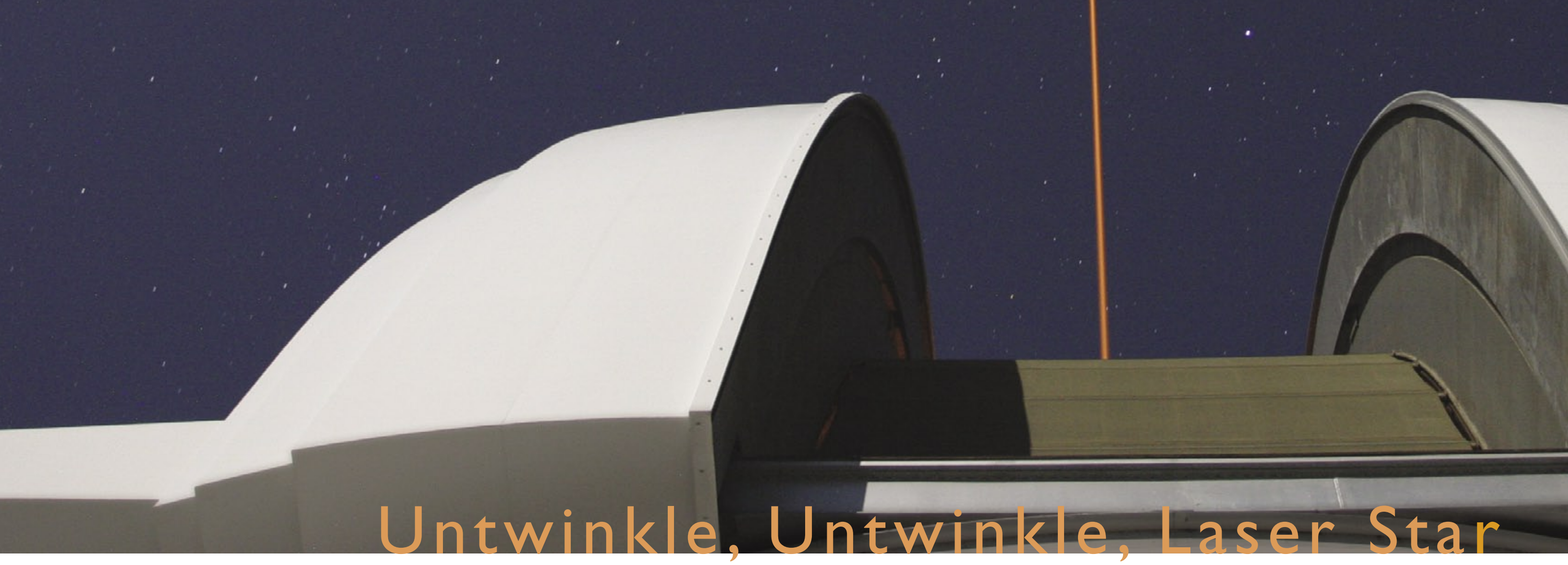
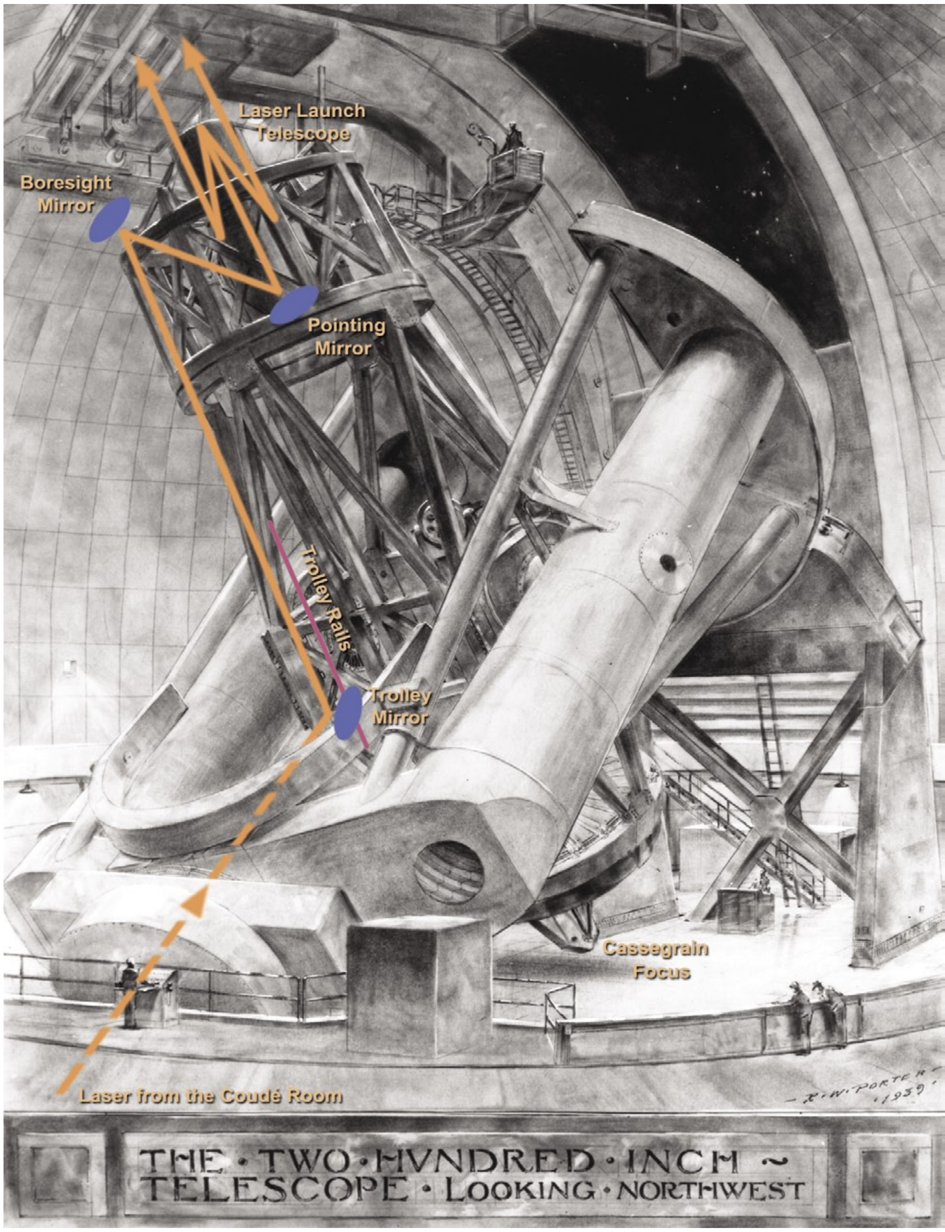


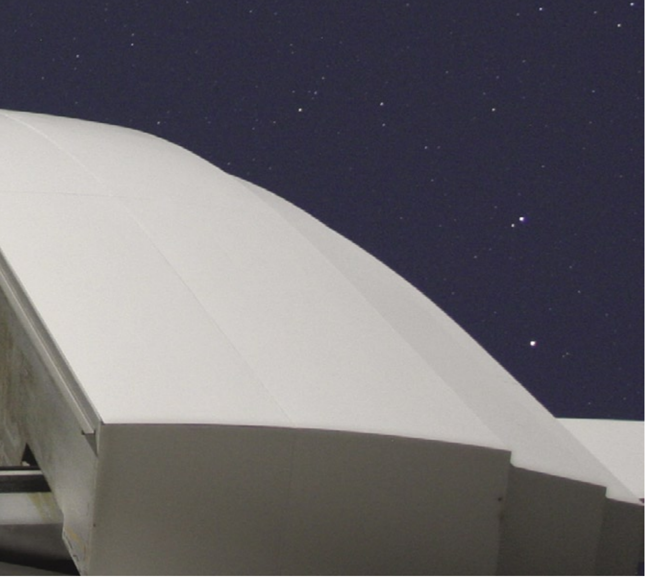
Untwinkle, Untwinkle, Laser Star

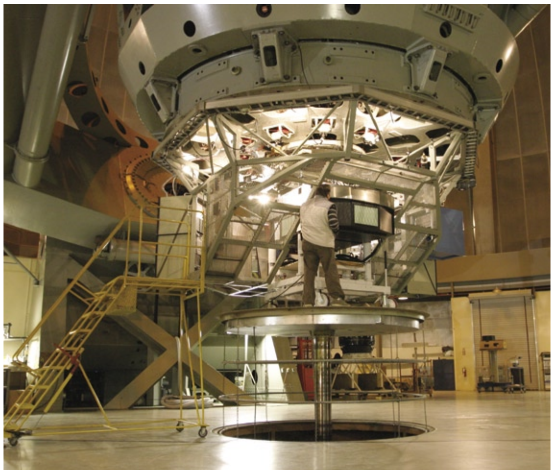
by Scott Kardel

Scott Kardel is the public affairs coordinator at Caltech's Palomar Observatory.



Above: Like the Luxor Las Vegas (although perhaps more Mayanesque in this perspective), the Hale sends a beacon into the night sky. Right: A schematic of the laser guide-star system, superimposed on one of a series of drawings made by Russell W. Porter. (The adaptive-optics mirror and the wave-front sensor live at the Cassegrain focus.) Astonishingly, this set of magnificent pencil sketches, which took a dozen years to draw, were prepared from blueprints before the telescope was even built.





PHARO being installed for an observing run by Steve Kunsman and Karl Dunscombe (hidden behind camera), members of the Palomar day crew.

Imagine what the lives of astronomers would be like if they were doomed to live at the bottom of the ocean. Even if the water were crystal clear, as they gazed up through it in an attempt to see beyond their world, the ocean's currents and ripples would greatly distort their view. In rare moments the water might briefly settle enough to see clearly, but the overall situation would be dismal at best. In fact, we live under an ocean of moving air. This ocean, our atmosphere, has its own currents and ripples that, among other things, make the stars twinkle. Even the best telescopes' images are somewhat blurred, leaving some objects and details forever hidden in the fuzz.

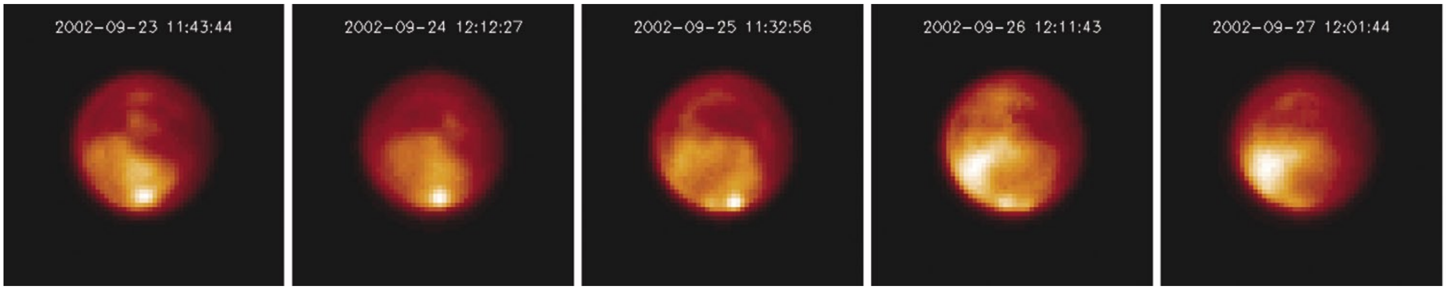
In an attempt to defeat these distortions, astronomers have been putting telescopes above as much of the atmosphere as possible—on high mountains and even in space. Spaceborne telescopes have many advantages over their ground-based counterparts. From their lofty vantage point it is never cloudy, city lights do not brighten the sky, the stars do not appear to twinkle, and all types of light are accessible. (Our ocean of air absorbs many wavelengths of interest to astronomers—the ultraviolet, the far-infrared, and the microwave, to name a few.) However, it is far easier and much less expensive to build and service telescopes here on Earth.

Now there's a way to produce spacelike clarity from Earth-based telescopes. In 1991, the U.S. military declassified much of its research on a technique known as adaptive optics. Adaptive-optics systems make real-time corrections that undo the distortions of the atmosphere, providing almost spacelike sharpness from the ground.

A team of astronomers from Caltech, led by Richard Dekany (BS '89), and JPL, led by Mitchell Troy, started developing an adaptive-optics system for the Palomar Observatory's venerable 200-inch Hale Telescope about a decade ago. The system has been in wide use since 1999. When it is operating, incoming light passes through the telescope's normal optical path to the Cassegrain focus—the only place on the telescope that can hold something as massive as the adaptive-optics equipment. The system uses a device called a wave-front sensor to measure the changing, wavering shape of a bright star, called a guide star, that lies in the telescope's field of view. A computer then rapidly calculates what undistortions would be needed to make the star a pinpoint of light again. To make these corrections, the computer directs 241 actuators that push and pull on the back side of a flexible, 6-inch mirror to adjust the reflective surface on the front. The corrections take place faster than the atmosphere changes—up to 2,000 times a second, making this the world's fastest such system. The result is almost like getting a new pair of glasses—suddenly the universe comes into sharper focus. These images are currently recorded by the Palomar High Angular Resolution Observer (PHARO), a camera sensitive to the near-infrared, developed by a team from Cornell University; plans are in the works to build a spectrograph as well, which would give detailed information on such things as the chemical composition and velocity of the target.

Palomar's astronomers have used the adaptive-optics system for a variety of projects over the last few years. Within our own solar system, astronomers including Don Banfield (MS '90, PhD '94), Phil Nicholson (PhD '79), and Barney Conrath, all of Cornell, have made long-term weather observations of the distant gaseous worlds Uranus and Neptune as they slowly move through their seasons. The system even has enough resolution to accurately measure the composition of icy

A false-color image of Neptune, taken by Antonin Bouchez with the Hale's adaptive optics.



This series of pictures, shot variously by Troy, Dekany, JPL's Christophe Dumas, postdoc Maciej Konacki, then-postdoc Chad Trujillo, Bouchez, and grad student Stan Metchev, run from September 23 to November 18, 2004, during which Titan rotated 184 degrees. Careful analysis shows that some of the bright regions are methane clouds that come and go, while others are surface features that rotate with the planet.

Pluto and its moon, Charon. In a case of being at the right place at the right time, grad student Antonin Bouchez (PhD '04), now Caltech's Adaptive Optics Lead, watched Saturn's moon Titan occult, or pass directly in front of, a pair of stars, and in the process discovered new details in the structure of Titan's stratosphere, including strong, jet-stream-like winds at mid to high northern latitudes. (Movies of the occultation are available at http://www.gps.caltech.edu/~antonin/occultation.) Meanwhile, Cornell's Jean-Luc Margot is studying binary asteroids, pairs of asteroids that orbit each other tightly, to determine their compositions and their orbits about each other. And Palomar astronomers had balcony seats for the crash of JPL's Deep Impact probe with comet Tempel 1. In fact, because they were watching the event live rather than waiting for a downlink, they knew the mission had been a success before its own controllers did!

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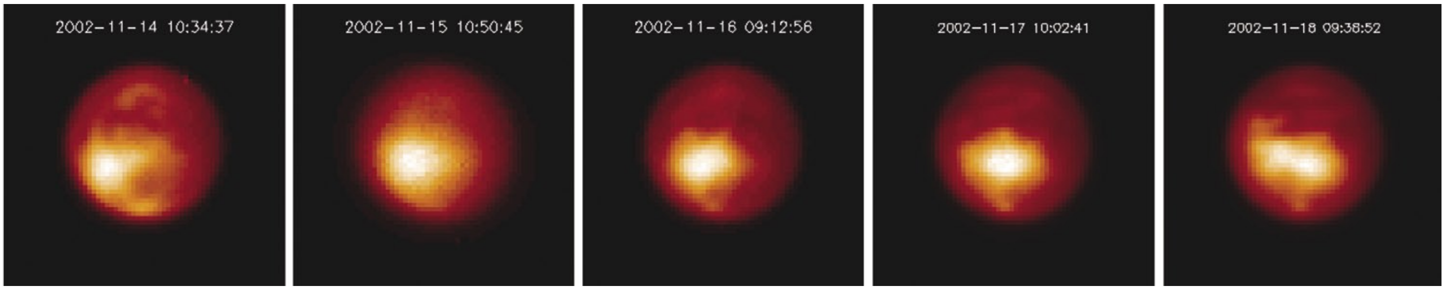
Beyond the solar system, astronomers have used the Hale's adaptive optics to study the intricacies of star formation and to search the area immediately around young stars for planetary or brown-dwarf companions. The key to such work is the ability to resolve fine details, especially in the quest for brown dwarves. Brown dwarves, which usually have masses between 10 and 75 times the mass of Jupiter, are too small to undergo nuclear fusion, like a star does, yet too large to be considered planets. Astronomers generally try to find brown dwarves by photographing them directly—a tricky proposition because they're tiny and very faint compared to their big, bright companion stars. But a special camera called a coronagraph, which blocks out most of the star's light with a small disc, allows the brown dwarf's light to emerge from the glare. (Incidentally, the first brown dwarf was discovered using Palomar's 60-inch telescope, which was armed with a primitive adaptive-optics system built into its coronagraph—see *E&S* 1996, No. 1.) Assistant Professor of Astronomy Lynne Hillenbrand and grad student Stan Metchev have searched some nearby stars for hidden brown-dwarf companions and found only one, which was actually overlooked in their Palomar images and noticed later at Caltech's 10-meter Keck II telescope, also sporting an adaptive-optics system. (The Palomar hunt *did* bag three low-mass stellar companions—0.13 to 0.2 solar masses, as opposed to the brown dwarf's 0.06.) Joe Carson, then with Cornell, now with JPL, also tried a brown-dwarf survey, and of the 80 young nearby stars he examined he didn't find any! This seems to confirm the notion, advanced in the late 1990s, that brown dwarves don't form too close to sun-like parents.

But a major breakthrough would be needed to make adaptive optics really useful for all astronomers. Guide stars of sufficient brightness are few and far between, and since the guide star and the object of the astronomer's desire have to be in the telescope's field of view at the same time, the technique can only be used over about 1 percent of the sky.

The obvious solution is to create your own guide stars and place them wherever you want them—and as silly as that may sound, that is exactly what astronomers at a handful of observatories are now doing. This involves shining a narrow sodium-laser beam up through the atmosphere. (The beam is the same yellow color produced by the low-pressure sodium streetlights that are recommended for minimizing glare and maintaining dark, astronomy-friendly skies.) At an altitude of about 100 kilometers, the beam interacts with a small amount of naturally occurring sodium gas, making it glow.



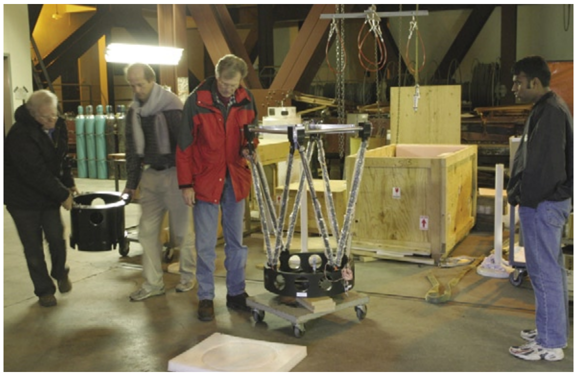
This glowing gas serves as the artificial guide star. The outgoing laser beam is too faint to be seen, except by observers very close to the telescope, and the guide star is even fainter. It can't be seen with the unaided eye, yet it is bright enough to allow astronomers to make their adaptive-optics corrections.

Planning work on the Hale's laser guide-star system began several years ago. Converting any telescope to make use of so much new technology is a challenge, and several large pieces of equipment had to be designed and built for the project.

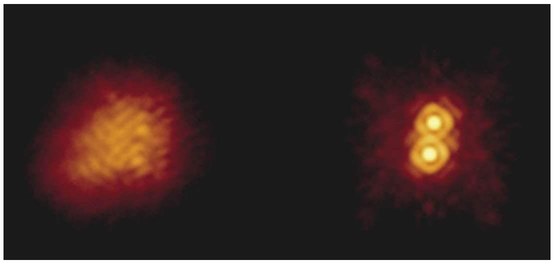
The heart of the system is the sum-frequency laser. Built by the University of Chicago's Ed Kibblewhite, the laser has a unique design that consists of two pulsed, diode-pumped, infrared lasers enclosed in a temperature-controlled box the size of a phone booth. The two invisible beams are mixed to produce a pulsed, visible beam at a wavelength of 589 nanometers, or billionths of a meter—the same wavelength emitted by sodium atoms. The pulsing helps avoid backward scattering of the laser light, allowing a smaller guide star to be produced. The laser is housed in a large room, known as the Coudé room, located just south of the telescope's mounting.

The beam travels out of the Coudé room to the side of the telescope, where it is met by a set of motorized mirrors that are controlled in real time to keep the beam accurately aligned. These mirrors direct the beam up the side of the telescope and are attached to another new piece of equipment—a

Right: Ed Kibblewhite and his sum-frequency laser. Far right: The laser trolley and its track were hoisted into place with the five-ton traveling crane on the underside of the dome. The trolley is the flat box at the top of the track, which dangles along the left edge of the picture. Below: Observatory Superintendent Bob Thicksten (far left) and Del Johnson carry a component of the Laser-Launch Telescope, the rest of which sits on a dolly between Member of the Professional Staff Hal Petrie (BS '68) and Viswa Velur.



IW Tau, a known binary star, as seen with (far right) and without the adaptive optics. The stars are 0.3 arc seconds apart. The images were taken by JPL's Charles Beichman, a senior faculty associate in astronomy at Caltech, and Angelle Tanner, a JPL postdoc.



"laser trolley" that rides on a track installed along the barrel of the telescope itself. This was no mean feat, as the track and trolley assembly weighs 800 pounds. But the telescope and its mounting weigh some 530 tons—many of its larger parts had to be built in shipyards, which were the only facilities capable of handling pieces of steel of such size; this also accounts for the Hale's battleship-gray paint scheme—so the extra weight wasn't an issue. What did take a little doing, however, was rebalancing the barrel by carefully adding 800 pounds of counterweights to the other side.

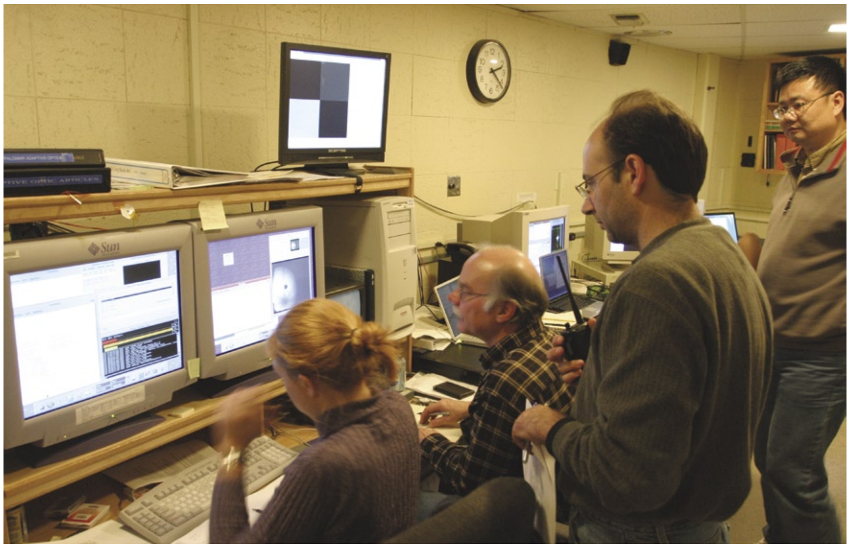
From the top of the barrel, the trolley shunts the beam to the telescope's center axis, where the third major component, the Laser-Launch Telescope, or LLT, sits high atop the Hale in the prime-focus cage—the same location where years ago astronomers would sit taking pictures throughout the night. The LLT widens the laser beam and sends it skyward toward the intended target. Each component attached to the telescope is computer-controlled to maintain its alignment against the shifting pull of gravity as the telescope tracks objects across the sky.

Not a scene from *The Ring*, but a Palomar staff member testing the new infrared camera. It was October, however.

As you might imagine in this post-9/11 era, it is not a good idea for astronomers to start shooting lasers into the night sky whenever and wherever they please. Last January a New Jersey man got into trouble with the law for aiming a five-milliwatt green laser—popular with amateur astronomers for pointing out objects in the sky—at a passing airplane. While the four-watt laser at Palomar still isn't powerful enough to shoot planes out of the sky, it could certainly play havoc with a pilot's night vision, so proper precautions must be taken. Each and every night the laser is to be used, clearance must first be granted by the Federal Aviation Administration (FAA), which will attempt to steer pilots away from Palomar. Because some air traffic might still veer into the target area, the FAA requires that radio-wielding spotters be posted outside the big dome to keep a constant lookout for aircraft. If one is seen on a course that might take it too close to the path of the beam, word is called in and the beam is safely shuttered. (An all-sky camera and a radar system may eventually replace the need for humans to stand out there in the sometimes freezing darkness.) A heat-sensitive infrared camera is also being used, because not all aircraft have their lights turned on. And nightly clearance must also be granted by the U.S. Army Space and Missile Defense Command, the folks who monitor satellites in Earth orbit. While the odds of one crossing the laser's path are remote, we don't want to "light up" any of our satellites, or those of other nations.

When all was ready and the proper clearances obtained, the laser emitted its first light at the telescope in October 2004. Three consecutive nights of precious engineering time—nights devoted to maintenance, repairs, and upgrades instead of astronomy—were granted to get the system up and running, and Palomar's day crew frantically worked alongside staff from JPL and campus to get ready. The first two nights were plagued with fog and alignment problems. The third night saw the proper confluence of good weather and engineer-

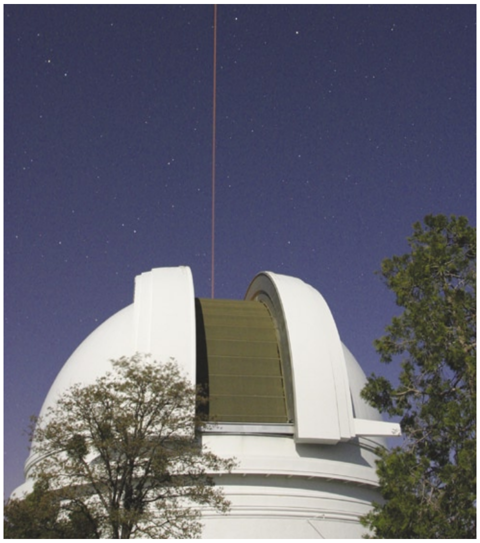
From left: JPL's Jennifer Roberts (seated), Chris Shelton, BS '66 (seated), Mitchell Troy, and Fang Shi in the Hale's data room early in the morning of April 27, 2005. Palomar's first laser-created guide star is visible (as a negative image) in the monitor just above Roberts' head.



ing, and the laser painted the sky for the first time. After 55 years of collecting light from the universe, the Hale Telescope finally sent some back!

Alas, the astronomers were unable to verify that an artificial star had been born. That feat had to wait until the next window of engineering time, which was dogged by the bad weather of a wetter than normal spring. Almost all of the time in the three nights granted in March was lost to rain and fog. April's nights started much like those in March, with fog ruining the first two attempts, but as they say, "the third time's the charm." On April 26, 2005, on the third night of the third engineering run, Palomar astronomers confirmed for the first time that they had created an artificial star.

The engineering work has not yet advanced enough to turn the system loose for research. So far, the laser has only been pointed straight up. Some final bugs have to be worked out in the beam-transfer equipment before the system can move around the sky, and the team still has to lock the adaptive optics onto the laser guide star. Both of these challenges should be overcome before the end of this year.



When the system is fully operational, it will place the Hale in elite company, along with the Shane three-meter telescope at the University of California's Lick Observatory and the Keck II, as only the third in the world to deploy a laser guide-star system. This, along with some expected upgrades to the camera and deformable mirror, should allow the earthbound Hale to produce visible-light images that will routinely surpass the sharpness of those obtained from the Hubble Space Telescope—and just in time, as NASA has put on hold a proposed 2006 shuttle mission to service the Hubble that would have extended its life to at least 2011.

Besides promising an exciting time for Palomar astronomers, the system's technical achievements move astronomy further down the path toward future large telescopes such as the Thirty Meter Telescope (TMT). Because of its immense aperture size, different parts of the TMT's giant segmented mirror will see different areas of turbulence in the atmosphere, so a star's look will depend on what region of the mirror it's in. As a result, giant telescopes may be required to use adaptive optics and artificial guide stars all the time. The Hale's adaptive-optics system will be a critical demonstration of many of the key technologies that will be used on the TMT.

Currently in the design phase, the TMT will eventually deliver images at visible and infrared wavelengths 12 times sharper than the Hubble's. The TMT is a collaboration between Caltech and the Associated Universities for Research in Astronomy, the Association of Canadian Universities for Research in Astronomy, and the University of California, and is projected to see its first light in 2015. When that time arrives, it will be a safe bet to say that the road to the TMT will have been paved by the adaptive-optics research under way at Palomar. □

PICTURE CREDITS:
8-9, 11-13 – Scott Kardel