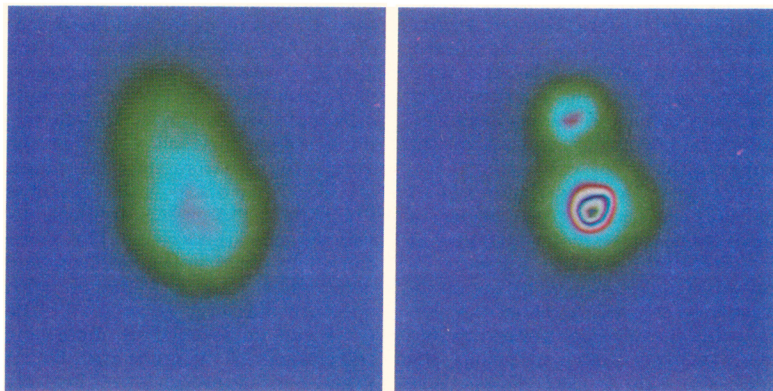


MAKING STARS TO SEE STARS: DOD ADAPTIVE OPTICS WORK IS DECLASSIFIED

Since the 1970s, researchers working first for the Defense Advanced Research Projects Agency and later under the aegis of the Strategic Defense Initiative have been developing and testing adaptive optics systems—systems for nullifying the effects of atmospheric turbulence on light that passes through it. In May 1991, to the delight of the astronomical community, much of the work became declassified.¹⁻³ Adaptive optics works by measuring the distorting effects of the atmosphere on the light from a guide star and adjusting a deformable mirror to conjugate these effects. In particular, the declassified research involves the use of laser beams to create one or more artificial beacons in the sky to act as guide stars.

Two separate developments led to the move to declassify the work on laser guide stars. First, researchers working behind the shield of classification knew from the open scientific literature and from discussions with Wayne van Citters, NSF program director for advanced technologies and instrumentation for astronomy, that much of the classified research was about to be redone. Indeed in 1985, independently of the classified work, Renaud Foy and Antoine Labeyrie,⁴ then at CERGA at the Observatoire du Calern in France, suggested the artificial guide-star techniques in unclassified literature, and in 1987 Laird Thompson and Chet Gardner⁵ of the University of Illinois at Urbana-Champaign unknowingly began to repeat prior DOD research. Robert Q. Fugate of the Phillips Laboratory (formerly the Air Force Space Technology Center, which included the Air Force Weapons Laboratory and other facilities) at Kirtland Air Force Base, New Mexico, says there was a push to get the material released so that the astronomy community wouldn't have to reinvent the wheel and so taxpayers wouldn't have to spend money on the same research twice.

The second precursor to the declassification was the changing world political scene. "Without that, I think this would have probably not



MIT LINCOLN LABORATORY

Images of the binary star Castor with (right) and without (left) adaptive optics compensation. The images were taken with a 60-cm telescope by MIT Lincoln Lab researchers at the Air Force Maui Optical Station on Mount Haleakala, Hawaii. The image was compensated using a 241-actuator deformable mirror and a Rayleigh beacon at an altitude of about 6 km.

been possible," says Fugate. It also helped that the SDI Organization had canceled its ground-based laser program, of which adaptive optics was a major portion. Even so, the process took about a year and involved much effort on the part of William E. Thompson of Phillips Labs. Thompson drafted the new classification guide to allow for release of the material while still satisfying everyone in the intelligence community and the Commerce Department.

Although the military objectives concerned the imaging of objects in space and the propagation of beam weapons, adaptive optics is also immediately applicable to astronomy. (See, for example, the figure above.) The effects of atmospheric turbulence on image quality are the limiting factor for ground-based observations in the visible and near infrared. (For ultraviolet observations the use of space-based telescopes such as the Hubble is necessary.) At a wavelength of 500 nm the diffraction-limited resolution of a 10-m telescope would be about 12 milliarcseconds, but in practice this ideal is 50 times beyond what even the best atmospheric "seeing" conditions allow. "People who have an 8-m

telescope without adaptive optics have no better resolution than a guy in the backyard with an amateur telescope," Fugate says.

Charles A. Beichman of the Jet Propulsion Laboratory in Pasadena expects the short-term goal of adaptive optics to be near-diffraction-limited imaging in the near infrared (that is, around 2000 nm). The more long-term goal of near-diffraction-limited imaging at optical wavelengths is far more challenging technically. A 3.5-m telescope at the diffraction limit could resolve a galaxy anywhere in the universe. (See the article by Beichman and Stephen Ridgway in *PHYSICS TODAY*, April 1991, page 48.) However, Beichman expects it to take four or five years before we see telescopes of that size being routinely corrected with full sensitivity by adaptive optics. (A review of Robert Tyson's book *Principles of Adaptive Optics* appears on page 100 of this issue.)

Distorted wavefronts

Atmospheric turbulence leads to disordered and rapidly changing local variations in the air's refractive index. As a result, a wavefront of light traveling through the air is distorted:

Different parts of the wavefront travel different optical path lengths and consequently get out of phase. The basic principle of adaptive optics, proposed by Horace W. Babcock⁶ of the Mount Wilson and Palomar Observatory in 1953, is to measure the distortion of the wavefront from a bright pointlike source—the guide star—and to adjust a deformable mirror to impart the conjugate deformation. Sophisticated real-time processing of the information is required because the mirror must be accurately deformed before the wavefront distortion changes by a significant fraction of a wavelength. The time scale for such variations in the distortion, the coherence time, is of the order of a few milliseconds at optical wavelengths.

The light from the guide star is typically analyzed with either a shearing interferometer (a type of interferometer that can measure local wavefront slopes) or a Hartmann wavefront sensor. A Hartmann sensor splits the telescope's aperture into many subapertures and brings the guide-star light in each subaperture to a focus. The displacement of each spot from its ideal position then acts as a measure of the local wavefront tilt.

However, the use of adaptive optics is limited because the guide star must be close to the celestial object to be imaged and more accurate corrections require a brighter guide star closer to the object. To achieve more accurate corrections the higher-spatial-frequency aberrations must be sensed by dividing the telescope's aperture into smaller subapertures. But if the guide star is too dim, not enough light can be collected in each subaperture to permit accurate measurement of the wavefront gradient. The problems are particularly bad at visible wavelengths because the coherence length and coherence time of the atmosphere vary as $\lambda^{6/5}$, where λ is the wavelength. Consequently, while much of the sky is available for correction at infrared wavelengths, less than 1% can be fully corrected at a visible wavelength of 500 nm using natural stars as wavefront sources.

Making stars

In 1981 Julius Feinleib of Adaptive Optics Associates in Cambridge, Massachusetts, suggested the laser guide star in a classified proposal to DARPA.¹ His idea involved focusing a laser in the lower atmosphere—in practice, at an altitude between 4 and 10 km. The beam is scattered off nitrogen and oxygen molecules by Rayleigh scattering, creating an artificial beacon that

can be placed anywhere in the sky. This "Rayleigh beacon" is a long pencil of light (see the photo on the cover of this issue), but of course appears to be a spot when viewed from the telescope used to project it. If a pulse is used, the electronics can be gated so that the wavefront sensors use only backscatter from a short section of the pencil.

However, the rays of light returning from the synthetic guide star are not as close to parallel as those from the astronomical objects to be observed. This leads to focal anisoplanatism: Away from the center of the aperture, the rays from the beacon and those from the real star sample different atmospheric turbulence. Focal anisoplanatism degrades the quality of the compensated image. David L. Fried of the Optical Sciences Company in Placentia, California, developed the theory for the error caused by focal anisoplanatism and determined that it increases with aperture diameter D as $D^{5/3}$. The error can be reduced by increasing the altitude of the guide star, but in practice this approach is prohibitively expensive with a Rayleigh beacon because of the increase in laser power required. For example, increasing the altitude from 10 km to 20 km requires a 16-fold increase in laser power for a beacon of the same magnitude.

A technique that reduces focal anisoplanatism was proposed in 1982 by Will Happer (now at DOE) in a then-classified Jason report. Happer suggested creating an artificial beacon for adaptive optics corrections by directing a laser beam tuned to the 589-nm sodium line to the mesospheric atomic sodium layer that exists at an altitude of 90–100 km. (See the figure on page 19.) Because the scattering is resonant, a laser tuned to 589 nm can create a beacon more than 10 000 times brighter than a Rayleigh system of equal laser power could achieve at such high altitudes. (See the figure on page 20.) A beacon at 90 km greatly reduces focal anisoplanatism and lies above the major contributions to the wavefront distortion, which are significant up to about 20 km.

Happer's idea arose in a military context, but the astronomical applications were immediately obvious. Indeed, Fugate says that some people at the 1982 Jason meeting expressed regret that they couldn't release the idea to the astronomical community.

Measuring wavefront distortions

Department of Defense work on the laser guide-star techniques began im-

mediately in 1982, sponsored by DARPA; after 1983 SDIO also funded the work. In 1983 a group working under Fugate tested the Rayleigh method at the Starfire Optical Range at the Kirtland Air Force Base.¹ A group working under Ronald A. Humphreys and Charles A. Primmerman from MIT's Lincoln Laboratory carried out experiments analogous to Fugate's but using a sodium-layer guide star in December 1984 at the White Sands Missile Range in New Mexico.²

Both of the early DOD experiments were "open loop"—they involved no deformable mirror and only measured the wavefront distortion as determined separately by using a real guide star and a laser-generated beacon. The aim was to test Fried's theory of the effects of focal anisoplanatism.

Fugate's group divided the 40-cm aperture of their telescope into 18 subapertures. The Lincoln Laboratory group used two 15-cm-diameter subapertures because their sodium beacon was extremely faint. Fugate's beacon was approximately equivalent to a first-magnitude star and was directed to within a few microradians of the second-magnitude star Polaris. (The magnitude scale is logarithmic; an increase of 5 magnitudes corresponds to a hundredfold decrease in luminosity.) His experiment used backscatter from a 1-km section of the beam at an average range of 5 km as the guide star. The outgoing laser beam was 10 cm in diameter in Fugate's Rayleigh experiments, whereas the Lincoln Lab sodium experiment produced a spot about a meter in diameter in the sodium layer. In the Rayleigh experiment the laser beam was polarized, allowing it to be separated from the starlight for analysis; the sodium experiment used a dichroic splitter. The results—the difference in wavefront distortions (other than "tilt") measured with the real and the synthetic guide stars—agreed remarkably well with theoretical predictions and was well explained by focal anisoplanatism. Due to the low light levels, the Lincoln Laboratory sodium experiment also had to contend with high photon noise.

Probably the greatest fundamental limitation of the laser guide-star method is the inability to correct for tilt or tracking using the laser guide star alone. Tilt, the lowest-order error, is equivalent to errors in the aiming of the telescope. Because the laser beam receives the same overall deflection going out as it does coming back, the beacon appears to be mo-

tionless when in fact it is moving around due to the tilt component from turbulence and tracking errors of the telescope. To correct tilt one still needs a real guide star, although one can use a much fainter star than is needed for higher-order corrections, because the aperture is not subdivided to make the tilt measurement. Stars of 14th-magnitude are widely expected to be adequate, and some researchers expect the much fainter and more numerous 18th-magnitude stars to suffice.

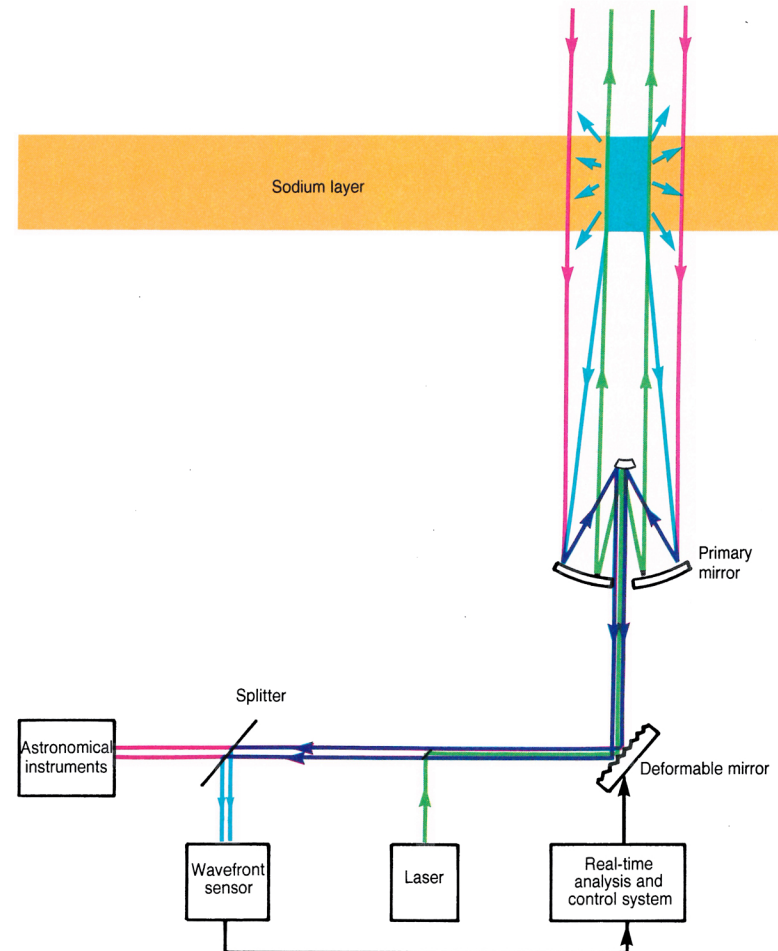
Adapting the optics

In August 1988 Primmerman and his collaborators at Lincoln Laboratory achieved atmospheric compensation with a synthetic beacon.³ Their experiment was another Rayleigh system, and used a 60-cm telescope on the top of Mount Haleakala on the island of Maui, Hawaii.

This experiment used a "go to" system because of the low repetition rate (5 Hz) of the dye laser employed. In a "go to" system, when the laser pulse is sent out the deformable mirror is flat, and in each cycle the mirror is driven all the way from flat to the conjugate of the measured distortion. This method is in contrast to a continual closed-loop system, which samples the atmosphere fast enough to allow the mirror to remain deformed, with small adjustments made on each cycle.

Each cycle of the Lincoln Lab experiment consisted of a 1-millisecond (uncompensated) exposure of a natural star with a flat mirror (see the figure on page 17), followed immediately by a laser pulse to create a beacon at 4–8-km altitude. Within 0.5 millisecond, all of the sensing and analysis was completed and the 241-movable-actuator mirror was deformed. At that point a 1-millisecond compensated image of the natural star was recorded. (These times are well within the estimated coherence time of 6 milliseconds for the wavelengths observed.)

Looking at the first-magnitude star Procyon in the visible, the Lincoln Laboratory group achieved essentially diffraction-limited half-maximum widths and a Strehl ratio of 0.46 (a factor of 10 improvement over the Strehl ratios of uncompensated images). The Strehl ratio is the ratio of the central peak intensity of the image to that expected for an ideal diffraction-limited image. The reason for the apparent discrepancy between the observed diffraction width and the Strehl ratio (which would be 1.0 for a perfect image) is that energy is still thrown into the wings of the



Laser guide-star system in simplified form. A small patch of the sodium layer is excited by a laser beam (green), creating an artificial beacon close in the sky to the object to be imaged. Some of the light from this beacon (blue) returns through the optical system and is used to determine the distortions caused by turbulence in the atmosphere. The deformable mirror is adjusted to compensate for these distortions and therefore also corrects the image of the object (red). A star tracker and fast-tracking mirror (not shown) are also usually included. The colors in the diagram do not reflect the light frequencies used.

diffraction pattern—the distribution is something like a pancake with a central peak. To achieve higher Strehl ratios would require greater subdivision of the aperture, more actuators on the mirror and higher-altitude beams.

Achieving a high Strehl ratio is more important for military objectives than for astronomical observations. For example, to direct a high-powered laser beam at low-Earth-orbit satellites one wants to have as much energy in the central lobe of the diffraction pattern as possible. For astronomy and imaging objects in space, reducing the width of the

central lobe is more important, and diffraction-limited resolution can be achieved with comparatively low Strehls. Problems might occur, however, if one tried to look at extended objects, several close objects or, in particular, a dim object close to a bright object (such as a planet around a nearby star).

In February 1989 Fugate's group achieved continuous closed-loop compensation using a 1.5-m telescope at the Starfire Optical Range.¹ Looking at various stars in the near infrared with a Rayleigh laser guide star at 10 km, the team achieved essentially diffraction-limited resolutions—a fac-

tor of 10 better than the uncompensated seeing. Although the copper-vapor laser had a pulse rate of 5 kHz, the system overall operated at a closed-loop bandwidth of 30–65 Hz. That is, atmospheric distortions varying more rapidly than that rate would not be corrected.

Synthetic constellations

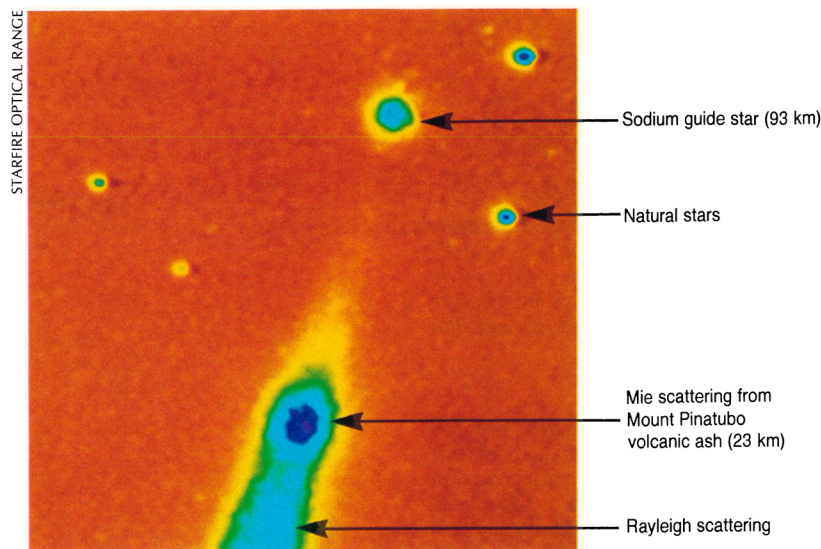
Much attention is currently focused on multiple guide stars. Clever use of the information from more than one guide star at once makes more accurate corrections possible. This method is particularly important for large telescopes (say, 8- or 10-m class), because focal anisoplanatism makes it difficult to apply corrections to the whole aperture with a single star, especially in the visible. In the visible an 8-m telescope would probably need from two to five sodium guide stars. Because of focal anisoplanatism, Primmerman doubts that any number of Rayleigh beacons could give adequate correction for an 8-m telescope in the visible.

Primmerman's group conducted a proof-of-principle experiment with multiple guide stars in October 1990.⁷ The group made two Rayleigh guide stars 30 cm apart, using two dye lasers. Because the telescope was small (60 cm) little improvement was seen over the use of a single star, but the experiment proved that information could be taken from multiple beacons and "stitched together" to make a single phase front.

Fugate's group is planning another multiple-beacon experiment. It will use a hybrid system with one Rayleigh beacon and one sodium beacon. The brighter Rayleigh beacon (about twice as luminous as a first-magnitude star) will be used to correct high-spatial-frequency distortions in regions smaller than the full aperture. The tenth-magnitude sodium beacon, sensed over only four subapertures, will be used to correct the low-spatial-frequency errors between those regions—it will "stitch" the regions together. Such an approach plays to the different advantages of the two systems. The fainter sodium beacon is not as well suited to dividing an aperture into very many small subapertures, which is important for shorter wavelengths. Conversely, because of focal anisoplanatism a Rayleigh beacon is not suited to correcting a large aperture.

Seeing ahead

One of the basic technological problems facing the sodium-beacon technique is development of a laser of sufficient power, collimation, pulse



False-color image of a sodium guide star at 93-km altitude. Light from Rayleigh scattering of the laser beam (visible at the bottom of the image) fades rapidly with increasing altitude and is supplanted by Mie scattering from the layer of Mount Pinatubo volcanic ash at 23 km. The image, which is about 125 arcseconds square, is from a $\frac{1}{30}$ -second exposure with a 1.5-m telescope. The 5-cm-diameter beam is produced by a 6.5-W laser pulsing 840 times per second.

length and reliability at the required frequency. Realistic astronomical observations of dim objects in the optical will require repetition rates of the order of kHz continued for relatively long exposure times.

At Lawrence Livermore National Laboratory, Claire Max and her collaborators have seized the unique opportunity to adapt a copper-vapor-pumped dye laser that was originally developed for DOE's Atomic Vapor Laser Isotope Separation program. The laser was originally engineered to be used 24 hours a day separating uranium for commercial nuclear power plants. At 1.5 kW the AVLIS laser is more powerful than is needed for astronomical applications, but this lets the Livermore researchers begin their experiments in a regime where they are sure they can demonstrate closed-loop correction (not yet achieved with a sodium beacon). The laser is impractically large for a real observatory, but the group has a design for a more compact laser that would put out 350 W of sodium light.

Achieving a bright sodium beacon is not just a matter of increasing laser power. To maximize the beacon intensity one wants sufficient flux to kick each atom to its excited state once every 16 nanoseconds—the decay time for the transition. At higher fluxes the sodium layer saturates and there is no increase in beacon intensity. This is particularly a problem with the AVLIS laser, which produces

short, intense pulses, but the Livermore group is exploring pulse-stretching techniques.

Meanwhile, Aram Mooradian and collaborators at Lincoln Lab have developed a very compact solid-state laser system specifically for producing sodium layer beacons (first reported in the open literature in reference 8). Their system combines the 1064-nm and 1320-nm lines of two Nd:YAG lasers in a nonlinear crystal, producing (by a fortuitous quirk of nature) sum-frequency radiation exactly corresponding to the 589-nm sodium line. The characteristics of the solid-state YAG laser are highly favorable for the guide-star application. The system can be made very efficient and compact by the use of diode-array pumping. Such a laser system would have a head size of less than 2 cubic feet, and the power supply and cooling system would be conveniently small for installation at an astronomical facility. Also, the pulses produced have the right length and the spectrally broadened waveform required to efficiently excite all the sodium atoms in a region of the layer. The figure above is an image of a beam produced with one of these systems. NSF has been instrumental in sponsoring the transition of this technology from the classified domain to the astronomical community.

Primmerman's group plans to use one of these sodium illuminators with a 1.2-m telescope located in

Westford, Massachusetts. Like the Livermore group, his group hopes to perform closed-loop compensation using a sodium guide star. The goal is to investigate compensation for dimmer objects (most experiments so far have studied brighter stars in order to have better signal-to-noise ratios for testing the system), and in particular the ability to image dim objects close to bright objects. Then the group will move its 241-channel system to a 4-m-class astronomical telescope. A principal astronomical goal will be to investigate whether these systems can be used to identify planets and planetary systems forming around other stars.

In work outside the US, the European Southern Observatory, together with industrial and scientific partners in France, has had a steadily advancing natural-guide-star adaptive optics development program since 1986. In October 1989 diffraction-limit resolution images at 2200 nm were obtained with the COME-ON system at a 1.5-m telescope at the Observatoire de Haute Provence in France. Since April 1990 the system has been used regularly at the ESO's 3.6-m telescope at La Silla in Chile.

While a laser guide-star system is not yet included in the ESO budget and formal plans, a development program has begun. Prototype tests could begin in two to three years on a 3.6-m telescope at La Silla, followed by a one-beacon system and finally a four-beacon system on one of the 8-m telescopes of the Very Large Telescope facility—most probably using the sodium layer. "The whole activity has reached a higher level of priority now that the declassified results have demonstrated feasibility," says Fritz Merkle of the ESO.

In unclassified research in the US,

Laird Thompson and Gardner⁵ produced their own sodium beacon in January 1987 on Mauna Kea, but their laser was not sufficiently focused to allow wavefront measurements. After a two-year hiatus in funding Thompson began to produce Rayleigh beacons in 1990, and he was working toward wavefront measurements when the DOD research was declassified.

Edward Kibblewhite of the University of Chicago produced focused continuous-wave sodium-light beacons in June 1991. His group is building a system to be used with a sodium laser and a 3.5-m telescope run at Apache Point, New Mexico, by the Astrophysics Research Corporation—a consortium of universities. Kibblewhite's group anticipates having use for the next five years of a 69-actuator adaptive optics system that SDIO developed for an experiment involving the space shuttle but whose title is expected to be transferred to NSF.

Kibblewhite points out that compared with astronomical needs some of the military applications—for example, tracking a satellite—require much higher response speeds from components such as the deformable mirror. For astronomical observations, the coherence time of the atmosphere is essentially the coherence length divided by the wind speed—the speed at which a given patch of turbulence crosses the line of sight. For a target moving at orbital velocities in low Earth orbit the apparent velocity of the target is 10–100 times greater than the wind speed, and the adaptive optics system needs 10–100 times greater bandwidth. Kibblewhite believes great savings can be made by avoiding the technical problems of working at such speeds.

Primmerman comments that as-

tronomers "really haven't faced up to the cost of these things. The astronomical community tends to view this still as instrumentation and they've pigeonholed it in that funding category. These systems will not be cheap, certainly not if we're talking about hundreds, perhaps thousands, of channels on an 8-m telescope. But given the cost of the telescope and the increase in resolution that's possible with these systems it seems to me they're cost effective."

For example, the 10-m Keck Telescope cost about \$93 million, and the Hubble Space Telescope cost about \$2 billion. Laird Thompson has estimated the cost of a multiple-Rayleigh-beacon system based on a 241-movable-actuator mirror manufactured by Itek to be \$3.5 million. "If you put a mirror like that on a 2.5-m telescope you can correct optical wavelengths," he says. He calls the price extremely reasonable.

—GRAHAM P. COLLINS

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COMPTON OBSERVATORY DATA DEEPEN THE GAMMA RAY BURSTER MYSTERY

To monitor Soviet compliance with the nuclear test ban treaty of 1963, the US deployed the Vela series of military satellites, instrumented to detect sudden bursts of gammas. The surveillance satellites did indeed find dozens of gamma bursts, but by 1967 it was clear that these were not instances of Soviet cheating. They were coming from all directions of the sky above. The Vela satellites had inadvertently discovered a new class of celestial phenomena. Not until 1973 did the military allow this new discovery to be made public.

But now, after a quarter-century of ever more sophisticated observation, we still don't know what these "gamma-ray bursters" are. For all the astronomers know, the sources of these outbursts, which can last for milliseconds or minutes, may be as close as the outer reaches of our solar system or as distant as the quasars. Correspondingly, speculations about the energy released in a gamma burst range over 26 orders of magnitude. The very lively debate is reminiscent of the early 1920s, when astronomers argued hotly over whether the nebulae were local or extragalactic objects.

lae were local or extragalactic objects.

Over the years the directions of about 400 celestial gamma bursts have been recorded with some precision. There is almost never anything along the line of sight, at optical or any other wavelengths, that might be a steady-state counterpart; and there's no evidence of repeaters.

The Gamma Ray Observatory

The Compton Gamma Ray Observatory, deployed into Earth orbit from the shuttle Atlantis last April, began accumulating gamma-burst data with