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# AO Group Annual Report

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## Adaptive Optics

The Adaptive Optics (AO) Group in I Division develops and tests a broad range of advanced wavefront control technologies. Current applications focus on

- Remote sensing,
- High power lasers
- Astronomy
- Human vision

In the area of remote sensing, the AO Group leads a collaborative effort with LLNL's Nonproliferation, Arms Control & International Security (NAI) Directorate on Enhanced Surveillance Imaging. The ability to detect and identify individual people or vehicles from long-range is an important requirement for proliferation detection and homeland security. High-resolution imaging along horizontal paths through the atmosphere is limited by turbulence, which blurs and distorts the image. For ranges over ~one km, visible image resolution can be reduced by over an order of magnitude. We have developed an approach based on speckle imaging that can correct the turbulence-induced blurring and provide high resolution imagery. The system records a series of short exposure images which freeze the atmospheric effects. We can then estimate the image magnitude and phase using a bispectral estimation algorithm which cancels the atmospheric effects while maintaining object information at the diffraction limit of the imaging system.

Field demonstrations of this technique, supported by NNSA/NA-22, have produced significantly improved images over the past several years. In 2004, we extended the capability to handle moving objects. [C. Carrano, J. Brase, "Adapting high-resolution speckle imaging to moving targets and platforms," Proc. SPIE Int. Soc. Opt. Eng, 5409, 96 (2004).] This requires additional image pre-processing steps of object tracking,

extraction, and windowing to make the object look as if it is stationary and to remove the relative motion between the target and its background. We experimentally demonstrated significant image enhancements of scenes containing vehicles moving at highway speeds. We also demonstrated enhanced imaging from a number of non-LLNL acquired imagery sources, most notably an aerostat platform flying at 2500 feet.



**Figure 1: Before and after speckle processing of a semi-truck at 13 km range traveling at highway speeds.**

The AO Group has also begun leading a collaborative effort with the NAI Directorate on Integrated Active Nanolaminate Optics. Lightweight space telescopes are a key ingredient in future persistent surveillance systems that are important to the detection, tracking, and characterization of proliferation activities. Nanolaminate optics are the enabling technology for future lightweight space telescopes. Nanolaminate materials are engineered at the atomic level to provide optimal strength, stiffness, and surface properties for lightweight optics, providing a path to optics that can reach areal densities as low as 1 kg/m<sup>2</sup>. These optics must actively control their shapes with integrated actuators. To reach the areal densities desired for space

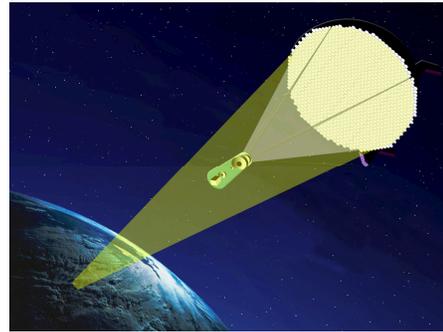
optics, the actuators must be an integral part of the overall nanolaminate structure. In this new project we will demonstrate the key technology capabilities needed to produce active nanolaminate optics with integrated actuation.

When successful, this project will create a fundamental paradigm shift in large optics technology – similar to, if not greater than, the paradigm shift caused by the development of actively controlled segmented and meniscus primary mirror technologies that enabled the current generation of 8-10 meter ground-based telescopes after over 50 years during which telescope apertures were unable to grow successfully beyond the 5-meter size of the Palomar Telescope. The implications of this paradigm shift for the capabilities of future space-based assets could be dramatic – enabling more than an order of magnitude growth in aperture size and drastically reducing fabrication times and deployment costs.

Actuated nanolaminate optics will also provide other new capabilities with direct application to proliferation detection, including deployable optics for small remote-sensing platforms, and multiple beam forming and atmospheric correction for horizontal path lidar systems. This new class of active optical element will also enable high resolution beam control for large laser systems for NNSA (e.g. NIF) and for DOD laser weapons applications.

NNSA/NA-22 began funding the development of next-generation nanolaminate optics with integrated micro-actuators in 2004. Design and modeling for a scaled prototype integrated active nanolaminate optic was performed. Novel space telescope architectures that make use of this new class of active lightweight mirror technology were studied. I Division also provided the design and implementation of a 1.5 meter coating facility for fabrication of large nanolaminate optics led by Chemistry and Materials Science Directorate personnel with

support from the National Reconnaissance Office.



**Figure 2: Design concept for a giant lightweight space telescope. The primary mirror is made from identical, meter-class, ultra-lightweight, spherical segments. The corrector optics module contains a lightweight, meter-class, deformable mirror with cm-scale actuation for compensation of primary mirror aberrations.**

The AO Group is also investigating fundamental issues in optical science, with application to remote sensing, in an LDRD project on Correction of Distributed Aberrations. In many imaging applications and beam propagation applications, aberrations are distributed along the full optical path from target to telescope and within the telescope itself. These distributed aberrations severely limit the field of view of the systems and cause amplitude fluctuations (scintillation). The objective of this project is to demonstrate approaches for sensing the three-dimensional distribution of aberrations and use phase correctors at multiple planes along the line of sight to correct for the effects of these aberrations. A system utilizing this technique will have improved imaging performance over a broader field of view, and these techniques will benefit many applications, such as surveillance imaging, broad-field laser radar, high resolution astronomical imaging, and correction of lightweight optics for future telescopes.

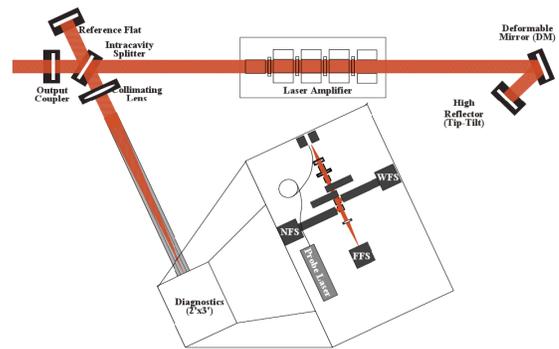
In 2004, we completed the construction of a test bed to study sensing and correction of

distributed aberrations. [K. L. Baker, S. S. Olivier, J. Tucker, D. A. Silva, D. Gavel, R. Lim, and E. J. Gratrix, "Design and progress toward a multiconjugate adaptive optics system for distributed aberration correction," Proc. SPIE 5553, 200-212(2004).] We developed and tested algorithms for tomographic reconstruction of distributed aberrations. We also studied the benefits of controlling both field amplitude and phase, compared with only controlling phase, for imaging and/or propagation through distributed turbulence.

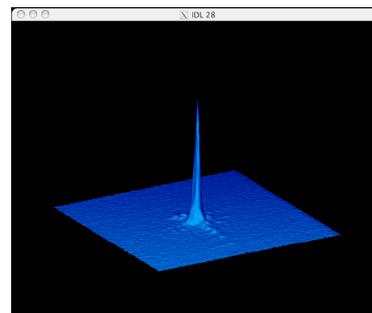
In the area of high-power laser systems, the AO Group is collaborating with the Laser Science & Technology (LS&T) Program in LLNL's NIF Programs Directorate to develop a solid-state, heat-capacity laser. Solid-state, heat-capacity lasers provide a technology for a compact, portable, high-average-power laser system. Supported by a contract with the U.S. Army, this project utilizes an adaptive optics system inside an unstable resonator cavity in order to compensate for optical aberrations in the gain media. These aberrations lead to degradations in beam quality that limit the ability to focus the beam on a target. LS&T is leading this project to develop and field a 10 kW, solid-state, heat-capacity laser with <3X diffraction-limited beam quality and a second phase to develop a 25 kW version using diode technology in place of flash lamps to pump the solid-state laser medium. I-Division is responsible for the wavefront control system using adaptive optics to meet the beam quality specification.

The technique of actively and precisely controlling the mode quality in a laser cavity subject to such large, rapidly changing optical aberrations has never previously been successfully demonstrated. In 2003, this adaptive resonator approach, originally proposed in the 1980's was successfully demonstrated for the first time. In 2004, further quantitative measurements of the beam quality

confirmed the production of a <3 X diffraction limited beam for the 10 kW, flash-lamp-pumped, solid-state, heat-capacity laser system. [K. N. LaFortune, R. L. Hurd, E. M. Johansson, C. B. Dane, S. N. Fochs, J. M. Brase, "Intracavity adaptive correction of a 10-kW solid state heat-capacity laser," Proc. SPIE-Int. Soc. Opt. Eng., 5333(1), 53-61, 1 June 2004.] In addition, the adaptive optics control system for the next-generation (diode-pumped) laser system was designed, procured and built. Closed-loop aberration control on the diode-pumped, solid-state, heat-capacity laser system was demonstrated, and <3 X diffraction limited beam quality was achieved at over 20kW.



**Figure 3: Schematic of the adaptive optics system for the diode-pumped, solid-state, heat-capacity laser, showing an expanded view of the compact, robust diagnostics package, which fits in a 2'x3' footprint.**

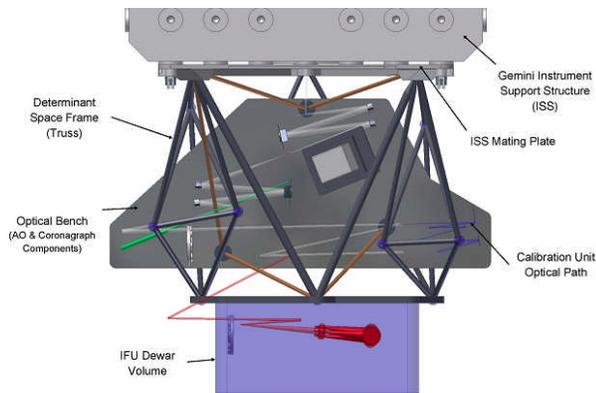


**Figure 4: Surface plot of laser intensity obtained with the diode-pumped, solid-state, heat-capacity laser. The beam quality is <3 X diffraction limited at an average power level over 20 kW.**

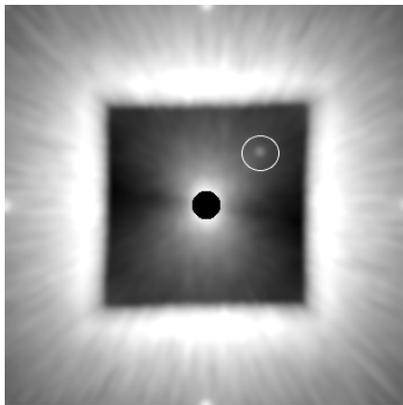
In the area of astronomy, the AO Group is a major participant in the National Science Foundation (NSF) Center for Adaptive Optics (CfAO) headquartered at the University of California, Santa Cruz (UCSC). Founded in 1999, the CfAO is focused on advancing the science and applications of adaptive optics to astronomy and medicine. The CfAO includes 11 university nodes around the country, 10 national laboratories and observatories, and over 20 industrial partners. In astronomy, the CfAO supports research activities on AO for extremely large telescopes and extreme adaptive optics for detection and characterization of planetary systems. Work on extreme adaptive optics has focused on an effort led by AO Group personnel to develop the world's most powerful AO system for an existing 8-10 meter telescope, with new capability for high contrast imaging required for the detection and characterization of planetary systems around nearby stars. [Macintosh, B., Bauman, B., Evans, J., Graham, J., Lockwood, C., Poyneer, L., Dillon, D., Gavel, D., Green, J., Lloyd, J., Makidon, R., Olivier, S., Palmer, D., Perrin, M., Severson, S., Sheinis, A., Sivaramakrishnan, A., Sommargren, G., Soummer, R., Troy, M., Wallace, J. K., Wishnow, E., "eXtreme Adaptive Optics Planet Imager: Overview and Status", Proc. SPIE-Int. Soc. Opt. Eng., 5490, 359, June 2004.] The Gemini Observatory is a multinational (US/UK/Canada/Australia) institution operating two 8-m telescopes, one in Hawaii and one in Chile. In 2003, a scientific review (in which we participated) identified an ultra-high-contrast next-generation AO system for direct detection of extrasolar planets, known as the Extreme Adaptive Optics Coronagraph (ExAOC) as one of the highest priority future instruments for Gemini. This instrument will combine the world's most advanced AO system, apodized coronagraph masks to suppress diffraction, a precision infrared interferometer for wavefront calibration, and a imaging infrared integral field unit (IFU)

spectrograph to detect and characterize extrasolar planets.

In 2004, a multi-institution team led by I Division personnel was selected by Gemini as one of two groups to carry out a detailed conceptual design study for the ExAOC instrument. We used Monte Carlo models of the populations of planets and stars in the solar neighborhood to design an instrument capable of surveying, detecting and characterizing a large (100+) number of planets. We developed several new techniques, including an optimal Fourier reconstructor that allows the system to adapt to changing atmospheric conditions and differing wavefront sensor signal-to-noise, a detailed error budget to predict final contrast, simulations of the AO system, coronagraph, and IR spectrograph including atmospheric scintillation. A paper on the spatially filtered wavefront sensor invented by AO Group personnel was selected as one of the best AO papers of the year by the Optical Society of America. [Poyneer, L., and Macintosh, B., "Spatially-filtered wavefront sensor for high-order adaptive optics", 2004 *Journal of the Optical Society of America A*, 21, 810] We produced a detailed, 4-volume conceptual design report for the whole instrument together with a proposal for the instrument construction. The design study and the \$20M, four-year proposal for the construction phase will be submitted to Gemini in March 2005, and a decision on this instrument is expected in May.



**Figure 5: CAD rendering of the ExAOC instrument mounted on the underside of the Gemini telescope.**



**Figure 6: Simulated ExAOC image of a nearby star (hidden behind the black occulting disk) with an extrasolar planet in a Jupiter-like 6 AU orbit. The ExAO system clears out a square “dark hole” in the halo of scattered light that would normally surround the star.**

The AO Group, in collaboration with the LLNL Institute for Geophysics and Planetary Physics, is also engaging in LDRD supported research on probing other solar systems with current and future adaptive optics. One of the most active areas in modern astrophysics is the search for extrasolar planets. Indirect detection (though Doppler techniques) of more than 100 extrasolar planets has galvanized public and scientific interest in this area. Direct imaging detection of such planets is barely within the reach of current telescopes and adaptive optics (AO) systems, particularly if the planets are young and hence bright. To truly probe the

environments of other stars on scales comparable to the size of our solar system will require the development of next-generation dedicated high-contrast adaptive optics systems, sometimes referred to as “Extreme” adaptive optics (ExAO). We have a three-pronged approach to advancing the study of extrasolar planetary systems. First, we are using adaptive optics on the current large telescopes to probe nearby stars, studying the circumstellar dust disks that form planets and the planets that may be shaping those disks. Second, we are developing the image analysis tools needed to distinguish planetary signals from complex noise. Third, we are developing the basic optical science and technology needed for the future planet-hunting ExAO systems.

In 2004, we carried out observations of dusty young stars at Keck Observatory. We developed new image processing techniques to use the sidereal rotation of the telescope to distinguish candidate companions from image artifacts. Using these techniques, we have reached sensitivity levels capable of detecting 1-2 Jupiter mass planets at 10-20 AU separations around a small number of young dusty stars. A paper on these observations is in preparation for submittal to the *Astrophysical Journal*. We have also participated in Hubble Space Telescope observations of candidate young extrasolar planets. We have also developed techniques for wave-optics modeling of light propagating through an AO system to investigate the effects of small optical errors on the final image, and we have developed a new analytic and numerical model for studying the time-evolution of the adaptive optics images in the case of multiple atmospheric layers with independent wind velocities. We have also participated in the initial definition of an ExAO system for the future Thirty Meter Telescope.

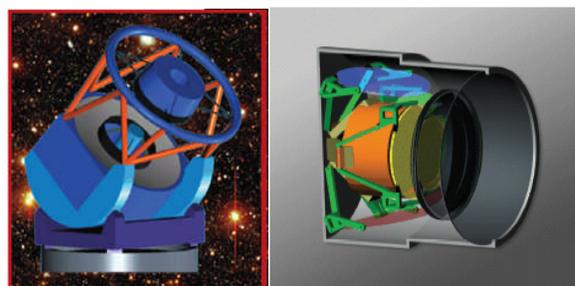
The AO group is also leading a new effort, supported by the NSF Adaptive Optics Development Program, to develop deformable

mirrors that are applicable to adaptive optics for the future Thirty Meter Telescope (TMT). These deformable mirrors will combine nanolaminate foils with dense actuator arrays based on micro-electromechanical systems (MEMS). Nanolaminate foils, which are man-made, flexible, robust metal nano-structures applicable to high-quality optical systems, have been developed at LLNL in the CMS Directorate and represent a revolutionary breakthrough in optical technology. Nanolaminate foils fabricated at LLNL have been demonstrated to have high tensile strength, ultra-low internal stress and super-smooth ( $\sigma < 0.5\text{nm rms}$ ) optical surface quality. Ongoing development of this nano-structure metal foil technology is currently supported by government agencies for application to large lightweight optics for space telescope applications. The structural/mechanical properties of the nanolaminates are expected to facilitate actuation by these methods, resulting in a new paradigm for deformable mirror technology. The specific technical goal of this project is to fabricate a nanolaminate mirror with a clear aperture of  $\sim 10\text{ cm}$  and  $\sim 1000$  MEMS actuators with appropriate characteristics for the TMT. In 2004, we completed the design and modeling of a subscale prototype deformable mirror using nanolaminate foils and off-the-shelf MEMS actuator arrays, and we demonstrated bonding of nanolaminate foils to silicon substrates while maintaining optical quality. The subscale prototype with  $\sim 100$  actuators will be assembled and tested in 2005, and work will begin on the  $\sim 1000$ -actuator device to be completed in 2006.

The AO Group also continued to support operation of the world's first fully functional laser guide star adaptive optics system, on the 3-meter telescope at the University of California's Lick Observatory. Major upgrades of the adaptive optics wavefront sensing system were accomplished in 2004. In addition, the

laser guide star adaptive optics system on the 10-meter Keck Telescope, built collaboratively by LLNL and Keck Observatory in a project begun in 1994, was made available to the astronomical community in 2004.

I Division is also participating in the development of the Large Synoptic Survey Telescope (LSST), which will perform full-sky time-domain surveys to map effects of dark energy distribution, discover and characterize the time-domain behavior of a variety of sources, and map our solar system to unprecedented accuracy. LLNL is addressing several of the most challenging design issues in the LSST Program. We have produced an innovative optical design for the telescope based on a three-mirror architecture that provides a 3.5 degree field-of-view with manufacturable optical components. We are responsible for the opto-mechanical design of the 3.3 gigapixel camera subsystem, which includes 1.7 meter refractive optics, the largest telescope lenses produced to date.



**Figure 7: Schematic of the Large Synoptic Survey Telescope and the wide-field camera assembly. When completed, this telescope and camera will provide an unprecedented view of observable universe, which will be used to study the nature of dark energy and dark matter.**

LSST will be one of first fully active telescopes – every major optical surface will be actively controlled. The control objective for LSST is different than for a typical active optics system. Here, we want to have a controlled predictable point-spread-function over the very wide field-of-view. The AO Group is applying concepts

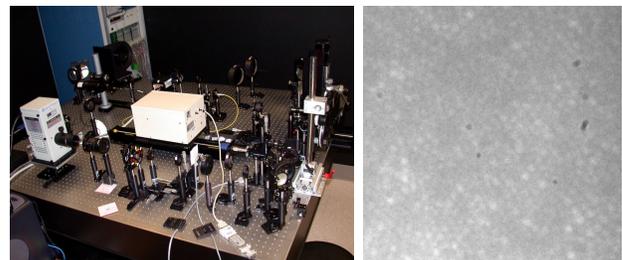
from both EUV lithography and multi-conjugate AO to this new control system design.

One of the biggest challenges in LSST is the management and processing of the massive data stream from the camera. The LSST database will grow at a rate greater than one petabyte per year; most science will be done by mining this large-scale database. With a team from Computations and the ICE SI, I Division is developing prototype image pipeline tools that will address performance and automation goals for the LSST pipelines. We have recently demonstrated an initial parallelized pipeline prototype that processes SuperMacho imagery.

In the area of human vision, AO can be used to compensate for aberrations in the optics of the human eye to enable clearer vision and higher quality imagery of the eye's interior. The AO Group is currently involved in two, 5-year Bioengineering Research Partnerships (BRP's), funded by the National Institutes of Health (NIH), National Eye Institute. The primary goal of these activities is to develop and test clinical ophthalmic instruments using MEMS adaptive optics devices to revolutionize the diagnosis and treatment of the diseases that cause blindness and to develop techniques for vision correction in the general population. The first BRP is led by the University of Rochester and includes UC Berkeley, LLNL, the Schepens Eye Research Institute in Boston, and the Doheny Eye Institute at the University of Southern California. For this program, the AO Group will develop a portable, MEMS-based, adaptive optics confocal scanning laser ophthalmoscope for use at the Doheny Eye Institute. This instrument will give ophthalmologists an unprecedented, cellular-level view of the retina, in a clinical instrument, which will aid in the diagnosis and treatment of blinding eye diseases. The second BRP is led by the UC Davis Medical Center and includes the University of Indiana, Duke University, and

LLNL. For this program, the AO Group will combine AO systems using MEMS technology with optical coherence tomography instruments developed at the partner universities. These instruments will further improve the ability of researchers and clinicians to visualize the retina in three-dimensions with cellular-level resolution. The AO Group is also partnered with the UC Davis Medical Center in a Campus-Laboratory Collaboration, supported by the UC Office of the President, which aims to develop new techniques for image processing and enhancement of data collected by these new ophthalmic instruments.

In 2004, we successfully completed the development of an adaptive optics corrected flood illuminated retinal imaging system at the UC Davis Medical Center. This system is now regularly imaging patients with blinding eye diseases that have been referred by doctors at the Center. This initial clinical testing is concentrating on studying the structure and changes in the retina, which are occurring as a result of diseases. We also completed the design of a high-resolution, 3-dimensional ophthalmic imaging system, using MEMS adaptive optics combined with optical coherence tomography for use at the UC Davis Medical Center. In addition, we completed the design of a compact, confocal scanning laser ophthalmoscope using MEMS adaptive optics for use at the Doheny Eye Institute.



**Figure 8: Flood-illuminated fundus imaging system using adaptive optics at the UC Davis Medical Center and an image made with the system of the human cone photoreceptor mosaic.**