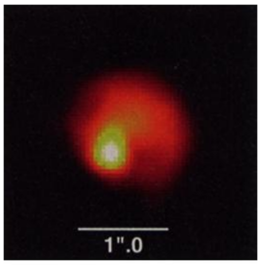
TECHVIEW: ASTRONOMY

Adaptive Optics

Roger Angel and Bob Fugate

About 400 years ago, Galileo discovered moons orbiting around Jupiter just like the planets around the sun. This remarkable verification of the Copernican theory was made possible by the invention of the telescope, which enabled detail to be seen that is invisible to the unaided eye. By grinding and polishing his own lenses from high-quality glass, Galileo reached the fundamental limit to image sharpness set by the wave nature of light, called the diffraction limit. In this limit, image resolution is proportional to telescope (or eye) diameter and inversely proportional to wavelength. However, as bigger lenses were made, astronomers found that images do not get any sharper beyond about 20 cm because of atmospheric blurring. For example, they could see no surface details on Jupiter's moons. This limit was only overcome about 10 years ago with the launch of the Hubble Space Telescope (HST). Its 2.4-m-diameter mirror increases the HST's sharpness by a factor of 10 compared with the best ground-based telescopes, and its many discoveries illustrate the power of sharper images to revolutionize our understanding of astronomy and cosmology.



Thermal Io. Thermal image of a volcano on Io at 3.5-μm wavelength with 0.1 arcsec resolution, obtained by speckle interferometry with a 6.9-m telescope (*8*).

But astronomers hunger for even sharper images. Larger telescopes in space are being planned. NASA's Next Generation Space Telescope (NGST), with a diameter of 8 m, is about a decade away from reality and will focus primarily on infrared wavelengths, where its resolution will be similar to HST's in visible light. Its advantage will come from its operation at cryogenic temperatures, enabling a huge increase in infrared sensitivity compared to ground instruments. An alternative approach aims to obtain images at visible wavelengths that are several times sharper than HST's with the use of ground-based telescopes. The new generation of 6- to 10-m telescopes is finally overcoming atmospheric blurring with the use of adaptive optics.

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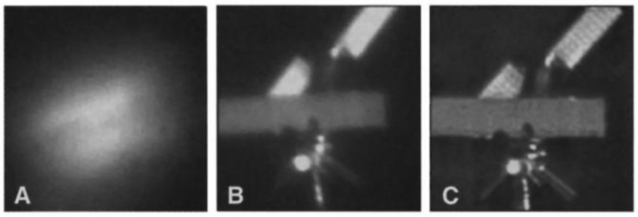
To understand how the blurring can be removed, we must first understand its origin. The undistorted wave crests from a star are flat, like long straight rollers coming to shore from the ocean. When such waves are reflected by the telescope's mirror, they become spherically curved and each converging crest increases in amplitude to yield a sharp local disturbance at the sphere's center, the image. (To visualize this, think of a movie of ripples spreading from a stone dropped in a pond, run in reverse.) But waves passing through air get bent out of shape. Light is slowed down by an amount that depends on the atmosphere's density, which varies from place to place, especially in regions where warm and cold air meet in a turbulent boundary. A roller that has passed through such regions arrives at the telescope with parts of the wave lagging behind, whereas other parts have moved ahead. For apertures larger than 20 cm, the wave is typically distorted so much that it is no longer coherent across the aperture. At the focus, the wave energy is spread out into a larger region where the displaced crests and troughs form a region of choppy waves. We see an extended region of speckles that continually reform as air currents eddy about and the wave distortion changes shape.

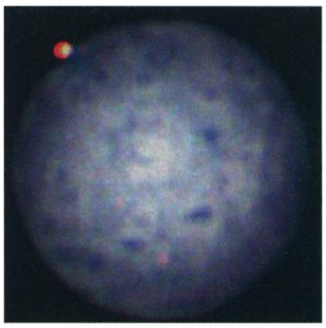


Seasat. Images of the satellite Seasat taken at the Starfire Optical Range. **(A)** Raw image, blurred by atmospheric turbulence. **(B)** Image compensated with adaptive optics. **(C)** Deconvolved version of (B) obtained by post processing. Detail of order 25 cm is resolved at a range of ~1000 km. The viewing angles for (A) and (B) are different due to satellite motion and rotation between exposures, but the atmospheric blurring is representative.

Sharp images can be recovered from "movies" of these speckles by a technique called speckle interferometry. Each frame is just a fraction of a second long, just long enough to freeze the rapid motion. Computer processing of many frames can yield images of bright objects at the telescope's full diffraction limited resolution, as long as the structure is relatively simple (see figure, above left).

Adaptive optics is a far more powerful technique, with the potential to image complex faint objects at the theoretical resolution limit. The idea, first set out by Babcock (*1*), is to restore the waves to their original form before they converge to the focus. This is done by reflecting them from a mirror whose surface is quickly bent to give equal but opposite distortion. In a region where the waves have moved faster through the air and have gotten ahead, the mirror surface is pulled back, so as to bring the reflected waves back into line. It is essential that the wavefront measurements and corresponding changes in mirror shape are made very quickly, before the atmospheric conditions causing the distortion change significantly.

For many years, technical difficulties severely limited practical applications of adaptive optics. But enormous progress has now been made. By 1982, the United States Air Force was operating the Compensated Imaging System with 168 correctors on a 1.6-m telescope in Hawaii to get sharper images of sunlit artificial satellites, and established the Starfire Optical Range (SOR) in New Mexico to further develop adaptive optics technology (*2*).



Infrared Io. Image of Io in the near infrared (1.2 to 2.2 μm) obtained by the Keck telescope with a 300 actuator system. It is sharper than the 3.5-μm wavelength thermal image because of larger aperture and shorter wavelength (*9*).

Most present-day adaptive optics systems work at infrared wavelengths because the longer wavelengths relax speed and accuracy requirements. But today's best systems can recover diffraction-limited images of bright objects even at the short wavelengths, which give the sharpest resolution for given aperture. The Seasat satellite images shown on the previous page was obtained at 0.8 μm (just beyond visible red light) with the 3.5-m telescope at Starfire. Its correcting mirror is bent by 1000 actuators, updating the complex distortion 1500 times per second. The infrared image of Io shown on the previous page was taken with the 10-m Keck telescope, which has an adaptive optics system used primarily for infrared imaging.

Current telescopes are limited to targets not much fainter than can be seen with the unaided eye because of the need for the fast, accurate wavefront measurement. Light is detected in the form of quanta of fixed energy (photons) that arrive at random. If an object is so faint that no photons or only a few are detected in the short time the turbulent distortion is "frozen" in an image, then the necessary accuracy is not achieved. However, it may be possible in such cases to use light from a brighter surrogate source whose waves pass through the same turbulence and are similarly distorted. In this way, extrasolar planets, whose existence so far is known only from indirect starlight measurements, may become accessible to direct imaging. Like Galileo's moons—but 100 million times fainter—extrasolar planets should appear adjacent to the adaptively corrected images of their bright parent stars (*3*).

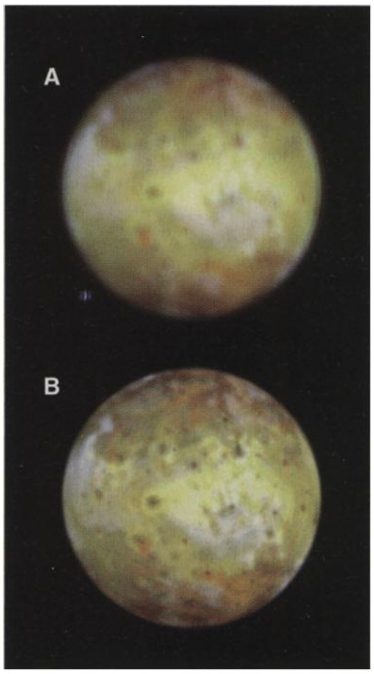
For most interesting faint objects, however, there will be no nearby stellar surrogate. Here, a needle-sharp laser searchlight can be used to create an artificial guide star. Laser light scatters from air molecules by the same process of Rayleigh scattering that makes the sunlit sky appear blue. A telescope looking up a scattering column from right beside the laser will see the column as a star. This original concept of generating an artificial star was proven at Starfire in experiments conducted in 1983 and was successfully used to correct star images at the 1.5-m telescope there in early 1989. The laser was focused 10 to 12 km above the telescope, where the air is still dense enough to scatter the laser light. A difficulty arises for large telescopes because laser guide star waves will not follow the same path as starlight to all parts of a large aperture. Thus they give an incorrect measure of wavefront error, especially when there is much turbulence at high altitude. For an artificial star to work for an 8-m telescope, it needs to be at a distance of 100 km or more. Even though there is essentially no air to scatter the laser light at that height, it is possible to scatter light from a very tenuous layer of sodium atoms. These will strongly scatter yellow laser light like a thin mist, provided that the wavelength is tuned precisely to the atomic resonance.

Sodium lasers. Sodium beams at the 3.5-m SOR telescope.

Experiments have proven the feasibility of sodium frequency lasers (see lower figure). Low-power (~3 W), continuous-wave commercial dye lasers at the University of Arizona's MMT telescope have been shown to scatter efficiently (*4*) and are employed in experimental astronomical systems today. Higher power (10 to 25 W) pulsed dye laser systems have been built by Lawrence Livermore National Laboratory and tested at Lick Observatory for future use at the Keck facility, but their pulse format is not optimal to maximize signal return (*5*). Both types of dye lasers require significant attention and maintenance.

One of the biggest future challenges is to develop and engineer lasers capable of exciting bright sodium guide stars. Solid state laser technology looks the most promising for providing a reliable, high-power system at a price that is affordable for purchase and operation for the current generation of 6- to 10-m telescopes.

The next improvement in resolution, requiring larger aperture, will come when adaptive optics is applied to the Large Binocular Telescope (LBT). This unique instrument, now under construction for operation in 2004, has two side-by-side 8.4-m mirrors, like a pair of binoculars. Adaptive correction capability is built into the telescope's secondary mirrors. The corrected beams will be combined such that the wave crest from the 23-m wide aperture arrives in phase at a common focus. The resulting sharpening in one dimension has been simulated for Io, based on an original Galileo spacecraft image (see upper figure, part A). Full high-resolution images will be recovered from separate images taken at different angles during the night by virtue of Earth's rotation. From three images like those in part A, Keith Hege has been able to recover the image quality of a full 23-m aperture by deconvolution (*6*) (part B). Using laser guide stars to correct both apertures, the LBT will image galaxies in formation in a deep field with 10 times the resolution of HST's deepest field.



Reconstructed Io. Simulated LBT images of Io in the near infrared, based on a visible light color image from the Galileo mission. **(A)** Single exposure image; **(B)** full resolution image reconstructed from three such exposures. The resolution was modeled for 0.8-, 1.25-, and 1.65-μm wavelength.

Given the enormous potential of very large aperture telescopes with adaptive correction, both Europe and the United States are considering new instruments with apertures of 30 to 100 m. The atmospheric turbulence at different heights in a column above the huge mirror will be sampled by natural and laser-generated light waves passing through at different angles. Very fast "movies" of Rayleigh scattering from short laser pulses traveling up through the column should yield good turbulence measurements, when analyzed by the technique of tomography developed for medical imaging (*7*). Correction will then be possible for appreciable fields of view as well as for individual objects.

So far, there don't seem to be any showstoppers. Thanks to adaptive optics, one of the oldest scientific instruments—the ground-based optical telescope—looks set for a continued leading role in astronomical discovery.

References and Notes

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