Giant Steps for Adaptive Optics

Recent advances make possible the routine direct imaging of extrasolar planets and an innovative x-ray deformable mirror.

LAST November, high in the Chilean Andes, an international team of scientists and engineers, including Lawrence Livermore researchers, celebrated jubilantly in the early morning hours. The cause for their celebration was the appearance of a faint but unmistakable image of a planet 63 light-years from Earth circling a nearby star called Beta Pictoris. The clear image was viewable from a ground-based telescope thanks to one of the most advanced adaptive optics systems in existence, a key element of the newly fielded Gemini Planet Imager (GPI).

GPI (pronounced gee-pie) is deployed on the 8.1-meter-diameter Gemini South telescope, situated near the summit of Cerro Pachón at an altitude of 2,715 meters. The size of a small car, GPI is mounted behind the primary mirror of the giant telescope. Although the imager is still in its shakedown phase, it is producing the fastest and clearest images of extrasolar planets (exoplanets) ever recorded. GPI is perhaps the most impressive scientific example of Lawrence Livermore's decades-long preeminence in adaptive optics. This technology uses an observing instrument's optical components to remove distortions that are induced by the light passing through a turbulent medium, such as Earth's atmosphere, or by mechanical vibration.

More than two decades ago, Livermore scientists were among the first to show how adaptive optics can be used in astronomy to eliminate the effects of atmospheric turbulence, which cause the twinkle we see in stars when viewing them from Earth. Those effects also create blurring in images recorded

by ground-based telescopes. Laboratory researchers have since applied adaptive optics to other fields, including lasers and medicine. For example, adaptive optics helped produce extremely high-resolution images of the retina with an instrument that won an R&D 100 Award in 2010. (See *S&TR*, October/November 2010, pp. 14–15.) Livermore teams are now working on an adaptive optics system to transport x-ray beams in a new generation of high-energy research facilities. In addition, outreach efforts by the Laboratory are strengthening educational opportunities in this field at U.S. colleges and universities.

Designed for Exoplanet Imaging

GPI is the first astronomical instrument designed and optimized for direct exoplanet imaging and analysis. Imaging planets directly is exceedingly difficult because most planets are at least 1 to 10 million times fainter than the parent stars they orbit. One way to improve image quality is to send telescopes into orbit, which boosts research costs enormously. A much less expensive approach is to equip a ground-based telescope with adaptive optics to compensate in real time for the distortions of light caused by Earth's atmosphere.

Livermore computational engineer David Palmer, GPI project manager and leader of its adaptive optics development effort, notes

The Gemini South telescope, near the summit of Cerro Pachón in Chile, is one of two telescopes operated by the Gemini Observatory. (Photograph by Marshall Perrin, Space Telescope Science Institute.)

that GPI comprises several interconnected systems and components. In addition to adaptive optics, the imager includes an interferometer, coronagraph, spectrometer, four computers, and an optomechanical structure to which everything is attached. All are packaged into an enclosure 2 cubic meters in volume and flanked on either side by "pods" that hold the accompanying electronics.

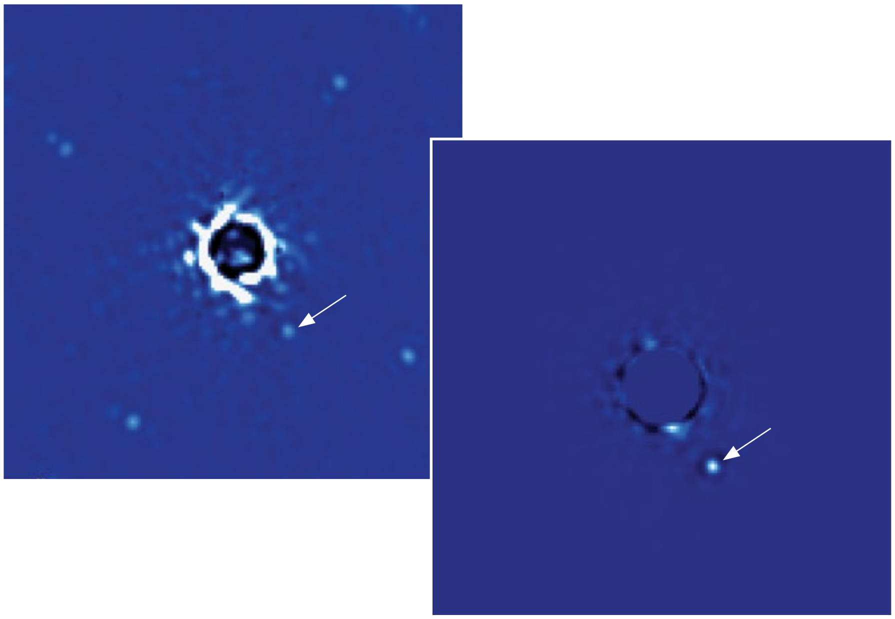
GPI hangs on the back end of Gemini South, a design that sharply constrains the imager's volume, weight, and power requirements. While in use, it constantly faces the high winds and hostile environment at high altitude. As the telescope slews to track a star, the instrument flexes, making alignment more complicated. Nevertheless, says Palmer, GPI has maintained its alignment "phenomenally well" and performed superbly. "The precision requirements worked up by the GPI design team are almost staggering," he says, "especially those for the adaptive optics system."

Laboratory electrical engineer Lisa Poyneer adds, "GPI features several new approaches that enable us to correct the atmosphere with precision never before achieved." Poyneer developed the algorithms (mathematical procedures) that control two deformable mirrors and led adaptive optics system testing in the laboratory and at the telescope.

Lawrence Livermore engineer Lisa Poyneer and Stanford University astrophysicist Bruce Macintosh (previously at Livermore) stand in front of the Gemini Planet Imager (GPI), which is installed on the Gemini South telescope in Chile. Two electronic pods (blue) on either side of the main enclosure hold GPI's electronics. (Photograph by Jeff Chilcote, University of California at Los Angeles [UCLA].)

GPI is an international project with former Livermore astrophysicist Bruce Macintosh (now a professor at Stanford University) serving as principal investigator. The Gemini South telescope is an international partnership as well, involving the U.S., Canada, Australia, Argentina, Brazil, and Chile. Macintosh says the first discussions concerning a ground-based instrument dedicated to the search for exoplanets began in 2001. "A lot of exoplanets were being discovered at that time, but the discoveries didn't tell us much about the planets themselves," he

In November 2013, members of the GPI first-light team celebrated when the system acquired its first images. The team includes: (from left to right) Pascale Hibon, Stephen Goodsell, Markus Hartung, and Fredrik Rantakyrö from Gemini Observatory; Jeffrey Chilcote, UCLA; Jennifer Dunn, National Research Council (NRC) Canada Herzberg Institute of Astrophysics; Sandrine Thomas, NASA Ames Research Center; Macintosh; David Palmer, Lawrence Livermore; Dmitry Savransky, Cornell University; Marshall Perrin, Space Telescope Science Institute; and Naru Sadakuni, Gemini Observatory. (Photograph by Jeff Chilcote, UCLA.)



(left) During its first observations, GPI captured this image within 60 seconds. It shows a planet orbiting the star Beta Pictoris, which is 63 light-years from Earth. (right) A series of 30 images was later combined to enhance the signal-to-noise ratio and remove spectral artifacts. The four spots equidistant from the star are fiducials, or reference points. (Image processing by Christian Marois, NRC Canada.)

says. "There was a clear scientific need to incorporate adaptive optics, and the technology was progressing quickly."

After more than eight years in development, GPI components were tested and integrated at the Laboratory for Adaptive Optics at the University of California (UC) at Santa Cruz in 2012 and 2013. The imager was shipped to Chile in August 2013, with first light conducted in November.

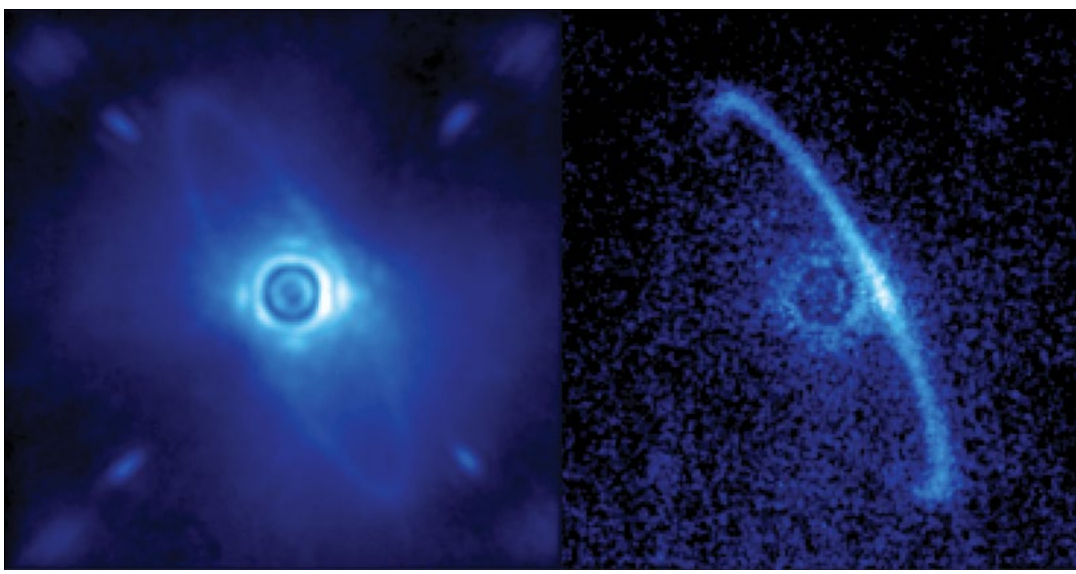
Scientists will use GPI over the next three years to discover and characterize dozens or more exoplanets circling stars located up to 230 light-years from Earth. In addition to resolving exoplanets from their parent stars, GPI uses a spectrometer to probe the composition of each exoplanet's atmosphere. The instrument also studies disks around young stars with a technique called polarization differential imaging.

Age of Exoplanet Discovery

The discovery of exoplanets was a historic breakthrough in modern astronomy. More than 1,000 exoplanets have been identified, mainly through indirect techniques that infer a planet's mass and orbit. Astronomers have been surprised by the diversity of planetary systems that differ from our solar system. GPI is expected to strengthen scientific understanding of how planetary systems form and evolve, how planet orbits change, and what comprises their atmospheres.

GPI masks the light emitted by a parent star to reveal the faint light of young (up to 1-billion-year-old) giant planets in orbits a few times greater than Earth's path around the Sun. These young gas giants (the size of Jupiter and larger) are detected through their thermal radiation (about 1.0 to 2.4 micrometers wavelength in the near-infrared region).

GPI is not sensitive enough to see Earth-sized planets, which are 10,000 times fainter than giant planets. (See *S&TR*, July/August 2012, pp. 12–14.) However, it complements astronomical instruments that infer a planet's mass and orbit by measuring the small gravitational tugs exerted on a parent star or, as with NASA's Kepler Space Telescope, by



GPI also records data using polarization differential imaging to more clearly capture scattered light. Images of the young star HR4796A revealed a narrow ring around the star, which could be dust from asteroids or comets left behind by planet formation. The left image shows normal light scattered by Earth's turbulent atmosphere, including both the dust ring and the residual light from the central star. The right image shows only polarized light taken with GPI. (Image processing by Marshall Perrin, Space Telescope Science Institute.)

blocking very small amounts of light emitted by the parent star as the planet passes in front of that star. "These indirect methods tell us a planet is there and a bit about its orbit and mass, but not much else," says Macintosh. "Kepler can detect tiny planets similar to the size of Earth. With GPI, we can find much larger planets, the size of Jupiter, so the two instruments provide complementary information."

The direct imaging of giant planets permits the use of spectroscopy to estimate their size, temperature, surface gravity, and atmospheric composition. Because different molecules absorb light at different wavelengths, scientists can correlate the light emitted from a planet to the molecules in its atmosphere.

Extreme Adaptive Optics

The heart of GPI is its highly advanced, high-contrast adaptive optics system (sometimes called extreme adaptive optics) that measures and corrects wavefront errors induced by atmospheric air motion and the inevitable tiny flaws in optics. As light passes through the Gemini South telescope, GPI measures its wavefront 1,000 times per second at nearly 2,000 locations. The system corrects the distortions within 1 millisecond by precisely changing the positions of thousands of actuators, which adjusts the shape of two mirrors. As the adaptive optics system operates, GPI typically takes about 60 consecutive, 1-minute exposures and can detect an exoplanet 70 times more rapidly than existing instruments.

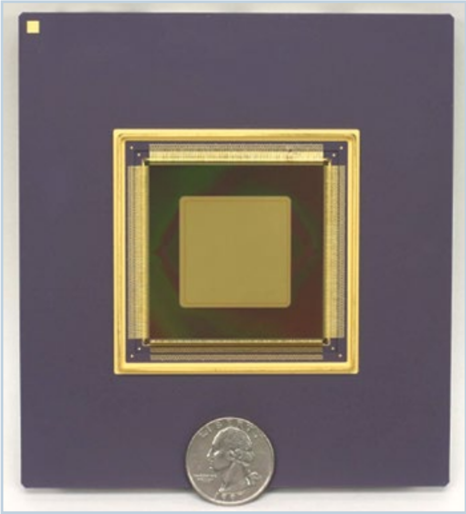
To meet GPI's stringent requirements, the Livermore team developed several technologies specifically for exoplanet science. A self-optimizing computer system controls the actuators, with computationally efficient algorithms determining the best position for each actuator with nanometer-scale precision. A spatial filter prevents aliasing (artifacts).

Livermore optical engineer Brian Bauman designed the innovative and compact adaptive optics for GPI. He has also worked on adaptive optics components for vision science and Livermore's Atomic Vapor Laser Isotope System and has developed simpler systems for telescopes at the Lick Observatory and other observatories. Says Bauman, "We wanted GPI to provide much greater contrast and resolution than had been achieved in an adaptive optics system without producing artifacts that could mask a planet or be mistaken for one."

The system corrects aberrations by adjusting the shape of two deformable mirrors. Incoming light from the telescope is relayed to the first mirror, called the woofer. Measuring about 5 centimeters across, this mirror has 69 actuators to correct atmospheric components with low spatial frequencies.

The woofer passes the corrected light to the tweeter—a 2.56-centimeter-square deformable mirror with 4,096 actuators for finer corrections. The tweeter is a microelectromechanical systems– (MEMS-) based device developed for GPI by Boston Micromachines. It is made of etched silicon, similar to the material used for microchips, rather than reflective glass. The tweeter's actuators are spaced only 400 micrometers apart; a circular patch of 44 actuators in diameter is used to compensate for the high-spatial-frequency components of the atmosphere.

GPI has 10 times the actuator density of a general-purpose adaptive optics system. Poyneer explains that the more actuators, the more accurately the mirror surface can



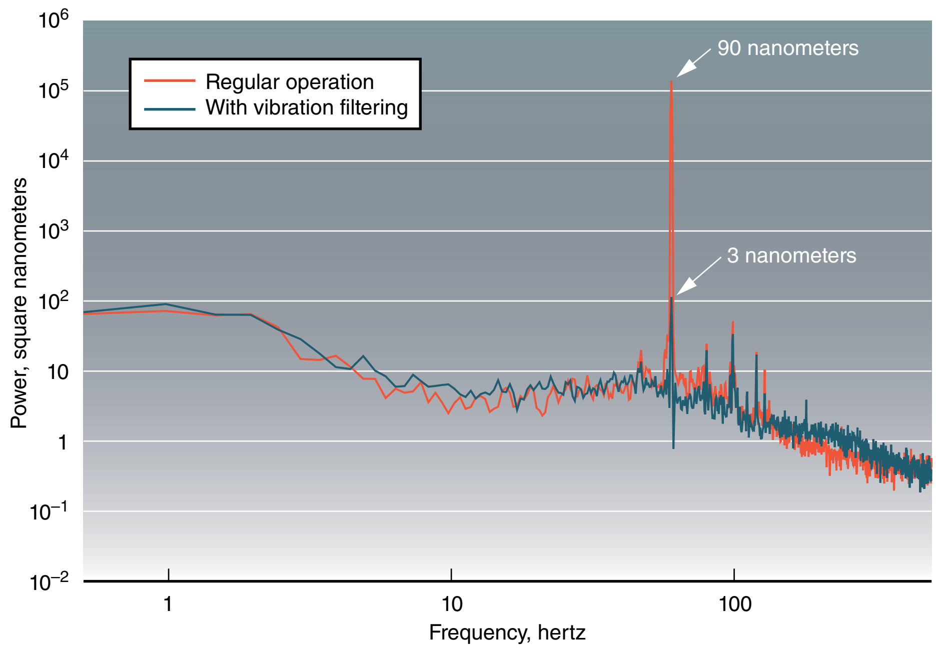
A 2.56-centimeter-square deformable mirror called a tweeter is used for fine-scale correction of the atmosphere. This microelectromechanical systems– (MEMS-) based device has 4,096 actuators and is made of etched silicon, similar to the material used for microchips. (Courtesy of Boston Micromachines.)

correct for atmospheric turbulence. "MEMS was the only technology that could give us thousands of actuators and meet our space and power requirements," she says. "Given the number of actuators, we had to design the system to measure all aberrations at the same resolution." This precision in controlling the mirrors is accomplished by a wavefront sensor that breaks incoming light into smaller subregions, similar to the receptors on a fly's compound eye.

A major challenge to the increased number of actuators is that existing algorithms required far too much computation to adjust the mirrors as quickly as needed. In response, Poyneer developed a new algorithm that requires

45 times less computation. "GPI must continually perform all of its calculations within 1 millisecond," says Palmer, who implemented the real-time software that achieves this goal. Remarkably, the system of algorithms is self-optimized. That is, says Poyneer, "A loop monitors how the operations are going and adjusts the control system every 8 seconds. If the atmospheric turbulence gets stronger, the system control will become more aggressive to give the best performance possible."

The mirrors forward the corrected light to a coronagraph, which blocks out much of the light from the parent star being observed, revealing the vastly fainter planets orbiting that star. Relay optics then reform the light onto a lenslet array, and a prism disperses the light into thousands of tiny spectra. The resulting pattern is transferred to a high-speed detector, and a few minutes of postprocessing removes the last remaining noise, or speckles.



The Livermore adaptive optics team has improved GPI's performance by minimizing vibration caused by the coolers that chill the spectrometer. Vibrations inject a large focusing error into the system as the telescope optics shake. The team developed filters that reduced the focusing error by 30 times—from 90 nanometers to 3.

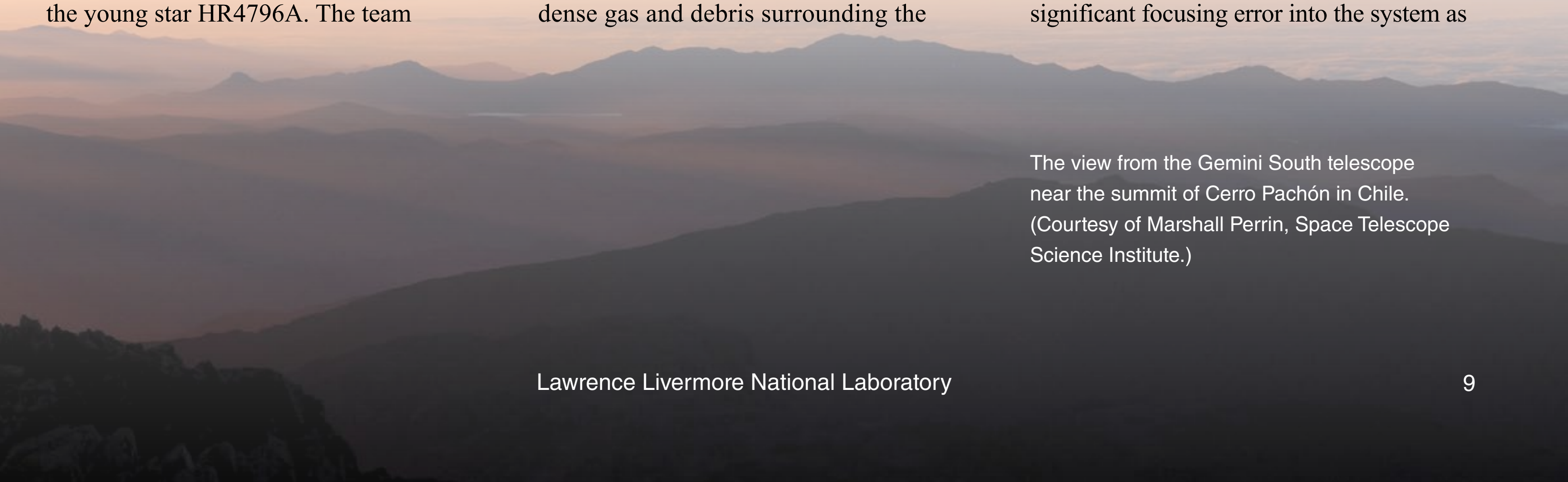
First Light November 2013

Researchers conducted the first observations with GPI in November 2013, when they trained the Gemini South telescope on two known planetary systems: the four-planet HR8799 system (codiscovered in 2008 by a Livermore-led team at the Gemini and Keck observatories) and the one-planet Beta Pictoris system. A highlight from the November observations was GPI recording the first-ever spectrum of the young planet Beta Pictoris b, which is visible as a small but distinct dot.

Using the instrument's polarization mode, the first-light team also detected starlight scattered by tiny particles and studied a faint ring of dust orbiting the young star HR4796A. The team released the images at the January 2014 meeting of the American Astronomical Society. "The first images were a factor of 10 better than those taken with the previous generation of instruments," says Macintosh. "We could see a planet in the raw image, which was pretty amazing. In one minute, we found planets that used to take us an hour to detect."

Data from the first-light observations are allowing researchers to refine estimates of the orbit and size of Beta Pictoris b. To analyze the exoplanet, the Livermore team and their international collaborators looked at the two disks of dense gas and debris surrounding the parent star. They found that the planet is not aligned with the main debris disk but instead with an inner warped disk, with which it may interact. "If Beta Pictoris b is warping the disk, that helps us see how the planet-forming disk in our own solar system might have evolved long ago," says Poyneer.

Since first light, the Livermore adaptive optics team has been working to improve GPI's performance by minimizing vibration caused by the coolers that chill the spectrometer to a very low temperature. Vibrations decrease the stability of the parent star on the coronagraph and inject a significant focusing error into the system as



The view from the Gemini South telescope near the summit of Cerro Pachón in Chile. (Courtesy of Marshall Perrin, Space Telescope Science Institute.)

the telescope optics shake. In response, the team developed algorithms that effectively cancel the errors in a manner similar to noise-canceling headphones. The filters have reduced pointing vibrations to a mere one-thousandth of an arcsecond and decreased the focusing error by 30 times, from 90 to 3 nanometers.

In November 2014, the GPI Exoplanet Survey—an international team that includes dozens of leading exoplanet scientists—will begin an 890-hour-long campaign to discover and characterize giant exoplanets orbiting 600 young stars. These planets are located between 5 and 50 astronomical units from their parent stars, or up to 50 times the distance of Earth from the Sun (nearly 150 million kilometers). The observing time is the largest amount allocated to one group at Gemini South and represents 10 to 15 percent of the time available for the next three years. In the meantime, GPI verification and commissioning efforts continue.

Adaptive Control of X-Ray Beams

Building on the adaptive optics expertise gained with GPI, the Laboratory has launched an effort, led by Poyneer, to design, fabricate, and test x-ray deformable mirrors equipped with adaptive optics. "We took some of the best adaptive optics people in the world and put them with our experts in x-ray mirrors," says physicist Michael Pivovaroff, who initiated the program.

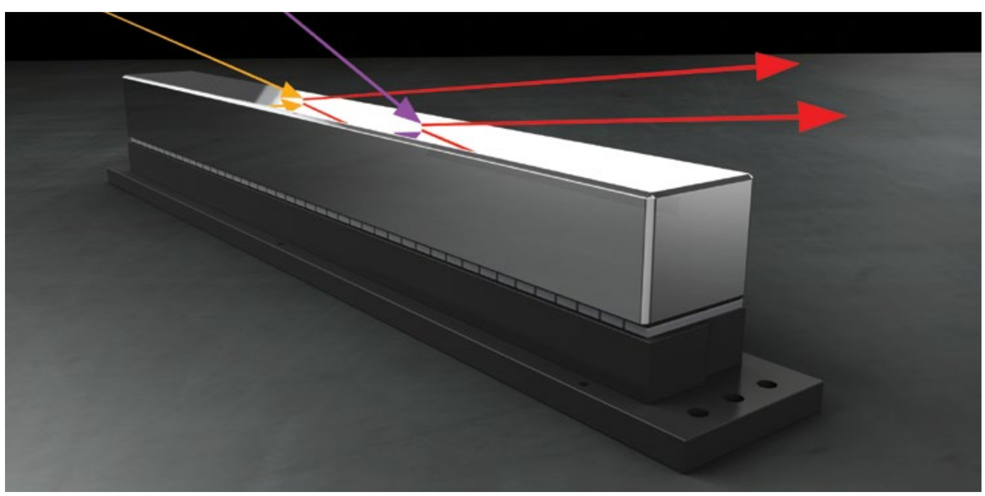
Livermore researchers previously applied their expertise in x-ray optics to design and fabricate the six advanced mirrors for the Linac Coherent Light Source (LCLS) at the SLAC National Accelerator Laboratory in Menlo Park, California. These mirrors transport the LCLS x-ray beam and control its size and direction. The brightest x-ray source in the world, LCLS can capture stop-action shots of moving molecules with a "shutter speed" measured in femtoseconds, or million-billionths of a second. With a wavelength about the size of an atom, it can image objects as small as the DNA helix. (See *S&TR*, January/February 2011, pp. 4–11.)

Despite the outstanding performance of current x-ray mirrors, further advances in their quality are required to take full advantage of the capabilities of LCLS and newer facilities, such as the Department of Energy's (DOE's) National Synchrotron Light Source II at Brookhaven National Laboratory and those under construction in Europe. "DOE is investing billions of dollars building x-ray light sources such as synchrotrons and x-ray lasers," says Pivovaroff. "Scientists working with those systems need certain spatial and spectral characteristics for their experiments, but every x-ray optic distorts the photons in some way. We don't want our mirrors to get in the way of the science."

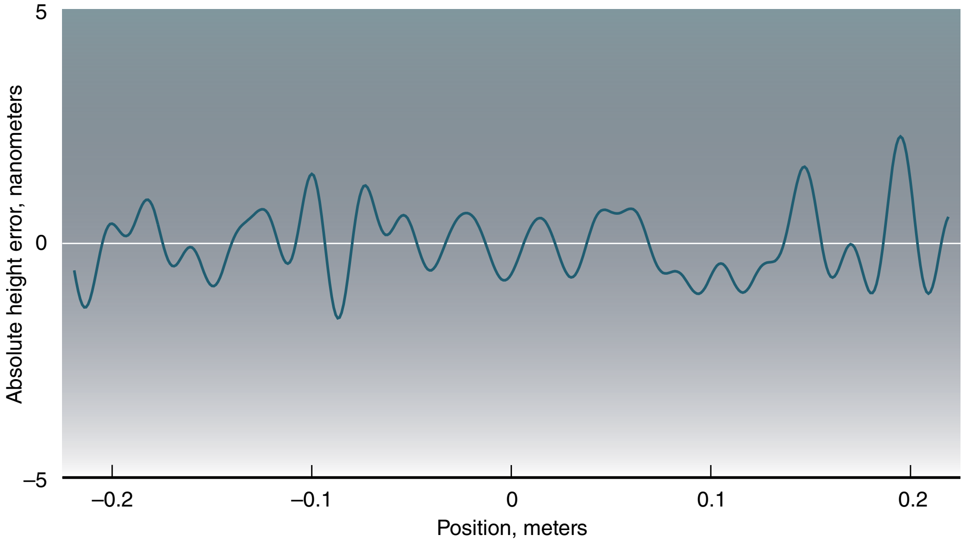
Combining adaptive optics with x-ray mirrors may lead to three significant benefits. First, active control is a potentially inexpensive way to achieve better surface flatness than is possible by polishing the mirrors alone. Second, the ability to change a mirror's flatness allows for real-time correction of aberrations in an x-ray beamline. This capability includes self-correction of errors in the mirror itself (such as those caused by heat buildup) and correction of errors introduced by other optics. Finally, adaptive optics–corrected x-ray mirrors could widen the possible attributes of x-ray beams, leading to new kinds of experiments.

Unlike mirrors used at visible and near-infrared wavelengths, x-ray mirrors must operate at a shallow angle called a grazing incidence. This requirement makes their design and profile quite different from deformable mirrors for astronomy. Traditional x-ray optics are rigid and have a longitudinal, or ribbon, profile up to 1 meter long. If adaptive optics systems can be designed to correct distortions in x-ray beams, next-generation research facilities could offer greater experimental flexibility and achieve close to their theoretical performance.

"As with visible and infrared light, we want to manipulate the x-ray wavefront with mirrors while preserving coherence," says Livermore optical engineer Tom McCarville, who was lead engineer for



Extremely small adjustments to the surface height on the x-ray deformable mirror correct the incoming beam, as depicted in this artist's rendering (not to scale). Unlike visible light, the x rays can only be reflected off the mirror at a very shallow incoming angle, called a grazing incidence. (Rendering by Kwei-Yu Chu.)



In an experiment, high-precision visible light measurements were used to flatten the x-ray deformable mirror to a surface figure error of only 0.7 nanometers average deviation.

the LCLS x-ray mirrors. "The fabrication tolerances are much greater because x-ray wavelengths are so short. Technologies for diffracting and transmitting x rays are relatively limited compared to those available for visible light. Reflective x-ray technology is, however, mature enough to deploy for transporting x rays from source to experiment. Dynamically controlling the mirror's surface figure will preserve the x-ray source's properties during transport and thus enhance the precision of experimental results."

First X-Ray Deformable Mirror

With funding from the Laboratory Directed Research and Development (LDRD) Program, the Livermore team designed and built the first grazing-incidence adaptive optics x-ray mirror with demonstrated performance suitable for use at high-intensity DOE light sources. This x-ray deformable mirror, developed with partner Northrop-Grumman AOA Xinetics, was made from a superpolished single-crystal silicon bar measuring 45 centimeters long, 30 millimeters high, and 40 millimeters wide, the same dimensions of the three hard x-ray mirrors built for LCLS.

A single row of 45 actuators bonded opposite the reflecting surface makes the mirror deformable. These 1-centimeter-wide actuators provide fine-scale control of the mirror's surface figure (overall shape). Actuators respond to voltage changes by expanding or contracting in width along the mirror's long axis to bend the reflecting surface. Seven internal temperature sensors and 45 strain gauges monitor the silicon bar, providing a method to self-correct for long-term drifts in the surface figure.

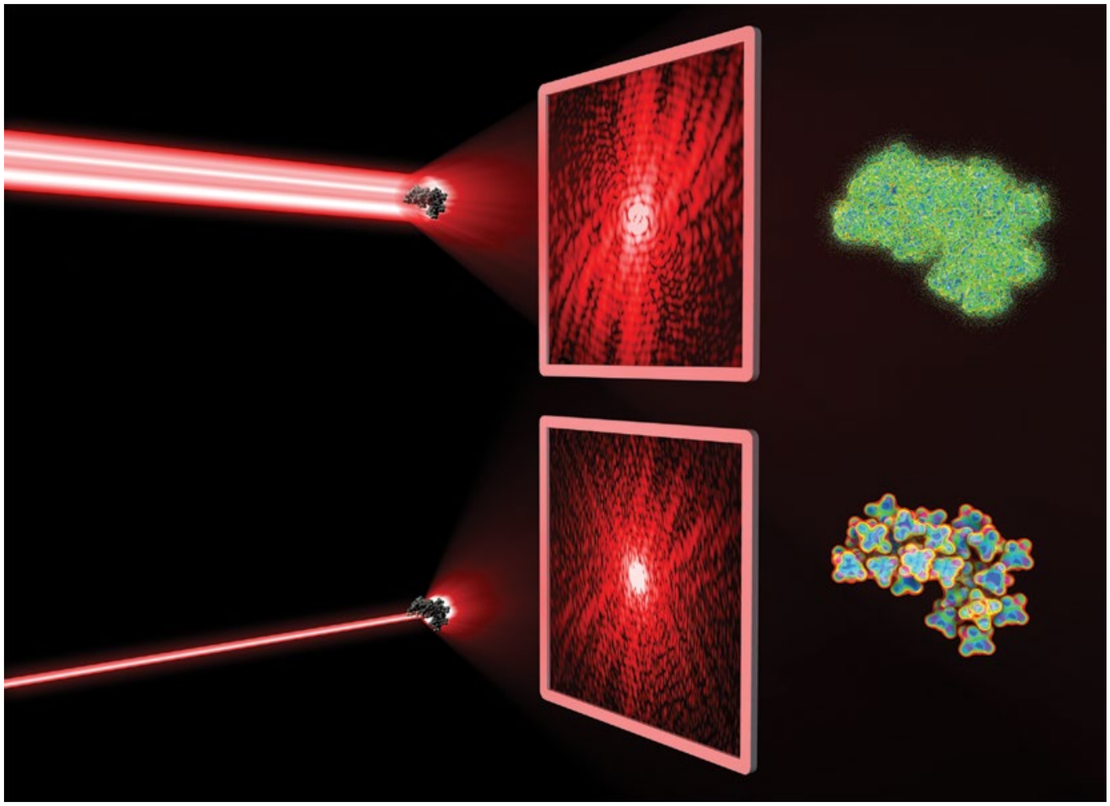
As with all x-ray optics, the quality of the mirror's surface is extremely important because the slightest bump or imperfection will scatter x rays. The substrate was thus fabricated and superpolished to nanometer-scale precision before assembly into a deformable mirror. The initial surface figure error for the deformable mirror was 19 nanometers. Although extremely small, it is substantially above the 1-nanometer-level required for best performance in an x-ray beamline.

To meet that requirement, the team used high-precision visible light measurements of the mirror's surface to "flatten" the mirror. With this approach, interferometer measurements are processed with specialized control algorithms. Specific voltages are then applied to the actuators to adjust the mirror's surface. The resulting figure error was only 0.7 nanometers. "We demonstrated the first subnanometer active flattening of a substrate longer than 15 centimeters," says Poyneer. "It was a very important step in validating our technological approach."

For deformable mirrors to be fully effective, scientists must develop better methods to analyze the x-ray beamline. "We need a sensor that won't distort the beam," says Pivovaroff. Such a sensor would provide a feedback loop that continuously feeds beam characteristics to the mirror actuators so they compensate for inconsistencies in the beam. Poyneer is working on new diagnostic techniques at Lawrence Berkeley National Laboratory's Advanced Light Source (ALS), and the Livermore team is scheduled to begin testing the mirror on a beamline at ALS. The long-term goal of that testing will be to repeat the subnanometer flattening experiment, this time using x rays to measure the surface.

Poyneer is hopeful the adaptive optics research effort will eventually result in a national capability that DOE next-generation x-ray light sources can draw on for new beamlines. She has shared the results with scientists at several DOE high-energy research centers and is working to better understand the needs of beamline engineers and the scientists who use those systems. "There's a lot of interest and excitement in the community because deformable mirrors let us do better science," says Pivovaroff. "The performance of our mirror has surprised many people. Controlling the surface of a half-meter-long optic to less than a nanometer is quite an accomplishment."

By enabling delivery of more coherent and better-focused x rays, the



This artist's concept illustrates the difference in reconstruction quality that adaptive optics could provide if installed at next-generation x-ray beamline facilities. At the top, a partially coherent x-ray beam hits the target object, producing a diffraction pattern on the detector and limiting the accuracy of the recovered image. At the bottom, adaptive optics provide a coherent beam with excellent wavefront quality, which improves resolution of the object. (Rendering by Kwei-Yu Chu.)

mirrors are expected to produce sharper images, which could lead to advances in physics, chemistry, and biology. The technology may enable new types of x-ray diagnostics for experiments at the National Ignition Facility.

Expanded Educational Outreach

The Laboratory's adaptive optics team is also dedicated to training the next generation of scientists and engineers for careers in adaptive optics and is working to disseminate expertise in adaptive optics technology to academia and industry. In a joint project between Lawrence Livermore National Security (the managing contractor for Lawrence Livermore) and UC, two graduate students from the UC Santa Cruz Department of Astronomy and Astrophysics are testing advanced algorithms that could further improve the performance of systems such as GPI. The algorithms are designed to predict wind-blown turbulence and further negate the effects of the atmosphere. Poyneer and astronomer Mark Ammons are mentoring the students, Alex Rudy and Sri Srinath.

Poyneer says, "GPI has demonstrated how continued work on technology developments can lead to significantly improved instrument performance." According to Ammon, "An important frontier in astronomy is pushing adaptive optics operation to visible wavelengths, which requires better control. GPI routinely meets these stringent performance requirements."

The lessons learned as part of the GPI experience will be critical input for next-generation adaptive optics on large telescopes, such as the W. M. Keck telescopes in Hawaii. Ammons adds, "While adaptive optics were first developed for military purposes, the loop has now closed—the advances made with GPI offer a wide range of potential applications for national security applications."

In addition, the Livermore team is applying its expertise to other fields, as exemplified by progress in the extremely flat x-ray deformable mirror. Thanks to adaptive optics, the universe—from planets to x rays—is coming into greater focus.

—Arnie Heller

Key Words: adaptive optics, Advanced Light Source (ALS), extrasolar planet (exoplanet), Gemini Planet Imager (GPI), Gemini South telescope, Kepler Space Telescope, Laboratory for Adaptive Optics, Linac Coherent Light Source (LCLS), microelectromechanical systems (MEMS), R&D 100 Award.

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