Adaptive Optics at Mount Wilson Observatory: Results from the 60-inch Telescope

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**Abstract.** We present results of an adaptive optics system originally built for defense applications but now mounted on the 60-inch telescope. With careful attention to thermal control on nights of good seeing, we have been able to obtain stellar images that are within 25% of the telescope diffraction limit at 700 nm. We discuss the use and utility of such a system for astronomical applications.

1. Introduction

Some real-time correction of atmospheric distortions for ground-based telescopes of non-trivial aperture is now possible (see, e.g., Babcock 1990; Hardy 1991; Roddier et al. 1991; Beckers 1993). The prospect of images with higher angular resolution than the limits of atmospheric seeing promises fundamental evolution of ground-based astronomy. At Mount Wilson Observatory, we began a collaboration with Lincoln Laboratories to operate an extant adaptive optics system on an existing astronomical telescope for compensation of visible light. The Department of Defense declassified and loaned the Atmospheric Compensation Experiment (ACE, Hardy 1978) to Mount Wilson in order to test the feasibility of operating an adaptive optics system under various meteorological conditions and for high-angular and high-spectrum resolution research on nearby bright stars. The adaptive optics project at the 60-inch telescope is a prelude to a more advanced program planned for the 100-inch Hooker telescope (Shelton and Baliunas, this volume). Mount Wilson offers conditions that make it a useful site for assessing different techniques and instruments: good natural seeing and large blocks of time on telescopes of substantial aperture.

Neither the 60-inch telescope (which was the largest in the world when it was built in 1908) nor the ACE system was constructed specifically for astronomical research based on image compensation. For example, the original purpose of the ACE system was to obtain high strehl ratio in visible-light laser beams propagating through the earth’s atmosphere. But many astronomical applications desire
not improvement in the strehl ratio, but rather improvement in the angular resolution of objects with poor contrast relative to the background sky. Another example of an apparent barrier to good active compensation is the bottle-glass objective of the 60-inch telescope, which was cast in 1894. By modern mirror standards it has a very large coefficient of thermal expansion. However, the combination of the ACE system on the 60-inch telescope, good natural seeing of the site, and careful thermal control has produced nearly diffraction-limited images in the visible, despite the disparate origins of the telescope and compensation system for this application.

The angular resolution, \( \Delta \theta \), by Rayleigh's criterion is

\[
\Delta \theta \approx \frac{\lambda}{D}
\]

(1)

at a wavelength, \( \lambda \), and diameter of telescope objective, \( D \). Improvement from the seeing limit to the theoretical resolution of the 60-inch telescope (\( \Delta \theta \approx 0.092 \) for \( \lambda = 700 \) nm) would be similar in magnitude to the improvement provided by Galileo's 2.6 cm telescope (\( \Delta \theta \approx 6'' \)), compared to the human eye (\( \Delta \theta \approx 72'' \)). We describe solutions to the problems encountered in and show results from the approach to the diffraction limit.

2. The ACE System

The adaptive optics system computes the degradation in the wavefront and controls a rapidly-deforming mirror in order to compensate a natural guide star in a closed control loop. The ACE system has a monolithic deformable mirror with 69 sub-apertures each with piezoelectrically-controlled throw of 0.7 \( \mu \) m (peak-to-peak) per subaperture. The mirror can be reshaped at a rate of 10 kHz.

A beamsplitter partitions the starlight so that light with \( \lambda \leq 600 \) nm is diverted to the wavefront sensor and longer wavelengths to the astronomical detector. The distortions in the wavefront are measured by two rotating, radial gratings sampling in orthogonal directions (labeled \( x \) and \( y \)) at a rate of 40 kHz. The gratings chop the image of the star in order to detect wavefront slopes in each subaperture. The advance or delay of timing of the light of a subaperture is recorded by a photomultiplier tube; the reconstruction of the shape of the deformable mirror is based on the tilts in the subapertures in both the \( x \)- and \( y \)- directions. In addition, compensation for the slope of the entire wavefront is made at a rate of 20 Hz with a tip-tilt mirror. The overall system bandwidth is variable, and typically operated at 50 Hz for astronomical applications.

The ACE system is fed by relay optics from the Coude focus. The optical bench and electronics occupy 10 m\(^2\) of floor space on the ground floor of the dome.

When closure is achieved, the compensated image often shows the first Airy diffraction ring, as recorded by eye or with a CCD camera.

2.1. Installation and Initial Considerations

In order to use the ACE system for astronomical research on the 60-inch telescope, we undertook several major tasks:
1. Improvement of the thermal control inside the dome.
2. Reduction of mechanical vibration in the adaptive optics system.
3. Automation of the system for one-person operation.
4. Improvement of the telescope pointing, tracking, alignment and collimation to work at the diffraction limit, not the seeing limit.
5. Improvement of the reliability of the electronics of the adaptive optics system.

By far the most important task was thermal control, because it meant achieving compensation at all. We discuss below the detection and reduction of thermal distortions and mechanical vibrations that effect the adaptive optics system. The other requirements were intended for ease and cost-effectiveness of operations. In an accompanying paper, Shelton and Baliunas (this volume) discuss the three last issues which are critical for efficient and inexpensive astronomical observations. Because the ACE system resides on the ground floor of the dome, no additional shielding from the electromagnetic interference caused by the nearby radio and television broadcast towers (Shelton et al. 1991) is necessary.

2.2. Thermal Control

In order to take advantage of the natural good seeing of the site (Babcock 1990; Walters et al. 1990), the thermal environment within the dome must be controlled. The dome was designed by Ritchey (1909) to reduce dome seeing. The dome is voluminous (18 m diameter) and double-walled. The telescope is well above ground level and has an isothermal bearing. On the other hand, the mirror is solid plate glass, weighs 2000 pounds and is susceptible to thermal distortion.

We gained great experience at ferreting out thermal problems. As various sources of heat were gradually controlled in the dome, compensation occurred, then the compensated image quality improved. First, the electronics racks of the ACE system dissipate 6500 watts, which is vented far from the dome. With that heat removed, the system achieved lock and produced images whose full-width at half-maximum intensity (FWHM) is 0.30. Next, removing heat sources on the optical bench yielded narrower profiles of FWHM 0.17. Finally, the installation of large exhaust fans in the dome's eight original ventilation flaps on the ground floor allowed daytime compensation (see below) and profiles of 0.125. These fans draw air through the dome opening, past the telescope, down to the ground floor and out the vents. The air flow near the telescope helps control thermal emission from observers.

3. Results on Compensation

We show results from two cameras used to record the following images – the RAC speckle camera loaned to us by J. Beletic and an SBIG ST6 camera. The former camera has a scale of the order of 0.0236 per pixel; we used only the interior field of 4.4 x 4.4 in size. The latter camera has pixels of dimension 0.0250 in z and 0.0297 in y, with a field size of 11.1 x 7.2.
3.1. Results from the Speckle Camera: High-speed Imaging

This CCD camera allowed us to diagnose vibrations in the compensated images that could be observed by eye or by the slightly degraded performance in exposures longer than several seconds. We chose the close binary $\beta$ Del as a diagnostic test of the jitter. We obtained images with exposures of 10 millisecond duration at a rate of 32 Hz.

The stream of images of $\beta$ Del was recorded sequentially over $\sim$ 80 seconds. We measured the intensity of the brightest pixel and its drift in position relative to an arbitrary fiducial point as a function of time in the series of 2900 unselected but corrected frames. Figure 1 shows an intensity variation with a frequency of 1.2 Hz, so noticeable by eye.

The origin of significant power at a frequency of 1.2 Hz in the spectrum of the peak intensity is confirmed by the periodicities in the periodograms of the motions of the peak intensity. The power spectra reveal one strong frequency in $x$ and two in $y$: $f_1(x) = 41.714 \, Hz; f_1(y) = 41.7127 \, Hz; f_2(y) = 42.9030 \, Hz$.

The frequencies, $f_1(x)$ and $f_2(y)$ are the rotation rates of the $x$- and $y$-radial gratings. The 1.2 Hz frequency difference in $x$ and $y$ positions ($f_2(y) - f_1(x)$) is the difference in the rotation rates of the grating wheels. The grating wheels were unbalanced and not phased locked, which induced vibration in the relay optics on the optical bench. The $y$-direction sees both frequencies. Those mechanical vibrations have since been greatly reduced.

The rms values of the average jitter in position are $\sigma_x = 0.048$ and $\sigma_y = 0.062$ ($\sigma_{tot} = 0.078$), which contribute image vibration on the order of at least half
the size of the theoretical diffraction limit. However, the peak intensity in each frame is not well-correlated with its position. That fact led to identification of the other component of jitter—the atmosphere itself and lack of response in the electronics to the tilt. Initially, tilt only below a frequency of 20 Hz was corrected by the tip-tilt mirror. The electronics of the deformable mirror subtracted tilt, leaving tilt above 20 Hz uncorrected, in amounts that depend upon atmospheric conditions. We have since modified the feedback pathways in the system electronics to improve tip-tilt response.

By means of simple processing to reduce the effect of those sources of jitter in the stream of data, we produced the image of β Del in Figure 2. The frames with the highest peak intensities, about one-third of the 2900 frames, were centered and averaged. Details of the image are given in Table 1. The image with tilt-only correction has a FWHM of 0.73; the raw seeing was ≈ 1. Static aberrations, which make the partially-compensated image asymmetric, are corrected by the deformable mirror. However, such aberrations use some of the stroke of the deformable mirror. We have since reduced the amount of static aberrations in order to work in poorer seeing.

The FWHM of both stars in the compensated images is 0.115, only 25% larger than the theoretical diffraction limit of the telescope. The first Airy ring of both components (at 5% of peak intensity) is easily seen by eye or in a radial profile of the compensated image. Roughly one-third of the uncompensated light is corrected to near the diffraction limit; some two-thirds is left in the penumbra of the "fried egg".

The "shift-and-add" technique used to reduce jitter in the production of Figure 2 may be a useful option for obtaining additional correction to images beyond real-time compensation. For example, a relatively few number of actuators or modes in a compensation system might be combined with speckle or speckle-like imaging techniques to provide a cost-effective instrument choice. We plan to include the capability of rapidly selecting only frames of high strehl ratio and computing a "shift-and-add" recorded image at the telescope in order to reduce atmospheric jitter uncorrected by the ACE system whose deformable mirror has limited stroke.

3.2. Recent Observations with the ST6 Camera

With correction of mechanical jitter and rigorous thermal control in the dome, the ACE system achieves lock consistently on nights when the raw seeing has FWHM ≤1.7. Even for integration times over several seconds, compensated images can have FWHM ≈0.15 without processing. Some results obtained with the ST-6 camera are shown in Figures 3 - 6; details of the images are listed in Table 1.

The images of α Leo (Regulus, Fig. 3) were obtained in daylight, with the use of a ~5 field stop at Coude focus. Compensation on objects with low contrast relative to the background is possible with radial-grating wavefront sensors (such as in the ACE system) or curvature sensing. On the other hand, standard Shack-Hartmann wavefront sensors can have difficulty working at high background.

Figures 4, 5 and 6 show uncompensated and compensated images of λ Oph, ζ Her and η Oph.
Figure 2. Three-dimensional view of β Del with tip-tilt correction alone left and full compensation, including modest processing right. The separation of the components is 0."21 (Hartkopf and McAlister 1992); the FWHM of the individual stellar profiles is 0."115. The improvement in peak intensity is ~7.
Figure 3.  Three-dimensional view of uncompensated (left) and compensated (right) images of λ Oph. The separation of the components is 1.″43. No processing has been done to the images. See Table 1 for details.

Table 1.  Information on images shown in figures.

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<tr>
<th>Figure No.</th>
<th>Star Name</th>
<th>B-mag</th>
<th>Binary Separation (″)</th>
<th>Exposure Time (sec)</th>
<th>FWHM Uncomp(C)</th>
<th>FWHM Comp(C)</th>
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^a Uncompensated image, assumed comparable to raw seeing
^b Compensated image
^c Ratio of peak intensity of compensated to uncompensated image
^d ≈ 900 frames of 10-millisecond exposure were averaged over an 80-second interval
^e FWHM of partially-compensated image; no uncompensated image available
^f Ratio of peak intensity of fully- to partially-compensated image
^g Daytime exposure
Figure 4. Three-dimensional view of compensated (left) and compensated (right) images of α Leo (Regulus) observed in daylight. No processing has been done on these images. See Table 1 for details.
Figure 5. Three-dimensional view of uncompensated (left) and compensated (right) images of ζ Her. The separation of the components is 1.″52. The raw seeing on this night was ≈ 2″ and the exposure time for the compensated image was 120 sec. This is representative of the limit of poor seeing for which lock still occurs. No processing has been done to the images. See Table 1 for details.
Figure 6. Three-dimensional view of uncompensated \textit{left}) and compensated \textit{right}) images of \( \eta \) Oph. The separation of the components is \( 0.\text{"}50 \). No processing has been done to the images. See Table 1 for details.
4. Discussion

We have been using the adaptive optics system and recording meteorological data in order to monitor the system performance under different weather conditions. In collaboration with D. Walters, we are making measurements during all adaptive optics observations with a 10-inch telescope-scintillometer mounted on the 60-inch telescope structure, and occasionally with an acoustic sounder (Walters et al. 1990). Temperature, humidity and wind velocity are continuously measured by sensors located on top of the dome. Temperatures of the air and equipment structures are also measured by sensors located on the optical bench of the ACE system, near the Coude focus, on the cell of the primary mirror, on the support spider of the secondary mirror and inside the dome slot.

The ACE system on the 60-inch telescope requires a natural guide star brighter than $B \approx 6$ and raw seeing better than $1.7''$ for consistent lock and substantial improvement in angular resolution. The system performance, which is roughly a function of raw seeing alone, smoothly degrades as light levels diminish, down to $B \approx 6$, the limit to which we have tested. The declination limits of the 60-inch telescope's Coude train are very restrictive: $-25^\circ < \delta < 35^\circ$. In addition, atmospheric dispersion must be corrected to the diffraction limit at blue wavelengths (due to the wavefront sensor). With the arrival of the new atmospheric dispersion corrector, we will proceed with our plans to conduct spectroscopy with compensated starlight.

The ACE system operating at the 60-inch telescope has demonstrated great success in employing an early adaptive optics system to an historic telescope. A modern adaptive optics system designed for astronomical use could be efficient, relatively inexpensive and robust. The wisdom gained from the use of the ACE system has led to a design for an adaptive optics system for the Hooker telescope, which supplanted the 60-inch telescope as the largest in the world in 1917 (Shelton and Baliunas, this volume).

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References

Babcock, H. 1990, Science, 249, 253
Hardy, J. 1978, Proc. IEEE, 66, 651
Shelton, J.C. and Baliunas, S.L. 1994, this volume.