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Adaptive Optics at Lawrence Livermore National Laboratory

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ABSTRACT

Adaptive optics enables high resolution imaging through the atmospheric by correcting for the turbulent air's aberrations to the light waves passing through it. The Lawrence Livermore National Laboratory for a number of years has been at the forefront of applying adaptive optics technology to astronomy on the world's largest astronomical telescopes, in particular at the Keck 10-meter telescope on Mauna Kea, Hawaii. The technology includes the development of high-speed electrically driven deformable mirrors, high-speed low-noise CCD sensors, and real-time wavefront reconstruction and control hardware. Adaptive optics finds applications in many other areas where light beams pass through aberrating media and must be corrected to maintain diffraction-limited performance. We describe systems and results in astronomy, medicine (vision science), and horizontal path imaging, all active programs in our group.

Keywords: Adaptive optics, atmospheric compensation, real-time imaging

1. INTRODUCTION

Adaptive optics methods and technology has been pursued at LLNL since the 1980s in a number of laser programs. Perhaps the most visible application was for the propagation of high power laser light over long distances through the atmosphere as one component of the Strategic Defense Initiative (SDI) strategy. The goal was to direct laser energy to a small spot on incoming missiles. The required high beam quality demanded active control of the wavefront at very high bandwidth to compensate for atmospheric aberration. A perhaps somewhat less publicized application was in controlling the laser beams used in the atomic vapor laser isotope separation (AVLIS) processes for enriching nuclear fuels. The beams had to traverse long distances zigzagging through enrichment chambers, so initial laser wavefront had to be of the best quality for even illumination throughout the path. Although high speed control was not an issue, it did require active wavefront sensing and electro-optic wavefront control to track drifting thermal aberrations in the laser. AVLIS requirements, and later, the requirements of the national ignition facility (NIF) program, were responsible for driving much of the development of deformable mirror technology.

Through-the-atmosphere imaging applications within the DOD also began to exploit the possibilities of adaptive optics and other techniques for wavefront compensation in the 70s and 80s. Most notably the Starfire Optical Range (SOR) at Kirtland Air Force Base in New Mexico developed an adaptive optics system for imaging of satellites from the ground. LLNL was involved in the late 80s in collaborative work at the Air Force Maui Optical Station (AMOS) in the use of speckle imaging for satellite imaging[1]. During the mid-80s Claire Max, Will Happer, and a number of others involved in a JASONs study proposed the use of lasers to fluoresce sodium in the upper atmosphere to form a wavefront reference beacon, although since this work was classified it was not published until it was declassified in 1991[2]. Meanwhile, French researchers Foy and Laberie had suggested the use of sodium fluorescence in a paper published in 1985[3]. Upon declassification, astronomers immediately picked up on the possibilities for high resolution science imaging and began considering LGS adaptive optics for the Keck 10 meter telescope, the world's largest, and soon thereafter at a number of other telescopes as well. In 1996, a prototype system built by LLNL at the University of California Lick observatory was the first to demonstrate Sodium guidestar adaptive optics correction[4]. This system, on the Shane 3-meter (120 inch) telescope, remains the only operating laser guide star adaptive optics system in use by astronomers today, until the Keck laser system comes on line later this year.

LLNL is actively involved in developing atmospheric compensation technology in several application areas today. These include ongoing activities with the astronomy, vision science, and defense communities through the NSF Center for Adaptive Optics (CfAO)[5], the Defense Advanced Research Projects Agency (DARPA), the National Institute of Health (NIH), and LLNL internal R&D programs.

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2. ADAPTIVE OPTICS TECHNOLOGY

The image resolution is degraded by distortions to the incoming light caused by turbulence in the atmosphere. Adaptive optics corrects the distortion through the use of a wavefront compensation element that counters the optical path variations introduced as light waves travel through the atmosphere. An adaptive optics system basically consists of five main components (Figure 1), 1) a telescope feed using traditional fixed optics, 2) a deformable mirror (DM) or other phase corrector element, whose function is to advance or retard the light so as to restore wavefront phase coherence, 3) a wavefront sensor which measures the phase aberration, typically after correction by the DM, 4) a control computer for calculating corrections to the DM in response to wavefront sensor measurements, and 5) the high resolution imaging detector, which utilizes the corrected light. The split between wavefront sensor and imaging detector, called the diagnostic split, can be based on wavelength. For example, in current astronomy applications, the wavefront is sensed in the "visible" (0.4-1.0 micron) range, while science imaging is done in the near infrared (1.0-3.0 microns).

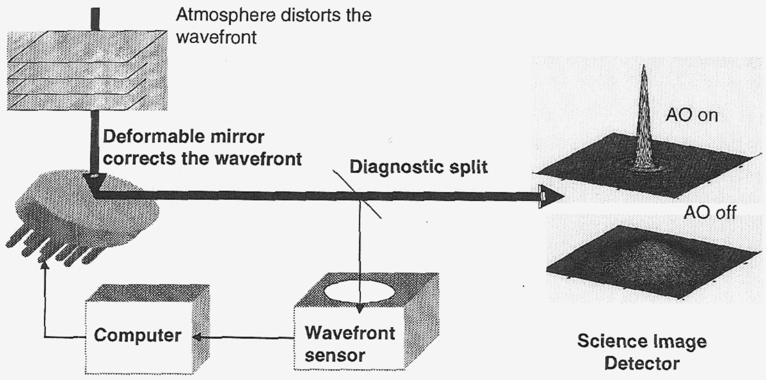

Figure 1. Components of a typical adaptive optics system in closed loop or wavefront nulling configuration

The development of adaptive optics stressed the technologies in several areas. First generation deformable mirrors are made of a thin (~4 mm thick) piece of glass that deforms in response to piezo-electric or piezo-magnetic electrostrictive actuators. A new generation of micro-electromechanical (MEMs) technology DMs promises to make the DM quite a bit smaller and cheaper. The number of actuators required is set by the degree of atmospheric turbulence (characterized by transverse coherence length, r_0), the imaging wavelength, and the size of the primary receiving aperture. Typical good sites for astronomy have r0 in the infrared of about 50 cm. For the Keck telescope (D = 10 meters), the number of actuators is approximately $(\pi/4)(D/r_0)^2 \approx 314$. Future giant (30-100 meter) telescopes imaging at shorter wavelengths and over wider fields of view will require DMs with thousands of actuators.

Wavefront sensor technology is also an area where advancement has been rapid over the past two decades. The CCD technology enables very high quantum efficiency (for maximum use of the expensive laser guide star photons). High speed, low noise readouts developed by the MIT Lincoln Laboratories, and more recently EEV / Marconi Electronics (now E2V), has provided the necessary bandwidth and signal to noise ratio. The most widely used wavefront sensor is the Hartmann sensor, which is based on measuring the local slope of the wavefront (Figure 2). The slopes are related to the wavefront surface through a 2-D version of Poisson's equation

$$\nabla \cdot \mathbf{s}(\mathbf{x}) = \nabla^2 \phi(\mathbf{x}) \tag{1}$$

where s is the wavefront slopes measured by the Hartmann sensor, ϕ is wavefront phase, and x is the position on the aperture. Equation (1) is solved in the wavefront reconstruction computer and the result sent to the DM drive electronics.

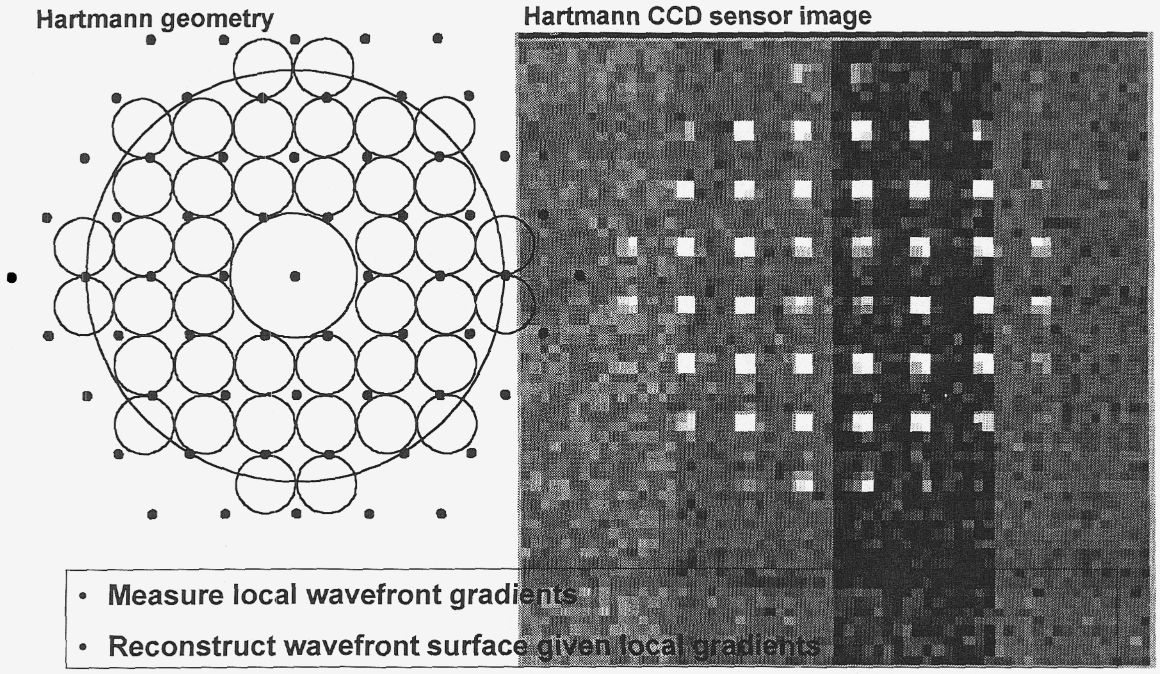

Figure 2. DM actuator and Hartmann sensor geometry for the Lick adaptive optics system. The system has 40 slope measurements and controls 61 degrees of freedom on the DM at an update rate of 500 Hz.

3. APPLICATION TO ASTRONOMY

Photographs of the Lick adaptive optics system are shown in Figure 3. The guide star laser is mounted on the side of the telescope with a 30 cm projection aperture displaced by 1 m from the edge of the Shane telescope primary. As the beam propagates up through the atmosphere, the unwanted backscattered Rayleigh light is kept out of the wavefront sensor because it is out of the field of view by the parallax angle 1 m / 20 km ~ 10 arcseconds, where 20 km is roughly the highest altitude from which significant Rayleigh scatter occurs. The sodium mesospheric layer, in which the guide star is formed, is at 90 km altitude.

Astronomical adaptive optics can be performed using a naturally occurring star instead of a laser beacon, but is limited to portions of the sky in which there is a bright natural star suitable for the wavefront sensing. The high resolution image of Neptune[6] in Figure 4 was taken using the planet itself as the guide star.

The limit of the dimmest usable natural guide star is set by the collecting area of the Hartmann subaperture and the wavefront correction update rate. At least 100 photons/subaperture/frame are needed for sensing the wavefront to the ~1/20'th of a wave necessary for phasing. These parameters are basically determined by the atmosphere via the coherence length r_0 and the wind speed in the turbulent layers respectively. For imaging in the IR, the guide star magnitude limit in typical conditions at Lick is roughly astronomical magnitude R = 12. The angle over which sensing is valid (the so-called isoplanatic patch) is about 20 arcseconds in the IR at Lick (this number is determined by the atmospheric turbulence profile in altitude; further away turbulence decreases the isoplanatic angle). Since the probability of finding a 12'th magnitude star on an arbitrary 20 arcsecond patch on the sky is about 1 in 1000, very little sky coverage is afforded by natural guide star adaptive optics. However, it is easier to do because it doesn't require a laser, and several interesting astronomical science targets are near bright stars.

The laser technology required to fluoresce the 589 nm Sodium D2 line at sufficient brightness is quite challenging. The Lick and Keck systems use a tunable dye laser technology developed for the AVLIS program. These particular lasers produce on the order of 15 watts at 589 nm. The technology can be scaled to even higher power levels with additional amplifiers. Practical difficulties with the expense and safety considerations of operating a dye laser on a mountaintop have driven astronomers to want to develop a turnkey solid state laser at this wavelength and power level, an activity in which the Center for Adaptive Optics is currently actively involved.

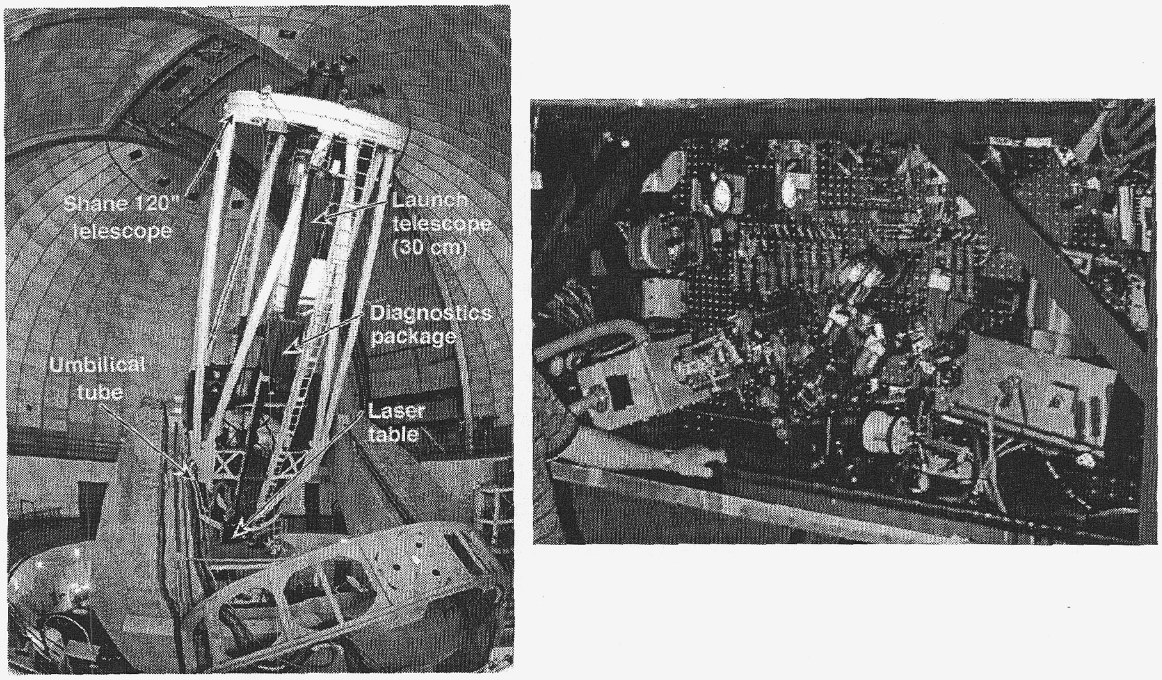

Figure 3. Adaptive optics system on the 120 inch Shane telescope at Lick Observatory. The guide star laser is mounted on the side of the telescope with a 30 cm projection aperture 1 m displaced from the edge of the Shane telescope primary. The adaptive optics bench is located at the Cassegrain focus (bottom of the telescope tube). The most prominent features visible are the wavefront sensor camera on the right and the science imaging camera dewar on the left. The DM is located in the upper right of the photo.

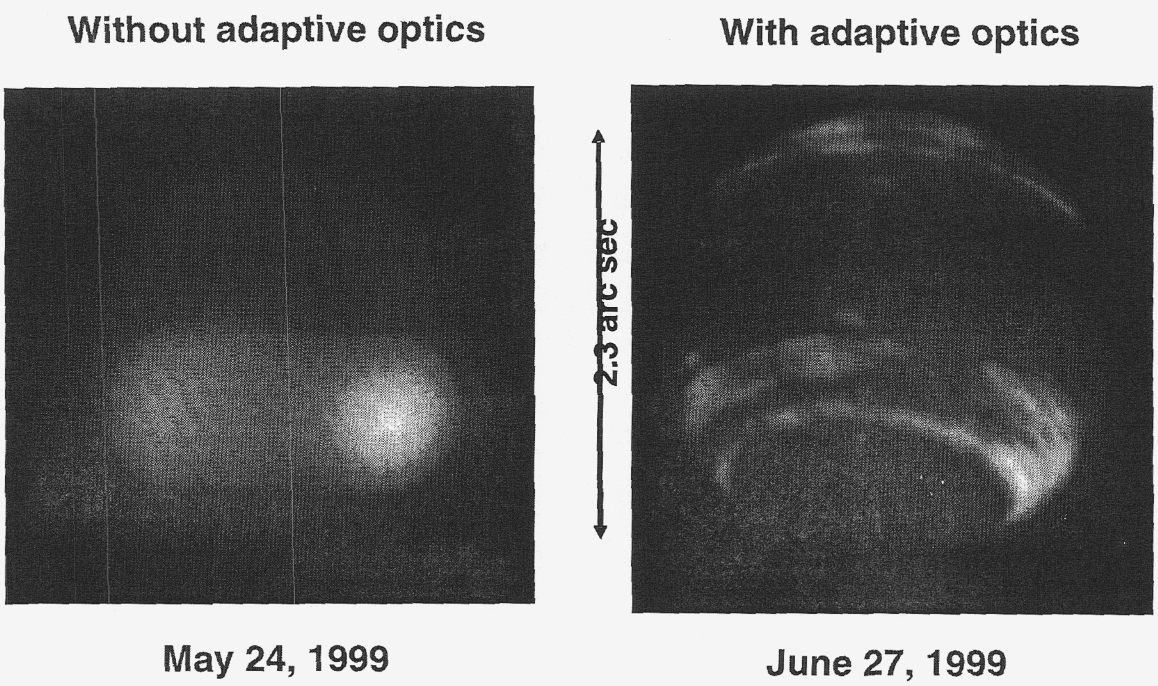

Figure 4. Image of Neptune taken with the Keck telescope adaptive optics system and NIRC-II camera at 1.6 microns wavelength. Weather bands in Neptune's upper tropospheric layer are visible and were tracked over time[6].

LLNL is involved with the development adaptive optics systems for future giant telescopes, in particular the 30-meter CELT telescope proposed by UC astronomer Jerry Nelson who designed the Keck telescope. The CELT goals call for an adaptive optics system that can correct at wavelengths less than 1 micron and over a wide field of view. Extension of the field of view beyond the isoplanatic angle requires a multi-conjugate approach to wavefront correction, where multiple DMs are placed at positions conjugate to turbulent layer heights and multiple laser beacons are used to probe the atmosphere in various directions. Determining the wavefront components to assign to each layer height, given wavefront beacons and sensors that probe through the entire volume, is a problem that is analogous to that of tomography. This new phase of adaptive optics application to astronomy will once again stress the deformable mirror, sensor, and laser technologies.

4. APPLICATIONS TO OPTHALMOLOGY AND MEDICAL VISION SCIENCE

In collaboration with partners in the CfAO and with grants from the NIH, LLNL has been involved with vision scientists in the development of adaptive optics systems that can image the retina of the eye at high resolution, or improve visual acuity. The system shown in Figure 5 was build for UC Davis ophthalmologists testing the psychophysical effects of the greatly improved human vision that might be possible with correction of higher order aberrations of the eye. The analog of a laser guide star beacon is produced by sending a low power beam to reflect off the retina. A similar system now in clinical trials is designed to pre-test laser eye surgery patients and provide pre-operative feedback to the patient on the quality of the intended correction. LLNL is also involved in designing adaptively corrected scanning laser confocal ophthalmoscope (SLO) and optical coherence tomography (OCT) instruments, which can provide high resolution three-dimensional images of the retina.

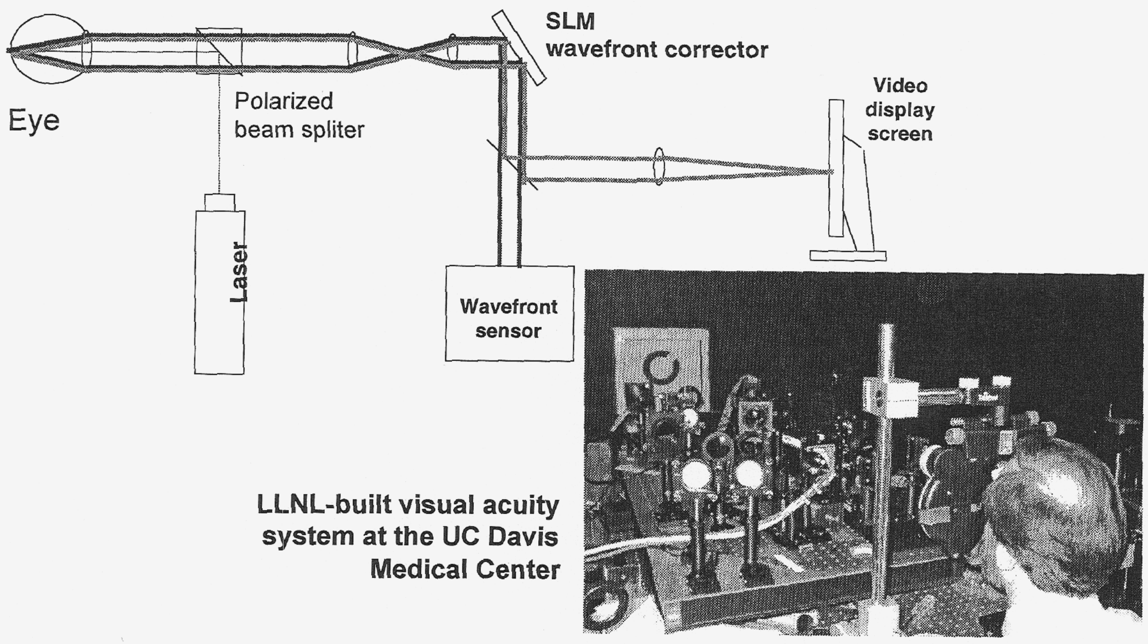

Figure 5. Adaptive optics vision correction system for the UC Davis Medical Center in a visual acuity test configuration.

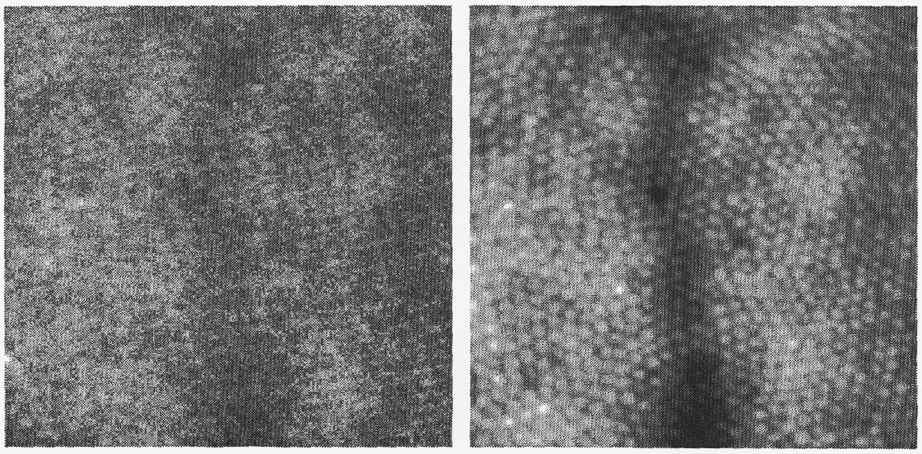

Figure 6. Image of the photoreceptors in the central fovea region of the retina. Left, AO off, right, AO on. The adaptively corrected image detects the individual cone photoreceptor cells, and the shadow of a blood vessel. Images courtesy of Austin Roorda, University of Houston.

5. APPLICATION TO COMMUNICATIONS

The capability of adaptive optics to maintain high beam quality in atmospheric transmission is useful in free space optical communications applications. By keeping the beam intact, as if it had propagated in vacuum, the system provides lower bit error rate and fewer fade periods, and reduces the communication laser power needed. The DARPA Coherent Communications, Imaging, and Targeting (CCIT) program is sponsoring the development of MEMs technology for such applications. At LLNL we are incorporating these newly developed MEMs devices in a testbed for testing CCIT concepts. Using 1 ns pulsed laser, the atmospheric path can be probed holographically. The wavefront sensor registers in-phase and quadrature-phase interferometric images formed by timing the local oscillator pulse to mix with a beacon pulse sent by the cooperating agent at the other end of the free space link. The MEMs device is not a continuous DM as typically used in astronomy but instead is an array of phase (piston) elements which can be positioned continuously to affect the phase over a range of one wavelength. More than one wave of phase aberration is handled by phase wrapping, since the system is single-wavelength.

We tested the device in conjugated-link mode to determine the reduction in bit error rates. Essentially, a factor of 10 improvement of Strehl ratio (a measure of beam quality, the ratio of on-axis intensity to that of a diffraction-limited beam) results in a factor of 10 reduction in laser power needed to maintain a given bit error rate. The increased factor of available laser power can be used to increase the channel bandwidth. Alternatively, a secure channel based on single-photon encryption is conceivable, whereby if an eavesdropper intercepts communication it is immediately noticed by the loss of the photon, since adaptive optics ensured that that photon would enter the receiver aperture and not be scattered by the atmosphere.

6. APPLICATION TO HORIZONTAL PATH IMAGING

Speckle imaging technology has been advanced at LLNL since the 1980s, when Lawrence, Goodman, Johansson, and Fitch[1] used it for imaging satellites at the Air Force Maui Optical Station. Since then it was applied to imaging the comet Shoemaker-Levy 9 collision with Jupiter in 1994 with the Lick 3 meter telescope, before adaptive optics was installed[7]. Recently, with heightened concern for homeland security, we have been adaptive this technology to horizontal path imaging. The horizontal path provides an challenge to atmospheric compensation of images on a wide field of view since the turbulent atmosphere is distributed almost equally along the entire path, severely reducing the isoplanatic angle. Speckle imaging does not use a beacon but instead utilizes contrast information throughout the field and hence appears to mitigate anisoplanatic effects somewhat. Recent field experiments (Figure 7) have shown remarkable improvement to image resolution and contrast.

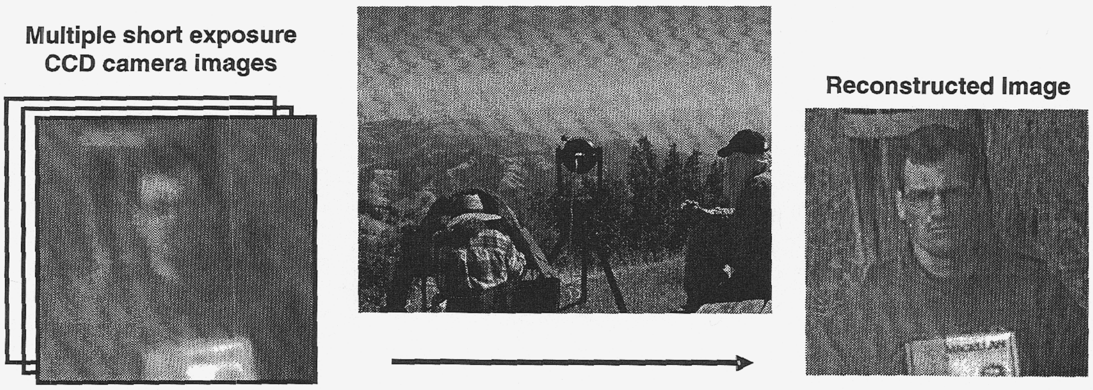

Figure 7. Example of horizontal path imaging using speckle image reconstruction

7. CONCLUSION

Adaptive optics provides the means to correct for atmospheric distortion of optical information. Sensing and controlling the wavefront stresses the technology in detectors, wavefront control devices, lasers, and computation. Future applications will require smaller, lower cost components, such as MEMs devices. In partnership with the NSF Center for Adaptive Optics, NIH, and DARPA, LLNL is leading efforts in developing and applying adaptive optics technology to astronomy, vision science, communications, and homeland security applications.

ACKNOWLEDGEMENTS

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