront sensor output looking at an isolated sunspot.

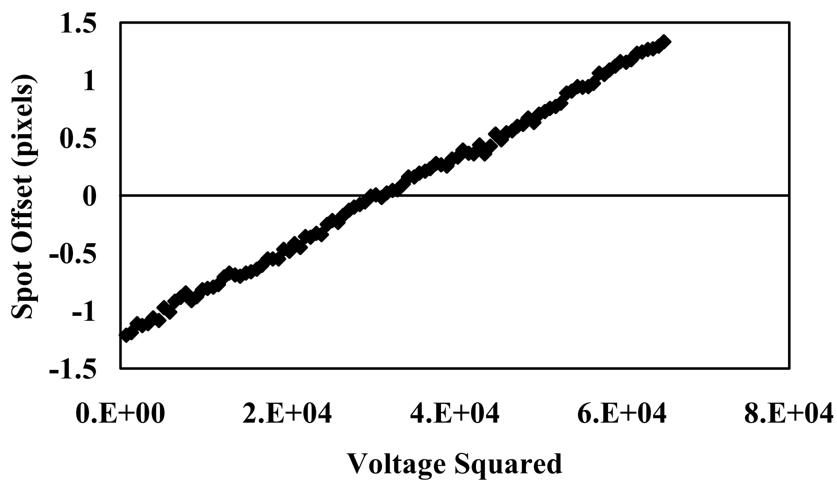

Fig. 3: The relation between the voltage squared applied to a particular aperture and the shift measured in a particular subaperture. The relation is highly linear with a correlation coefficient of 0.988.

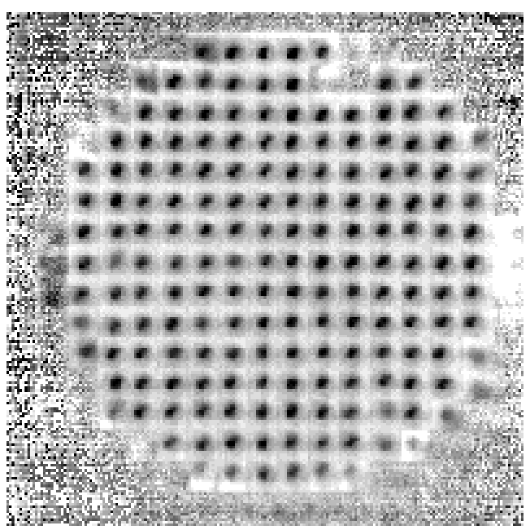

Fig. 4: Dark-current and flat field corrected output from the wavefront sensor. Here, an isolated sunspot is used for wavefront sensing. Note the large number of subapertures.

There are currently two independent optical setups. One is for tip-tilt correction only and is called the Universal Tracker (UT). It has already been used with three very different post-focus instruments. The other setup is the full AO setup whose science instrument has so far been limited to a simple video camera.

4. SOFTWARE APPROACH

As mentioned above, keeping hardware costs low is insufficient; for an AO system to be truly “low-cost”, software expenditures must also be minimized. The industrial PC described above is operating under Linux

RedHat 7.1. This provides a flexible, general-purpose environment where the AO code can be run simultaneously with development and data analysis tools. Running the AO process with soft-realtime priority under the Linux 2.4 kernel ensures that the AO process has exclusive access to the CPU whenever feasible. This limits the typical wavefront sampling jitter to a few microseconds with the exception of when entire images from the wavefront sensor camera are displayed.

For the UT setup, the camera looks at an image of the telescope focal plane without the lenslet array. There are three tip-tilt correction modes:

1. Digital quad-cell for sunspots: a dark feature such as a sunspot or pore is observed. The intensity in four quadrants is averaged and the normalized differences between opposite quadrants are used to control the tip-tilt mirror.
2. Digital limb tracker for vertical and horizontal limb orientations: the solar limb is positioned either horizontally or vertically across the fast camera. The control signal is the ratio of the intensity measured across the limb divided by the sum of the intensities measured inside and outside of the limb. This makes the limb position measurement inherently insensitive to scattered light level, changes in seeing, and the overall intensity level. The mirror is only driven in the appropriate axis while the other one is kept in its center position.
3. Correlation tracker: this mode can operate on any solar surface feature. A reference image is acquired, and subsequent images are compared to this reference by calculating the sum of absolute differences (SAD) as a function of displacement between the two images. The sub-pixel accurate displacement that minimizes the SAD is used to drive the tip-tilt mirror. Reference images are automatically updated after a user-defined period (typically 30 seconds).

In all three modes, the set point can be moved digitally instead of moving the camera. This allows the telescope image to be moved across the slit of a spectrograph or the position on the science camera to be fine-tuned. Currently, the loop update rate is 500 Hz, which corrects image motion to about 50 Hz. Improvements of the software will allow us reach the 1-kHz maximum frame rate in the future with the existing hardware.

The correlation tracker approach is somewhat different from previous work in that almost the whole 256 by 256 image is used for the tracking. This large field of view allows tracking on features that have contrasts as low as 1%. This does not require that the seeing be good enough to discern solar granulation. The larger-scale pattern of solar convection is sufficient to provide reasonably stable image motion compensation (see Fig. 5). The correlation tracker provides better stable image motion compensation than other systems that use much smaller fields of view.

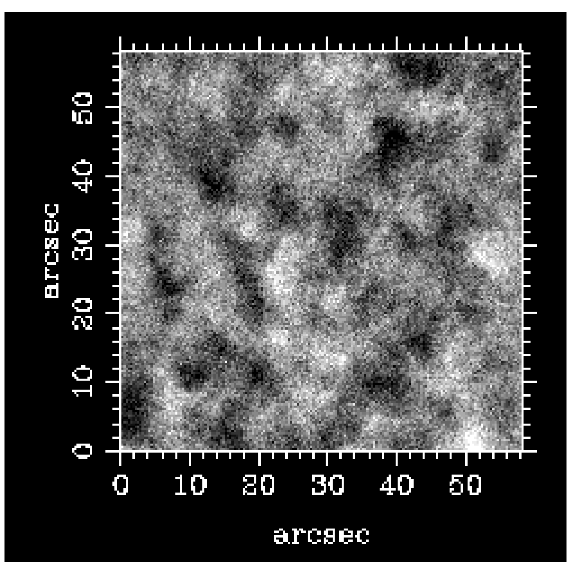

Fig. 5: Image of solar convection pattern as seen in seeing of a few arcsec. Note that while granulation is not visible, a larger-scale pattern is easily discernible that can be used for tracking.

```
#define NS 256 /* number of subapertures */
#define RX 16  /* size of reference subaperture in x */
#define RY 16  /* size of reference subaperture in y */
#define SX 8   /* size of subapertures in x */
#define SY 8   /* size of subapertures in y */

uint8_t  cimag[NS*SX*SY] __attribute__ ((aligned (32)));
uint8_t  refim[RX*RY] __attribute__ ((aligned (32)));

/* calculate sum of absolute differences for one subaperture */

int sae(int dx, int dy, int sn) {
  /* dx, dy: current shift vector
     sn:     subaperture number   */

  uint32_t c1 = 0;
  uint8_t *ip, *rp; /* pointers to appropriate rows */

  ip = &cimag[sn*SX*SY]; /* start at first pixel of each subaperture */
  rp = &refim[(dy+4)*RX+dx+4]; /* reference is loaded unaligned with movq*/

  /* assembler code for one subaperture */
  asm("movq   (%1),   %%mm1 \n\t" /* load 8 reference pixels unaligned */
      "psadbw (%2),   %%mm1 \n\t" /* sum of absolute differences */
      "movq   16(%1), %%mm0 \n\t" /* reference is 16 pixels wide, skip */
      "psadbw 8(%2),  %%mm0 \n\t" /*              by 16 pixels per row */
      "paddw  %%mm0,  %%mm1 \n\t" /* add to previous sum in MMX register */
      "movq   32(%1), %%mm0 \n\t"
      "psadbw 16(%2), %%mm0 \n\t"
      "paddw  %%mm0,  %%mm1 \n\t"
      "movq   48(%1), %%mm0 \n\t"
      "psadbw 24(%2), %%mm0 \n\t"
      "paddw  %%mm0,  %%mm1 \n\t"
      "movq   64(%1), %%mm0 \n\t"
      "psadbw 32(%2), %%mm0 \n\t"
      "paddw  %%mm0,  %%mm1 \n\t"
      "movq   80(%1), %%mm0 \n\t"
      "psadbw 40(%2), %%mm0 \n\t"
      "paddw  %%mm0,  %%mm1 \n\t"
      "movq   96(%1), %%mm0 \n\t"
      "psadbw 48(%2), %%mm0 \n\t"
      "paddw  %%mm0,  %%mm1 \n\t"
      "movq   112(%1),%%mm0 \n\t"
      "psadbw 56(%2), %%mm0 \n\t"
      "paddw  %%mm0,  %%mm1 \n\t"
      "movd   %%mm1,  %0    \n\t"
      "emms                 \n\t"
      : "=g" (c1)
      : "r" (rp), "r" (ip)
      );
  return c1;
}
```

Fig. 6: Source code for calculating the sum of absolute differences for an 8 by 8 subaperture in a 16 by 16 reference aperture. This requires a Pentium III or compatible CPU and the GNU C compiler. The loop over all 8 rows of pixels has been unrolled to avoid branch misses in the heavily pipelined Pentium III architecture.

There are two crucial parts of the software. The first is the Linux driver for the digital frame grabber, which is provided by GOM in Germany as an open-source project (http://oss.gom.com). The company has proven to be very responsive to our needs, in particular in adapting the code to our Dalsa camera. The test program supplied with the driver was used as the backbone of all of our software developments. We could therefore concentrate on the few crucial pieces of code that derive the control signals and control the mirrors.

The other crucial software aspect consists in the use of the MMX and SSE instructions provided by the Pentium III to (1) dark and gain correct the images coming from the camera and (2) calculate the sum of absolute differences between an image and a reference for various displacements. These time-critical pieces of software have been implemented in inline assembler code within the C program. MMX and SSE instructions provide parallel processing on up to 8 pixels. Dark and gain corrections are performed with 16-bit accuracy and then the calibrated images are truncated to 8 bits.

The sum-of-absolute-differences algorithm is shown in Fig. 6. The **movq** instruction moves 8 pixels simultaneously into MMX registers. The **psadbw** instruction calculates the sum of absolute differences of 8 pixels in the captured image with 8 pixels of the reference image. This instruction can be scheduled every 2.5 clock cycles (2.5 ns for our 1GHz processor) since the Pentium III has two execution units that can handle **psadbw** instructions. However, the 1-GHz Pentium III can, on average, only load 1 byte per clock cycle, meaning that the performance is typically limited by the 1GByte/s I/O limit and not by the processing power. Nevertheless, this is sufficient to run the 256 by 256 pixel correlation tracking at more than 500 Hz or analyze 200 wavefront sensor subapertures with 8 by 8 pixel images and a 16 by 16 pixel reference image within a millisecond. The 200 subapertures are about 10 times more than in any other working solar AO system and at least a factor of 2 more than any solar AO system currently under development.

5. FIRST RESULTS AND OPERATIONS

The Universal Tracker has been used for scientific observations since April 1, 2002. More than half of the observations since then have requested the UT. The limb-tracking mode, for the first time, has allowed us to measure the CO emission off the solar disk with the FTS. Polarimetry at 1.56 and 12.3 μm has been improved significantly because the slow polarization modulation schemes used at those wavelengths are particularly sensitive to image motion. Correlation tracking in the quiet Sun has provided stable time series of the evolution of granulation as seen in CO at 4.6 μm. Figure 7 shows an example of the achieved image motion compensation as measured in real time.

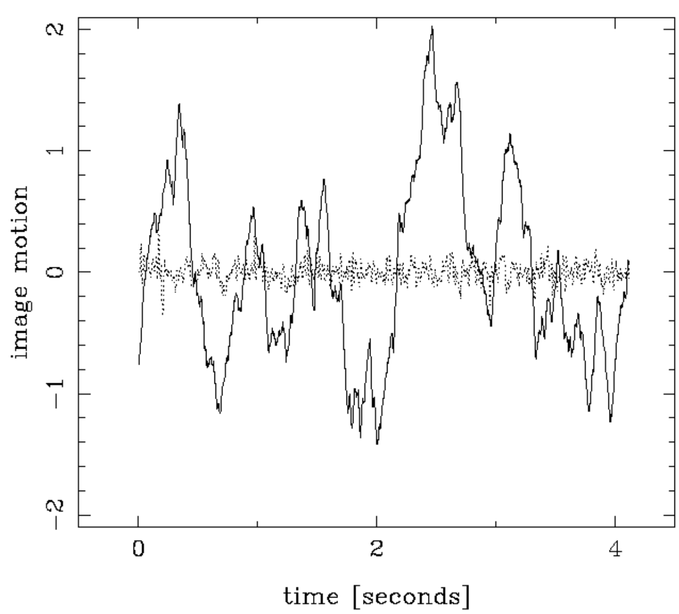

Fig. 7: Performance of limb tracking as measured over 4 seconds. The image motion excursions are over 3 arcsec p-p without the compensation (solid line), while the closed-loop measurement reduces this by more than a factor of 10.

The loop on the breadboard AO system including the tip-tilt mirror was closed for the first time on July 2, 2002. The wavefront sensor was operated in a 10-nm bandpass around 830 nm with 193 subapertures and a 250 Hz loop update rate. A video camera was in the science focus with a 10-nm bandpass around 990 nm. Figure 8 shows the performance achieved in this initial test on a sunspot. For this initial test, the solar beam from the McMath-Pierce West Auxiliary telescope was utilized with its aperture stopped down to a circular aperture of 50 cm. The diffraction limit at this wavelength is about 0.4 arcsec. Clearly, small-scale structures at this scale can be seen over a large part of the AO-corrected image. A movie showing the raw video footage with the adaptive optics loop opened and closed can be found at http://www.noao.edu/noao/staff/keller/irao.

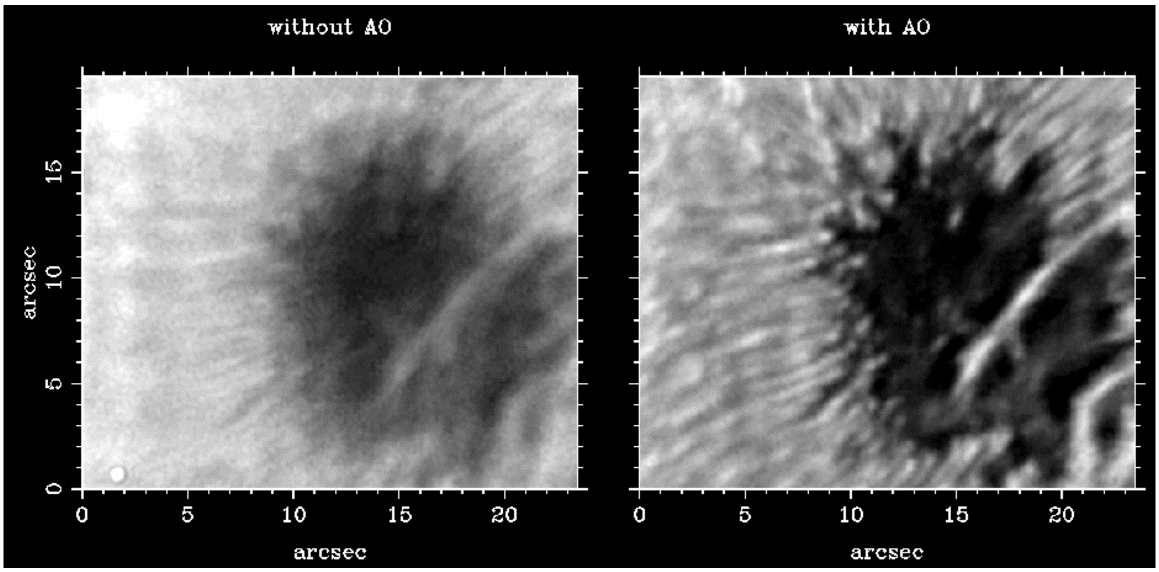

Fig. 8: 16-ms exposure-time images of a sunspot at 990 nm without (left) and with (right) adaptive optics. Both images were filtered with an unsharp mask to compress the large intensity range, and both are displayed at identical contrast. The image to the left was among the sharpest images recorded without adaptive optics.

An important operational aspect is worth discussing here. The number of subapertures is much larger than the number of actuators of the deformable mirror. This allows us to directly measure the mirror influence functions with the existing wavefront sensor without having to use a separate system for calibrating the deformable mirror. By putting a pinhole in the telescope focus and running the actuators through their full range, we can accurately determine the influence functions within a few minutes. Linear fits to the measured subaperture shifts as a function of the applied voltage squared are calculated to obtain an accurate measurement of the subaperture shift as a function of the voltage squared. These data are combined in a matrix and inverted with a singular value decomposition routine, allowing us to select the number of orthogonal mirror modes that are kept in the mirror control matrix.

6. CONCLUSIONS AND OUTLOOK

We have built and successfully tested an initial breadboard version of the low-cost adaptive optics system for the 1.5-m McMath-Pierce solar telescope. The total hardware cost is less than $25,000 for a 37-actuator system. Key differences between the described adaptive optics system at the McMath-Pierce and other solar AO projects include:

- The all-reflective design needed for observations beyond 2.5 μm; Other systems use refractive elements that limit scientific operations to below 2.5 μm;
- 100 to 200 subapertures in the wavefront sensor are needed to adequately sample the wavefront under mediocre seeing conditions (about r_0 =4 cm at 500 nm) at the McMath-Pierce telescope. This allows us to accurately measure the mirror influence function with the same wavefront sensor;
- Flexible size and location of wavefront-sensor subapertures, which can handle varying pupil geometries;

- The possibility to operate at the limb and correct aberrations perpendicular to the limb.

During 2003 we will transition the breadboard system into a user instrument. Improvements to the breadboard system will include:

- Increasing the loop update rate to an initial rate of 500 Hz by moving a few lines of C-code into assembler, eventually reaching the full 1-kHz frame rate of the camera by modifying the frame-grabber driver;
- Improving the calculation of the mirror control matrix by minimizing the wavefront variance instead of minimizing the subaperture shifts;
- Reducing the coupling of image motion and higher-order aberrations by properly accounting for the wavefront tilts introduced by the membrane mirror;
- Providing flexible wavefront sensor geometries, including (1) fewer and larger subapertures for operation with low-contrast scenes such as quiet-Sun granulation or (2) operating on non-circular apertures (e.g. the apertures of the McMath-Pierce telescopes during the summer months).

On the long term, we expect to expand the existing system to a larger number of mirror actuators to adequately correct wavefronts for wavelengths as short as 1.56 µm. This wavelength is crucial for solar physics since it represents the opacity minimum at which the deepest layers of the solar atmosphere are seen. Furthermore, the weak magnetic fields occurring all over the Sun are probably best studied using two iron lines at 1.56 µm. Concerning this goal, a 119-actuator membrane mirror is currently available from Okotech. The future Linux 2.6 kernel will provide better real-time behavior by minimizing kernel latencies. This alleviates the necessity to switch to a true real-time operating system.

The wavefront sensor and analysis architectures scale well to larger systems such as those required for future solar telescopes with potentially more than 1000 subapertures: The Pentium 4 currently has an I/O limit of 3.2 GByte/s, and its SSE2 instruction set can operate on 16 pixels simultaneously. Larger on-chip caches of the Xeon version reduce the required I/O rate considerably. Multiple processors can reduce the load per processor. CMOS cameras with 1280 by 1024 pixels operating at 485 frames/s (corresponding to a data rate of 660MB/s) are now commercially available. Subarrays can be read out at higher frame rates. 64-bit, 66MHz PCI bus frame grabbers transfer up to 528 MB/s, which is a good match to the camera data rates.

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REFERENCES

1. H. Uitenbroek, "The CO fundamental vibration-rotation lines in the solar spectrum. I. Imaging spectroscopy and multidimensional LTE modeling ", *ApJ* **531**, pp. 571-584, 2000.
2. T.R. Rimmele, "Solar adaptive optics", *SPIE* **4007**, pp. 218-231, 2000.
3. G.B. Scharmer, M. Shand, M.G. Lofdahl, P.M. Dettori, W. Wei, "Workstation-based solar/stellar adaptive optics system", *SPIE* **4007**, pp. 239-250, 2000.
4. C. Paterson, I. Munro, and J.C.Dainty, "A low cost adaptive optics system using a membrane mirror", *Optics Express* **6**, pp. 175-185, 2000.
5. M. Shand, G.B. Scharmer, "Correlation Tracking and Adaptive Optics Control Using Off-The-Shelf Workstation Technology", *ASP Conference Series* **183,** pp.231-238, 1999.