Adaptive Optics Research at Lincoln Laboratory

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■ Adaptive optics is a technique for measuring and correcting optical aberrations in real time. It is particularly useful for atmospheric compensation—the correction of aberrations incurred by light propagating through the atmosphere. For more than two decades Lincoln Laboratory has been a leader in adaptive optics research and has performed seminal experiments in atmospheric compensation, including the first thermal-blooming compensation of a high-energy laser beam, the first compensation of a laser beam propagating from ground to space, and the first compensation using a synthetic beacon. In this article we describe the fundamental concepts of adaptive optics for atmospheric compensation and briefly review more than 20 years of Lincoln Laboratory work in the field.

ADAPTIVE OPTICS—the term almost defines itself—is a technique for performing real-time cancellation of optical aberrations. Adaptive optics can be used to correct various aberrations, including laser-device aberrations, aberrations resulting from optical fabrication errors, and thermally induced aberrations in telescopes, but the most common use for adaptive optics is in correction for atmospheric distortions.

Light propagating through the atmosphere can be severely aberrated by atmospheric turbulence. This turbulence-induced aberration is an easily observed, everyday phenomenon. It is what causes objects to appear distorted when viewed from across a black-topped runway on a hot, sunny day; it is what causes stars to twinkle and dance. For many people the twinkling of stars is a romantic phenomenon, but for astronomers the atmospheric-induced distortion of starlight means that the new generation of 8-to-10-m telescopes—although having impressive light-collecting capacity—will have visible-light resolution no better than that of an amateur astronomer's 10-to-15-cm backyard telescope.

With adaptive optics it is possible to compensate for atmosphere turbulence and, thus, to achieve the full resolution capabilities of large telescopes. Figure 1 outlines the basic arrangement for an imaging atmospheric-compensation system. Light from a star is collected by a telescope and is reflected off a deformable mirror. Part of the light is sent to an imaging camera, and part to a wavefront sensor. The wavefront sensor measures an array of local phase gradients, or wavefront tilts, which are processed in a wavefront reconstructor to derive a phase map of the incoming wavefront. The phase values are then used in a multichannel servo loop to drive the deformable mirror so as to flatten the incoming wavefront. If the incoming wavefront is flattened in this way, the image resolution will be near diffraction limited.

The required size and speed of the adaptive optics system are set by fundamental atmospheric-turbulence parameters. For good correction, the measurement/correction channels should be spaced by no more than r_0, where r_0 is the turbulence coherence length [1]. For typical conditions r_0 ranges from 5 to 15 cm in the visible-light region; thus an adaptive optics system for a 1-m telescope requires about a hundred channels, whereas a system for an 8-m telescope requires many thousands of channels. These values are for correction in the visible-light region; since r_0 is proportional to $\lambda^{6/5}$, where λ is the wavelength of light, correction in the infrared region re-

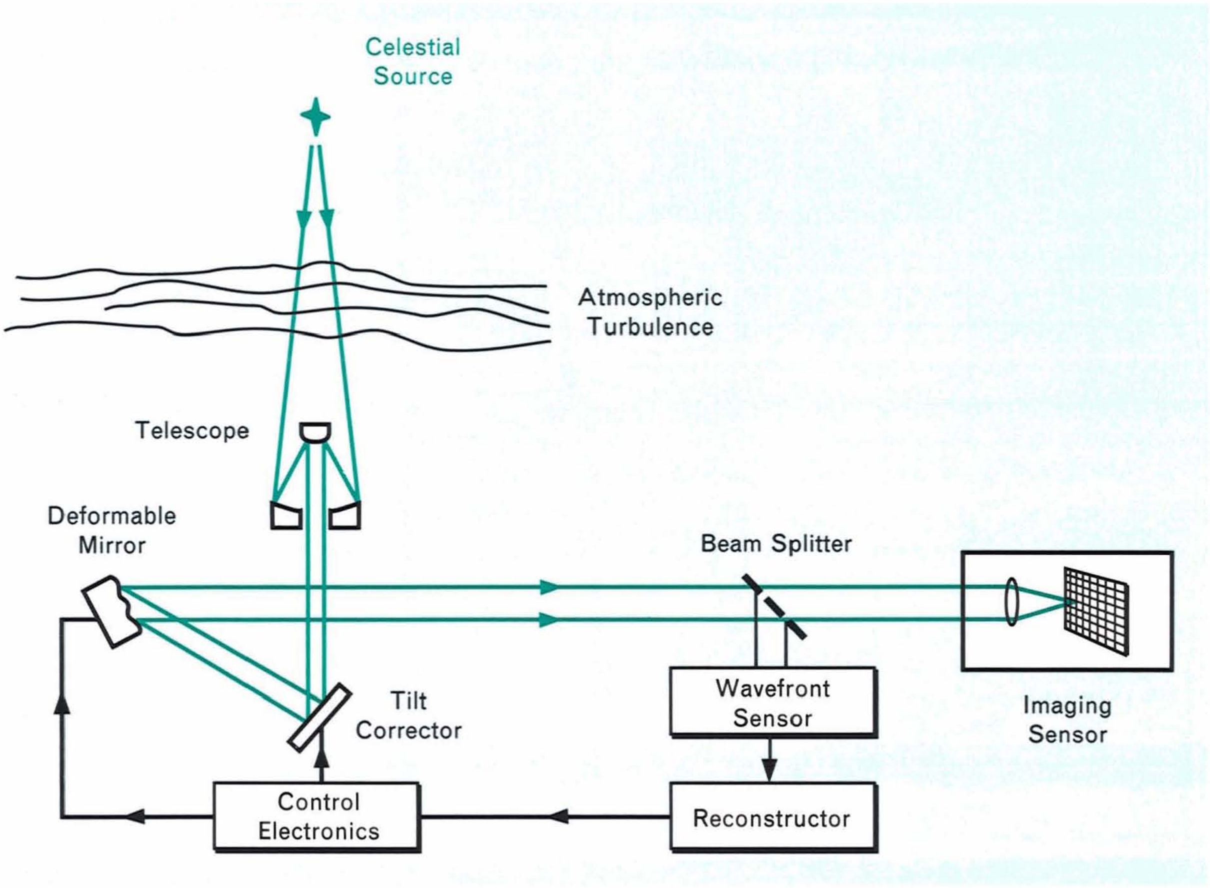


FIGURE 1. Adaptive optics arrangement for compensating the image of a bright star for the degrading effects of atmospheric turbulence. This arrangement is also suitable for compensating the image of a solar-illuminated satellite.

quires far fewer channels. The required correction bandwidth, which is a measure of how rapidly the correction must be updated, is given by the Greenwood frequency f_G [2, 3]. For typical turbulence and wind conditions, the required bandwidth is of the order of 100 Hz for correction in the visible-light region. The bandwidth scales as $\lambda^{-6/5}$, so again the system requirements are much less stressing in the infrared region. For typical turbulence conditions, the deformable mirror must correct for an optical-path difference of approximately 3 μm for a 1-m aperture and 16 μm for an 8-m aperture, independent of wavelength. Since more than half of the required correction is tilt, adaptive optics systems usually have a separate tilt-correction mirror to relieve the stroke requirement on the deformable mirror.

In Figure 1 the star that is being imaged is also used as the beacon for the adaptive optics system; but since more light is required to operate a wavefront sensor than to form an image, it can be helpful in imaging a dim object to use a nearby bright star, referred to as a natural guide star, as the beacon. For this natural-guide-star technique to be effective, the object to be imaged must be separated from the guide star by no more than the isoplanatic angle, θ_0, the angle within which the turbulence-induced phase distortion is approximately constant [4]. For visible-light wavelengths, θ_0 is about 10 to 25 μrad. The system illustrated in Figure 1 can also be used for imaging objects such as solar-illuminated satellites, as long as the angular extent of the object is less than θ_0. For satellite imaging, of course, the bandwidth requirements become much more severe: close to 1-kHz bandwidth is required for good compensation of low-earth-orbit satellites.

Thus far we have discussed adaptive optics for imaging applications, but the principal interest of the Department of Defense (DoD) and most of the Lincoln Laboratory work in adaptive optics have involved the propagation of high-energy laser beams through the atmosphere. Figure 2 shows the configuration for atmospheric compensation of a laser in a cooperative scenario, i.e., a scenario in which the laser is propagated to a friendly target that provides a properly placed beacon for the adaptive optics system. Examples of such cooperative scenarios include the Strategic Defense Initiative Organization (SDIO) ground-based-laser system, in which a laser beam would be sent from the ground to a relay mirror on a satellite, and the NASA power-beaming system, in which a laser beam would be sent from the ground to an array of photovoltaic cells on the moon or on an orbiting satellite. To aim and compensate the outgoing beam properly, the beacon shown in Figure 2 leads the target by an angle $2v_\perp/c$, where $v_\perp$ is the target speed perpendicular to the line of sight and c is the speed of light. For satellite targets, this angle is 20

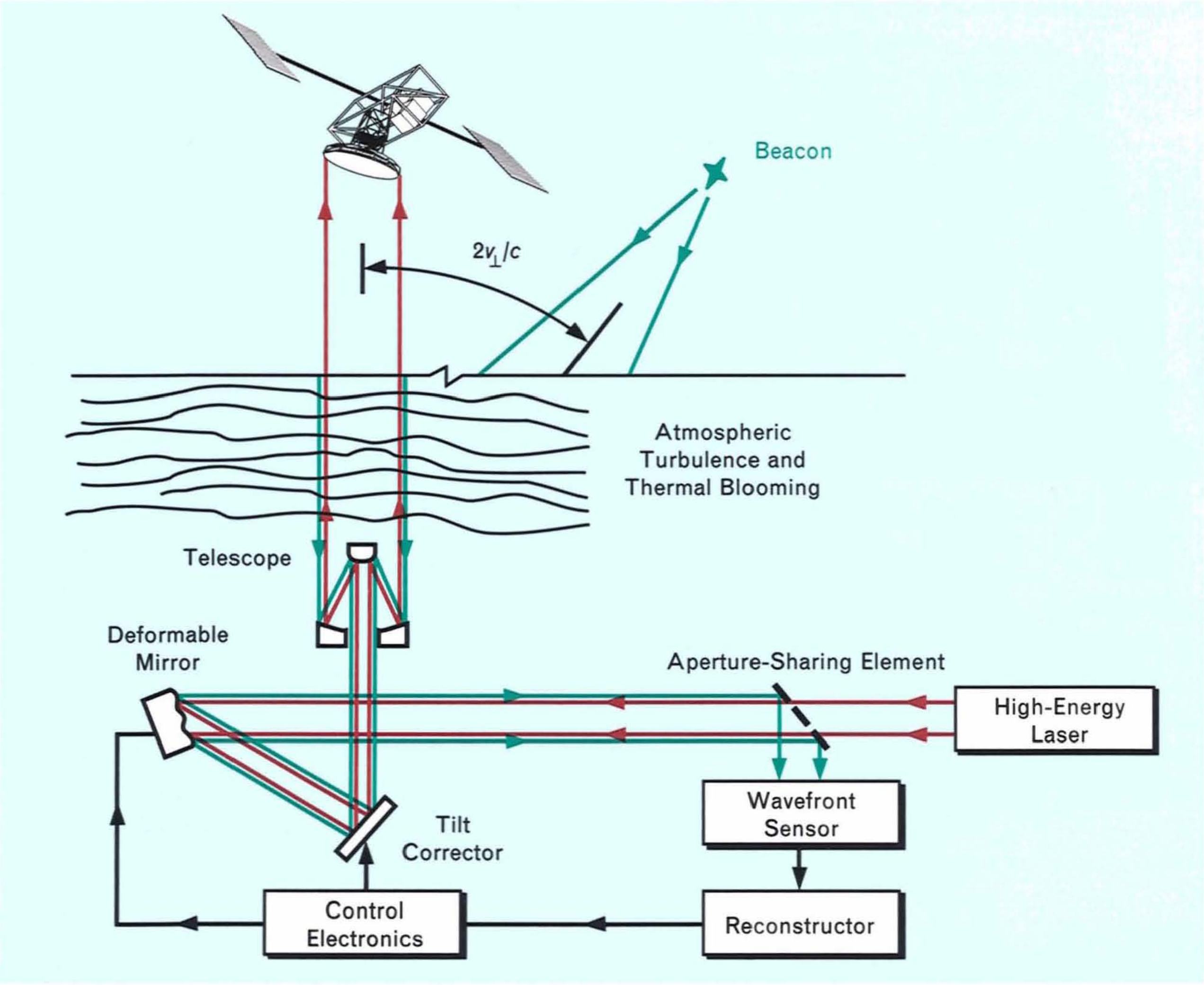


FIGURE 2. Adaptive optics arrangement for compensating an outgoing laser beam for the deleterious effects of thermal blooming and atmospheric turbulence in the cooperative-target scenario. A cooperative target is one that provides a properly located bright beacon for the adaptive optics wavefront sensor. Examples of cooperative-target scenarios are the Strategic Defense Initiative (SDI) ballistic-missile-defense scenario in which a laser beam is transmitted from the ground to a satellite-borne relay mirror and the NASA power-beaming scenario in which a laser beam is transmitted from the ground to photovoltaic cells on the moon or on man-made satellites.

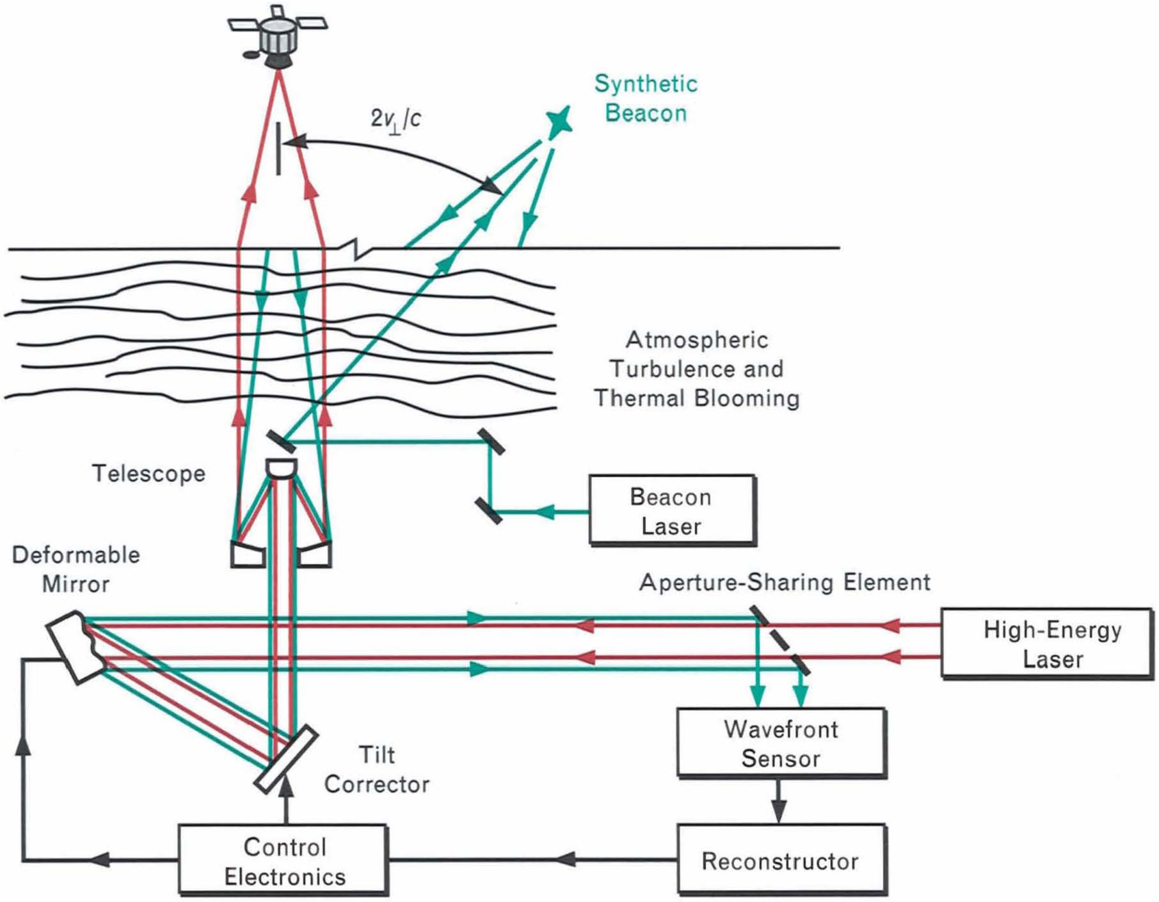
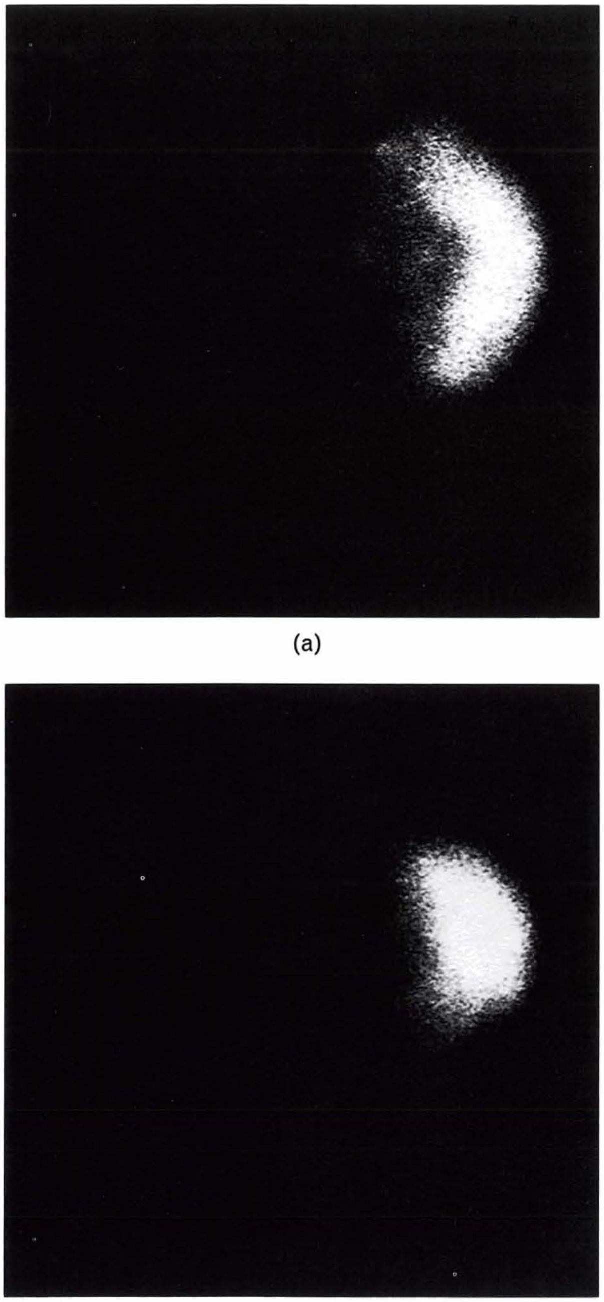


FIGURE 3. Adaptive optics arrangement for compensating an outgoing beam for the deleterious effects of thermal blooming and atmospheric turbulence in the uncooperative-target scenario. In the uncooperative-target scenario a synthetic beacon is generated by backscatter from a ground-based illuminator laser. Synthetic beacons can also be used in compensated-imaging applications in which the object being imaged is too dim to be used as a beacon for the adaptive optics wavefront sensor.

to 50 μrad. As in Figure 1, the adaptive optics system works to flatten the received wavefront of the beacon light. The high-energy laser beam is then inserted into the optical train by an aperture-sharing element and reflects from the deformable mirror, which precorrects the beam for the distortions it will experience in the atmosphere. Thus, as the laser beam propagates through the atmosphere, the atmospheric distortions cancel the phase that the deformable mirror applied so that the laser beam exits the atmosphere with a flat phase and propagates thereafter as a diffraction-limited beam.

Compensation of a high-energy laser introduces two major complications for the adaptive optics system. First, there are hardware difficulties associated with handling a high-energy laser beam: the deformable mirror must be cooled, and the aperture-sharing element must be capable of separating a very high-power beam from a very low-power beacon without introducing any significant distortion. Second, and more important, the high-energy beam introduces an entirely new physical effect: thermal blooming.

Thermal blooming is the spreading of a laser beam that results when the beam heats the medium through which it is propagating. As the laser beam passes through the atmosphere, some of the beam's energy is absorbed, heating the atmosphere. The heated region will be less dense and will, consequently, have a lower index of refraction. Since the hottest regions will normally be in the center of the beam, a negative lens will develop in the atmosphere, and this lens will diverge the beam. For many high-power scenarios of interest the magnitude of the spreading from thermal blooming is comparable to or exceeds that from turbulence.


(a)

(b)

FIGURE 4. Laboratory corrections for thermal blooming (1975): (a) classic crescent shape of a thermally bloomed beam and (b) beam corrected with a 57-channel deformable-mirror system. For this tactical scenario the peak irradiance increased by a factor of approximately 3.

Since light from the beacon will be distorted by thermal blooming as well as by turbulence, the system illustrated in Figure 2 will correct for both effects. Correction for thermal blooming typically requires fewer channels and lower bandwidths than correction for turbulence, but a somewhat higher deformable-mirror stroke. But although thermal blooming and turbulence are nominally corrected in the same way by the same adaptive optics system, there are fundamental physical limits to the ability of an adaptive optics system to correct for thermal blooming that do not exist for turbulence correction. Turbulence distortions are completely independent of the phase-

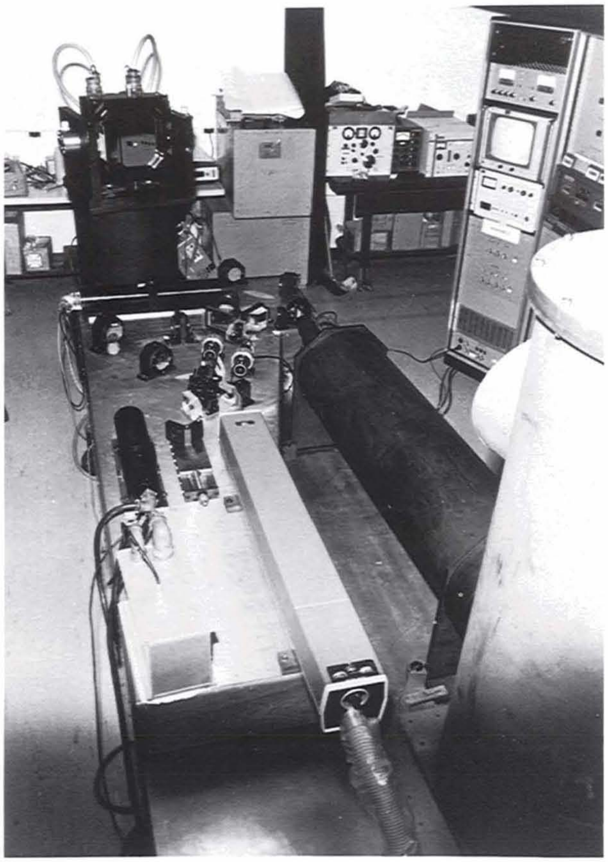


FIGURE 5. The 52-channel cooled deformable-mirror system (1975). The mirror itself is in the rear; in the foreground is the interferometer used to measure the surface figure so that the mirror could be actively controlled to apply a specified phase. This deformable mirror, developed by United Technologies Research Center, was the first deformable mirror to be used with a high-energy laser.

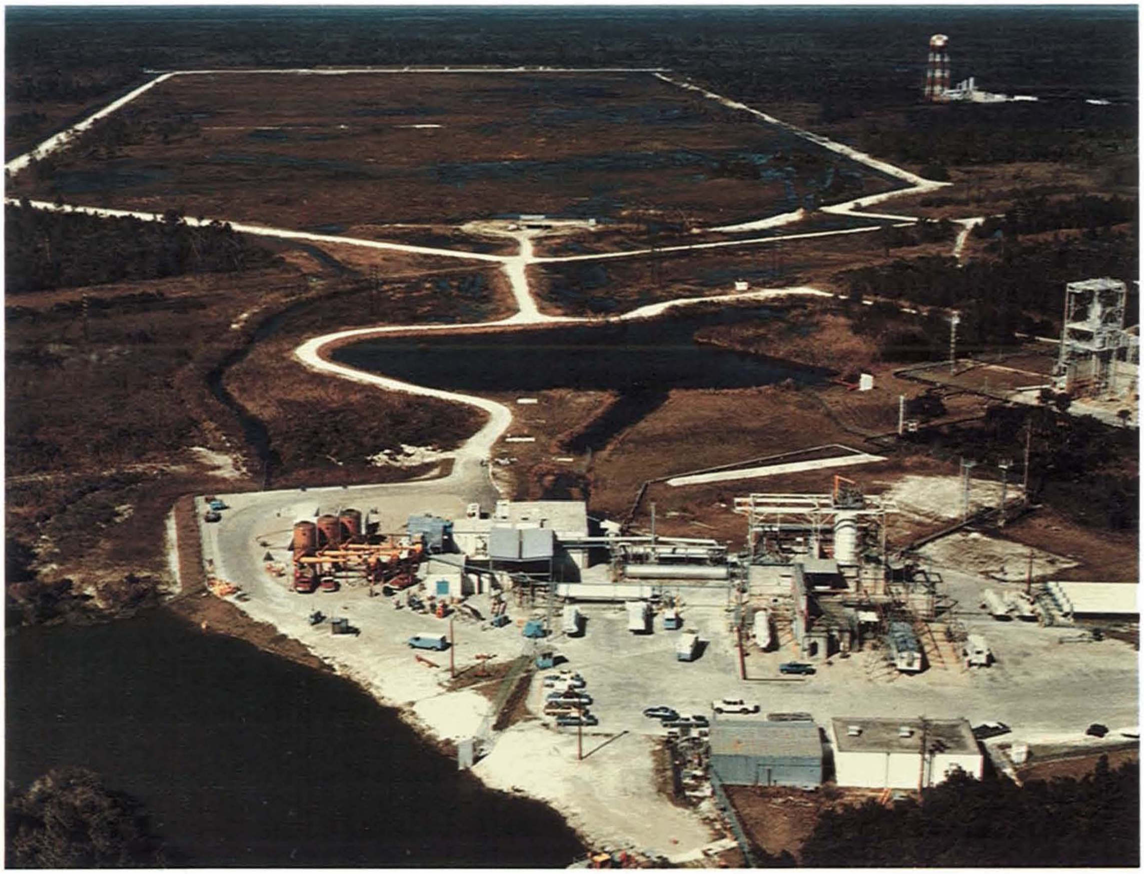


FIGURE 6. Pratt and Whitney high-energy-laser propagation range in West Palm Beach, Fla., site of thermal-blooming tests (1975 through 1977).

compensation process; thermal blooming, on the other hand, is induced by the same laser beam that is being corrected. Thus, phase corrections to the laser beam can cause changes in the heating pattern of the beam, and such changes can alter the atmospheric phase that needs to be corrected. The feedback path from phase correction to changed phase distortion can cause the adaptive optics correction for thermal blooming to become unstable. The instability, called phase-compensation instability (PCI), limits the energy that can be propagated through the atmosphere with good phase correction.

The system illustrated in Figure 2 can work well for a cooperative target, but obviously many targets are uncooperative, in that they do not come equipped with a beacon suitable for wavefront sensing. For short-range tactical targets, optical energy either emitted by or reflected from the target can be used as a beacon. For long-range targets such as satellites, however, such a beacon is usually too dim; more importantly, such a beacon is not in the right position because, as mentioned earlier, a beacon must lead the target by an angle $2v_\perp/c$ to permit the proper correction of the outgoing beam. A solution to the uncooperative-target problem is to generate a synthetic beacon (also called artificial beacon and sometimes laser guide star) by atmospheric backscatter from a ground-based illuminator laser.

Figure 3 illustrates the uncooperative atmospheric-compensation scenario. A ground-based laser is sent skyward at the proper point-ahead angle and generates a synthetic beacon, either by Rayleigh backscatter or by resonant backscatter from the mesospheric sodium layer. Rayleigh backscatter is simply scatter from atmospheric nitrogen and oxygen; with Rayleigh backscatter a synthetic beacon can be generated at any altitude, but practical considerations of illuminator power effectively limit Rayleigh beacons to altitudes less than 25 km. The mesospheric sodium layer is a layer of atomic sodium about 15 km thick centered at an altitude of about 90 km; by tuning the illuminator laser to the 589-nm sodium D_2 line, we can receive a strong resonant backscatter signal from the sodium layer. Once the synthetic beacon is generated, the atmospheric compensation is performed in much the same manner as in the cooperative-beacon scenario, with the exception that the synthetic-beacon system normally works in a repetitive-pulse mode, with the wavefront sensor switching on only to receive backscatter from the predetermined altitude.

Using a synthetic beacon solves the problem of generating a beacon at the correct point-ahead angle, but the technique introduces a new problem called focal anisoplanatism—the error that results from the beacon's being at a different altitude from that of the target (discussed in the article by Ronald A. Humphreys et al. [5] in this issue). Focal anisoplanatism has two components: (1) there can be unsensed turbulence above the synthetic beacon, and (2) below the synthetic beacon the optical rays from the beacon do not travel exactly the same path through the atmosphere as do the rays to the target (Figure 3). Because the rays increasingly diverge as the telescope aperture size increases, focal anisoplanatism limits the size of an aperture that can be corrected with a synthetic beacon at a given altitude. Focal anisoplanatism can be reduced by increasing the altitude of the synthetic beacon or by using multiple synthetic beacons and "stitching" their signals together to correct a single aperture. Since the multiple-beacon stitching process introduces its own fundamental and practical limitations, it is desirable to have the beacon altitude be as high as possible, which is what makes the sodium-layer beacon so attractive.

There is another significant difference between uncooperative and cooperative atmospheric compensa-

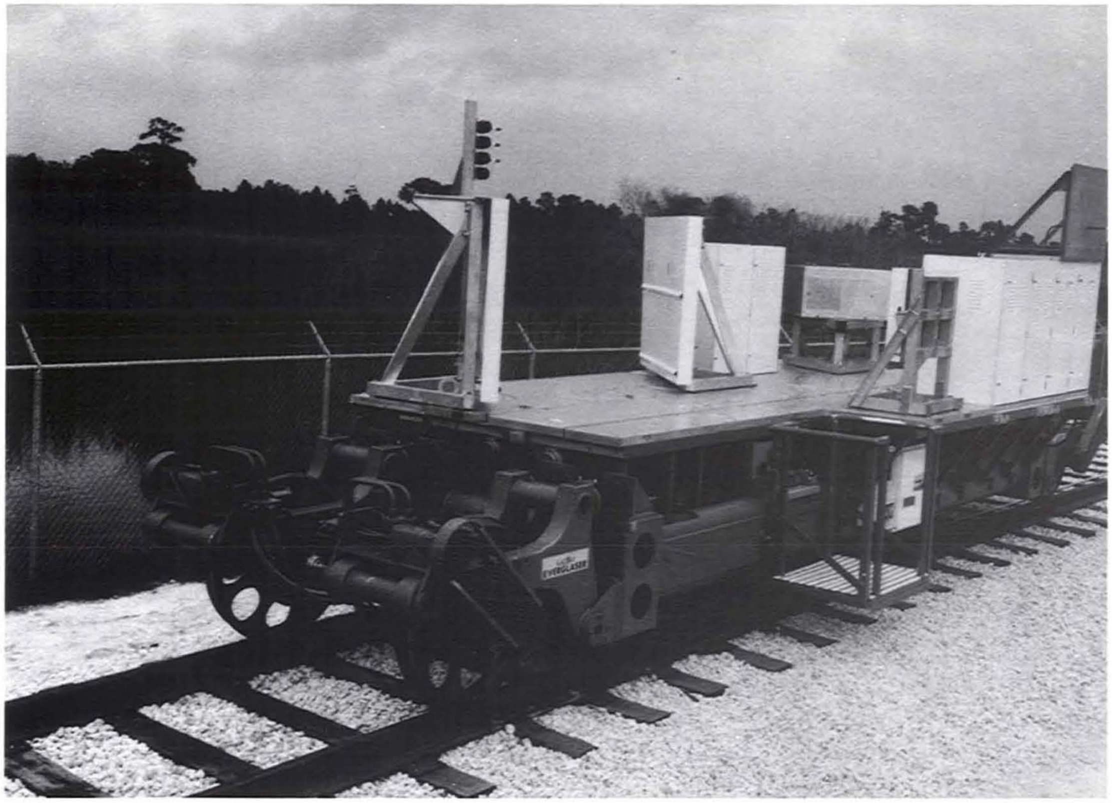


FIGURE 7. Everglaser instrumented target vehicle (1976). This vehicle, running on standard-gauge railroad track, served as the target at the end of the Pratt and Whitney 2-km propagation range shown in Figure 6. The XLD beam was focused on a thick metal plate carried by the Everglaser, and the focal spot was diagnosed by several on-board cameras.

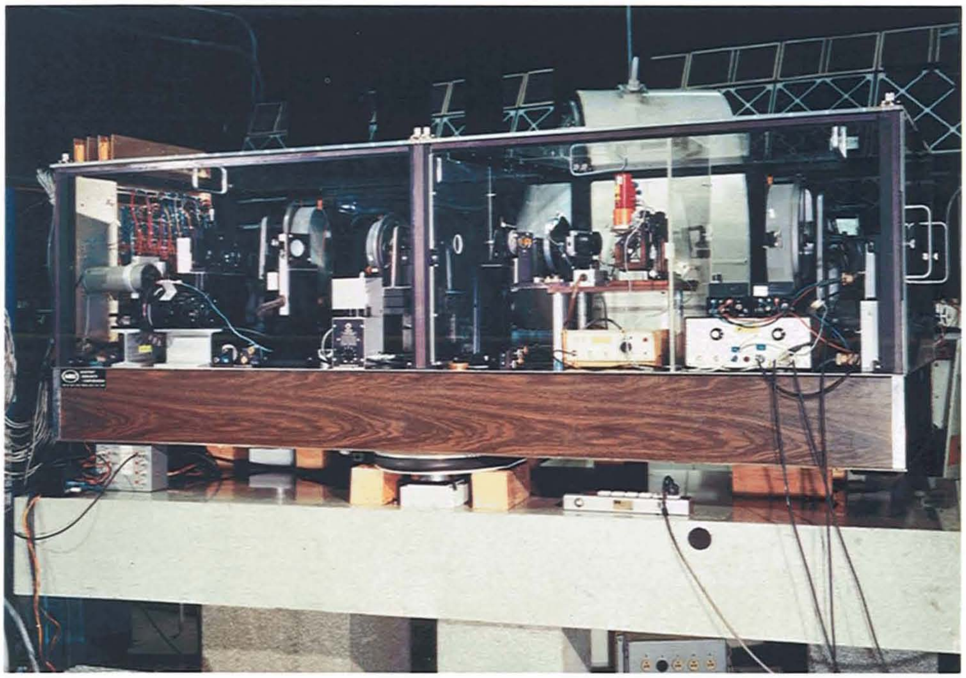


FIGURE 8. Optical Compensation of Uniphase Laser Radiation (OCULAR) multidither system installation at the Pratt and Whitney site (1977). The OCULAR system was used with the 52-channel cooled deformable mirror illustrated in Figure 5 to perform the first compensation for device aberrations in a high-energy laser.

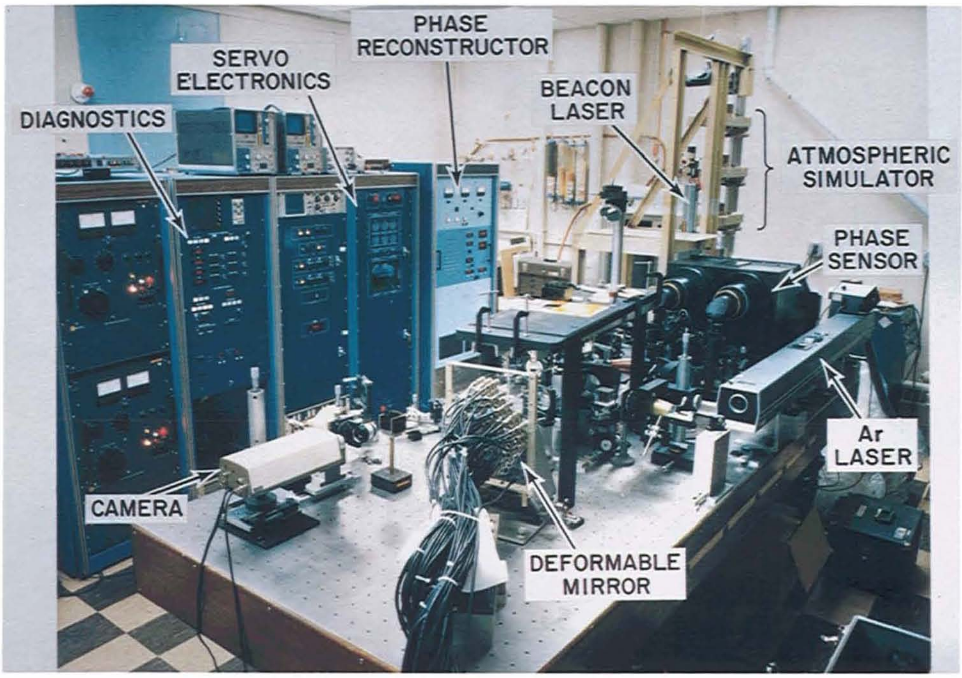


FIGURE 9. Atmospheric-Compensation Experiment (ACE) adaptive optics system (1981). The photograph shows the 69-channel ACE adaptive optics system as set up in the laboratory before being shipped to the field. In the laboratory the system was tested with simulated turbulence induced by rotating phase screens.

tion. Because the synthetic beacon is projected up through the turbulent atmosphere its angular position relative to the satellite target is not precisely known. Thus, the synthetic beacon cannot be used for tracking and tilt correction. Instead a separate tilt-correction system (not shown in Figure 3) must be employed by using light reflected or emitted from the target as the tracking beacon. This tracking beacon is, of course, not in the correct lead-ahead direction, but since turbulence-induced tilt fluctuations are correlated over larger angles than are fine-scale phase fluctuations—i.e., the tilt isoplanatic angle is larger than the overall isoplanatic angle—good tilt correction is often possible even with a non-optimally placed tracking beacon.

Figure 3 illustrates a synthetic-beacon atmospheric-compensation system for use with a high-energy laser, but synthetic beacons are also highly useful for astronomical imaging (as discussed in the article by Ronald R. Parenti [6] in this issue). Without a synthetic beacon, astronomers must depend on the presence of a bright natural guide star within an isoplanatic angle of the object they wish to image. Dependence on natural guide stars severely limits the fraction of the sky that can be observed with good compensation, particularly in the visible region of the spectrum. But a synthetic beacon can be generated in the direction of any object in the sky, thus allowing full, compensated coverage of the sky.

Origins of Adaptive Optics Research at Lincoln Laboratory

Lincoln Laboratory began investigating high-energy-laser propagation in the late 1960s and began investigating adaptive optics in the early 1970s. The initial emphasis was on compensating 10.6-μm CO_2 laser beams that would be used in tactical scenarios and, hence, would be focused in the atmosphere. (With

FIGURE 10. Air Force Maui Optical Site (AMOS) on top of Mount Haleakala on the island of Maui, Hawaii. Both the ACE experiments (1982 through 1985) and the Short-Wavelength Adaptive Techniques (SWAT) experiments (1988 through 1991) were performed with the 60-cm laser beam director in the small dome at the center of the photograph. The photograph shows the site in 1988, after completion of the building addition (enclosed by the curved wall at the lower right corner of the building) to accommodate the SWAT system.

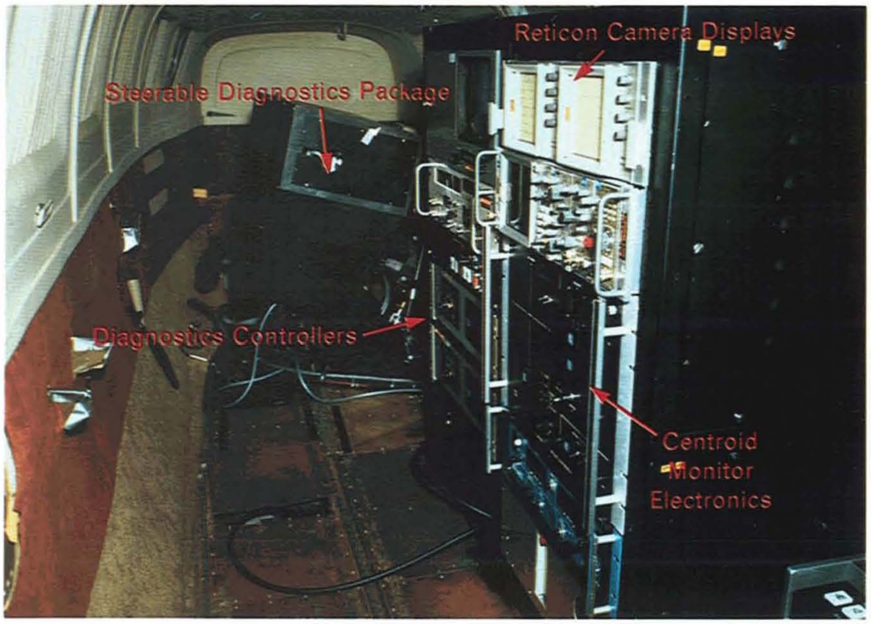


FIGURE 11. Diagnostic aircraft for ACE experiments (1983). The Phase II ACE experiments used this Cessna 441 Conquest to carry a beacon and diagnostic cameras. During the experiments the aircraft flew in a wide-banked turn 10,000 ft above the site, and a compensated laser beam was aimed through a window in a specially modified door of the aircraft.

the benefit of 20 years of hindsight, we realize now that we started with the most difficult problem first.) In the subsequent 20 years we have investigated adaptive optics for 3.8-μm deuterium-fluoride (DF) lasers, for excimer lasers in the ultraviolet region, for free-electron lasers at 1 μm. We have explored adaptive optics for aberrations induced in laser resonators, for ground-to-space propagation for various strategic scenarios, for astronomical imaging. Our work has involved a broad program of theory, laboratory experiments, hardware development, and field experiments.

Lincoln Laboratory's adaptive optics work began with computer calculations showing that thermal blooming could be at least partially corrected by phase compensation [7]. We subsequently verified these predictions in laboratory experiments [8]. These first thermal-blooming-compensation experiments used a 69-channel deformable mirror that was manually adjusted according to the computer predictions to maximize the intensity of the laser beam on the target. An example of thermal-blooming compensation in the laboratory is shown in Figure 4. Later we performed an experiment called Closed Loop Adaptive Single Parameter (CLASP) [9], in which the shape of the deformable-mirror correction was fixed but the amplitude was adjusted automatically to maximize the far-field intensity.

In the mid-1970s we conducted a long series of field experiments with the Pratt and Whitney XLD—a 10.6-μm CO_2 gas-dynamic laser that was, at the time, the most powerful laser in the free world—at the Pratt and Whitney site in West Palm Beach, Fla. The adaptive optics experiments were conducted using a cooled 52-channel deformable mirror (Figure 5), the first deformable mirror to be used with a high-power laser. The XLD laser beam was expanded to 1.2 m and propagated over a 2-km horizontal path (Figure 6) to an instrumented vehicle (known affectionately as the Everglaser) that ran on a short stretch of railroad track (Figure 7). With this arrangement we successfully performed the first thermal-blooming-compensation tests with a high-energy laser. We also successfully performed CLASP tests—the first closed-loop thermal-blooming compensation of a high-energy laser beam.

A second atmospheric-compensation experiment performed with the XLD was called Target Return Adaptive Pointing and Focus (TRAPAF). Instead of the 52-channel deformable mirror, TRAPAF used a mirror that could correct only for tilt and focus, to explore the efficacy of simple, low-order adaptive optics systems. Successful high-power and low-power tests were conducted along the 2-km path, with limited correction achieved.

The 52-channel deformable mirror was also used in several experiments to correct for aberrations on the XLD laser beam itself. The most successful of these experiments was the Optical Compensation of Uniphase Laser Radiation (OCULAR), which used a multidither technique that had been pioneered several years earlier by researchers at Hughes [10]. OCU-

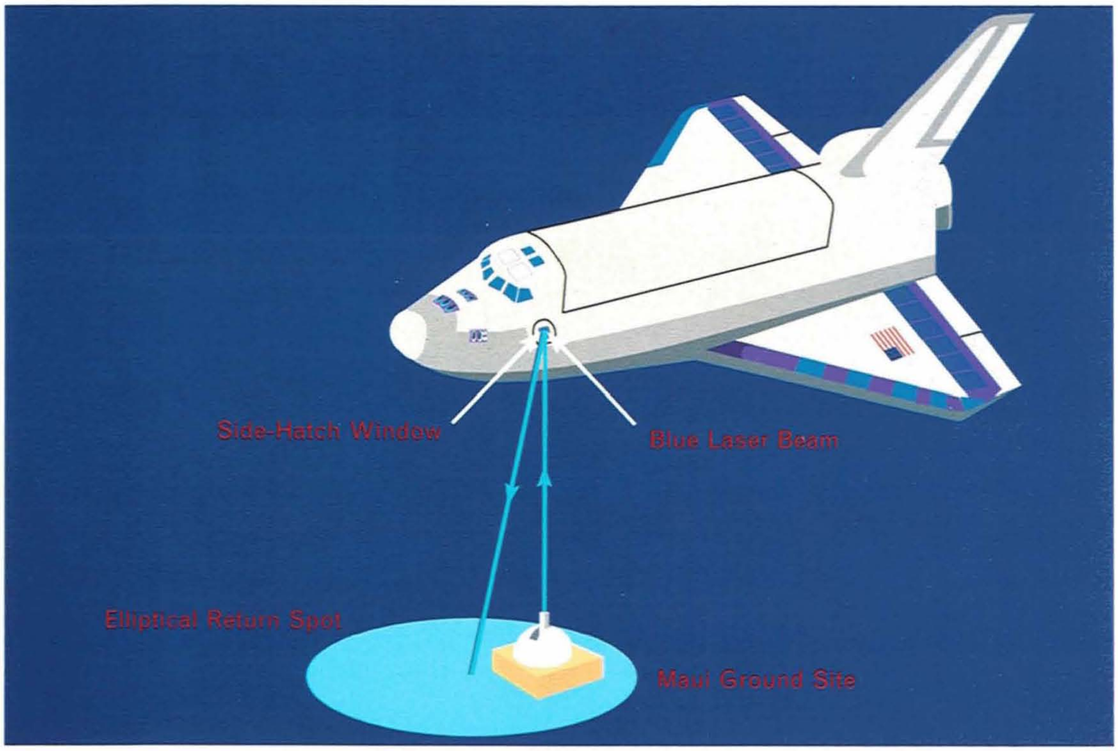


FIGURE 12. ACE experiment with the space shuttle Discovery (1985). The ACE system illuminated a retroreflector that was mounted in the side-hatch window of the shuttle, and the system used the return signal as a beacon to perform atmospheric compensation.

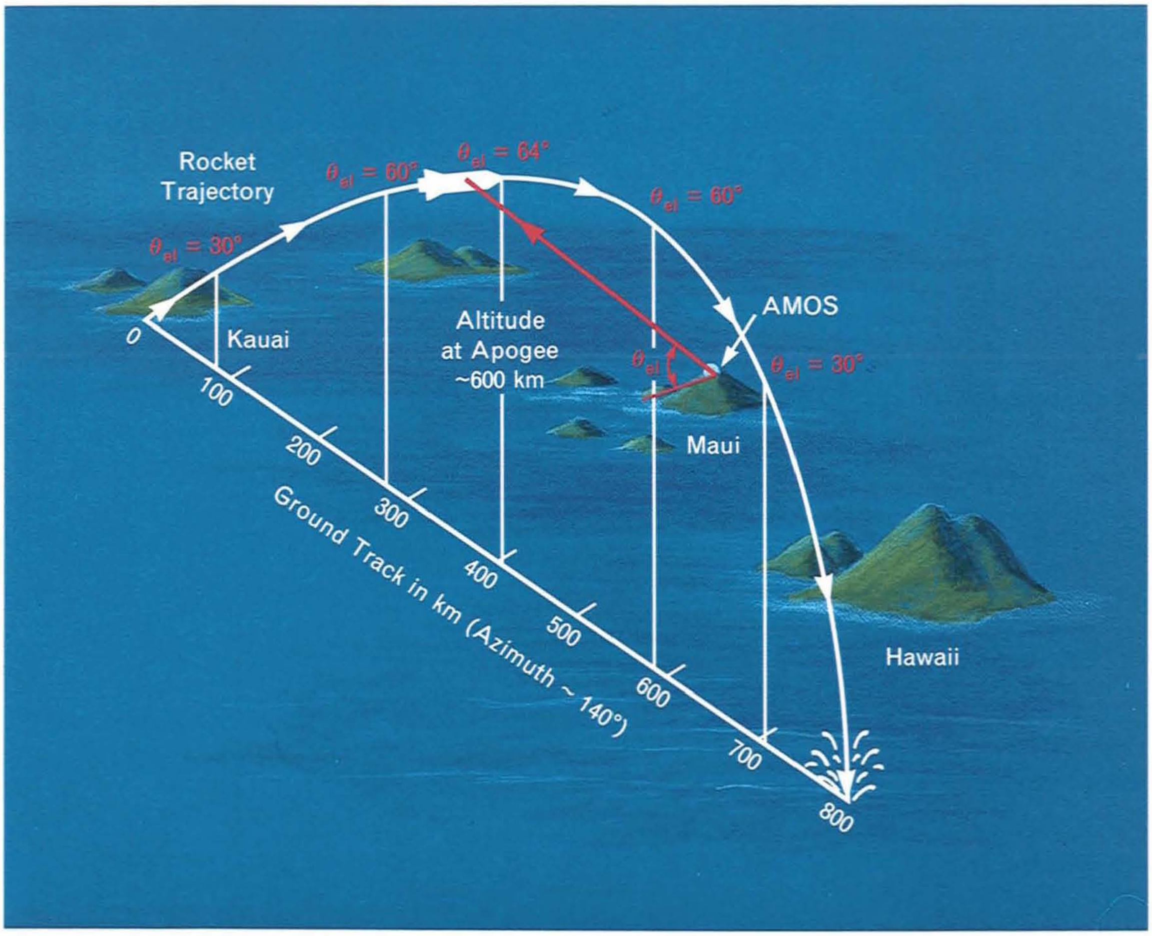


FIGURE 13. Rocket trajectory for ACE experiments (1985). Terrier-Malemute sounding rockets, developed by Sandia, were launched from Barking Sands, Kauai. The rockets reached altitudes of 600 km as they passed by the island of Maui. Each rocket payload contained an 8" retroreflector that served as a beacon and 20 detectors in a linear array.

LAR demonstrated the first ever compensation for device aberrations in a high-power laser. Figure 8 shows the OCULAR multidither mirror and its associated optics and electronics installed at the Pratt and Whitney site. We also attempted experiments with an early model wavefront sensor, but the temporal response of the sensor was inadequate to obtain good correction.

Atmospheric-Compensation Experiment (ACE)

In the late 1970s the DoD emphasis on lasers shifted from tactical applications to strategic applications involving ground-to-space propagation. As a result, Lincoln Laboratory began to develop the Atmospheric-Compensation Experiment (ACE) system to explore ground-to-space compensation. ACE is a complete 69-channel adaptive optics system that uses a deformable mirror and a shearing interferometer built by Itek. The sensor has photomultipliers for low-light operation, and the system has a correction bandwidth of 600 Hz. The ACE system was built on the technology of the pioneering 21-channel real-time atmospheric-compensation system, which was developed by Itek in the mid-1970s [11], and the system used technology similar to that of the 168-channel compensated-imaging system, which was used by Itek researchers to perform the first star-image-compensation experiments in 1982 [12].

We first tested the ACE system in 1981, with turbulence simulated by rotating phase screens (Figure 9). During the following year the system was shipped and installed on the 60-cm laser beam direc-

FIGURE 14. Time exposure of laser beams during an ACE rocket experiment (1985). The blue fan is Rayleigh backscatter from the 488-nm argon-ion laser that was used to illuminate the retroreflector. The bright white streak is the laser reflection from the retroreflector. This reflected light, which appears white because the film is saturated, was used as a beacon for the wavefront sensor. The scoring beam, a second argon-ion laser, which is measured by the 20-element detector array to diagnose the degree of atmospheric compensation, is also present, but because the 514-nm beam is weaker it does not show up in the photograph.

tor at the Air Force Maui Optical Site (AMOS) on the top of Mount Haleakala (Figure 10) on the island of Maui, Hawaii.

From 1982 through 1985 we conducted an extensive field-test program. In Phase I, completed in 1982, we demonstrated atmospheric compensation for a beam propagating along a 150-m horizontal path (with integrated turbulence equal to that for vertical propagation through the entire atmosphere). In Phase II, conducted from 1983 through 1984, we performed atmospheric compensation of a laser beam propagating to a small aircraft (Figure 11) flying above the site. The aircraft tests demonstrated compensation to a dynamic target.

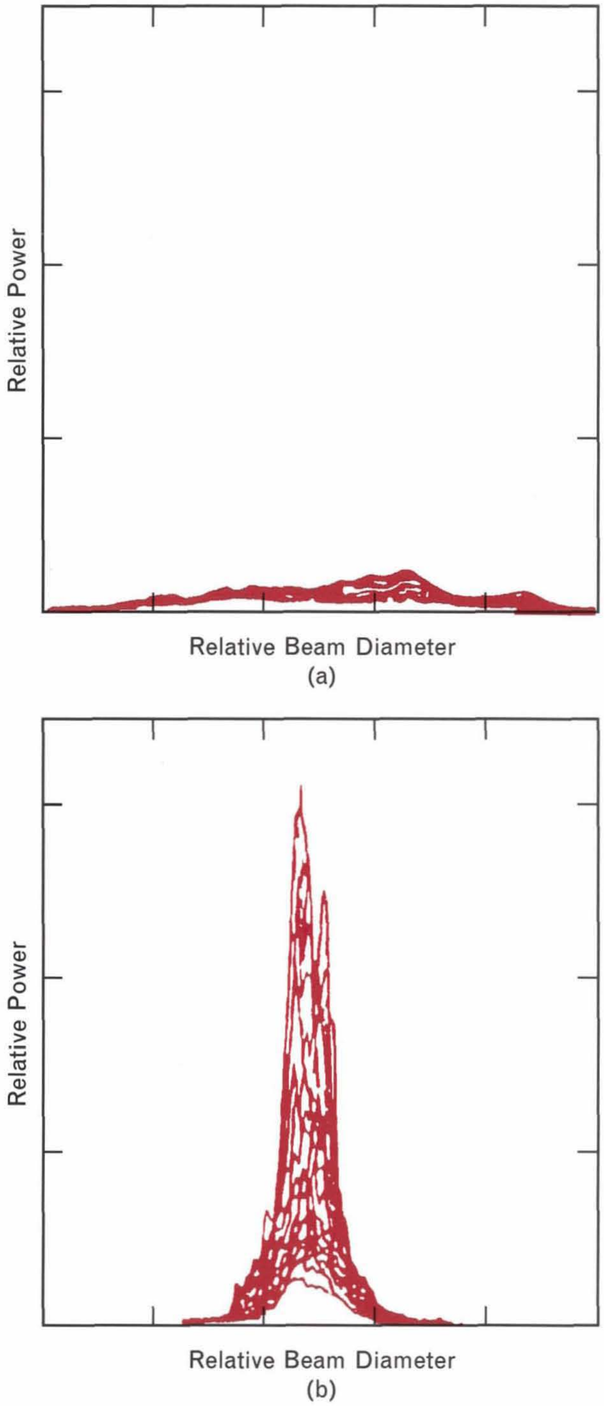


FIGURE 15. Compensation result from an ACE rocket experiment (1985): (a) uncompensated beam and (b) compensated beam, as measured by the 20-detector linear array on the rocket. Each plotted line represents one detector; the abscissa was obtained by scanning the beam across the array. The ACE experiments were the first to demonstrate compensation of a beam propagating from the ground to space.

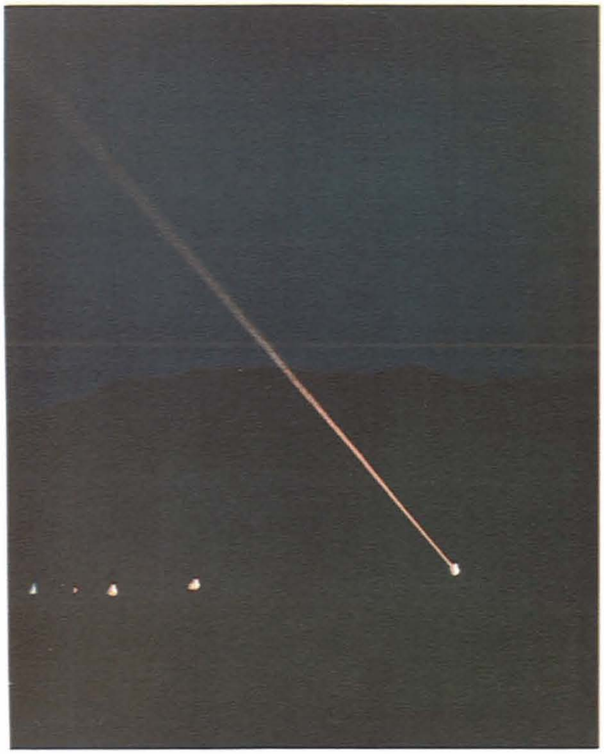


FIGURE 16. SWAT sodium-beacon experiment at the White Sands Missile Range in New Mexico (1984). The photograph is a time exposure of the 589-nm beam being sent skyward to generate a synthetic beacon in the sodium layer at an altitude of 90 km. This experiment was the first to demonstrate that atmospheric phase distortions could be measured with a synthetic beacon in the mesospheric sodium layer.

In the culminating phase of the ACE tests, we demonstrated compensation from ground to space. We first conducted an experiment in which we bounced a laser beam off a retroreflector carried by the space shuttle Discovery and used the return signal as a beacon to perform atmospheric compensation (Figure 12) [13, 14]. Our experiment to the space shuttle was the first SDIO space experiment and, as such, it received considerable publicity, especially when a NASA software error caused the space shuttle to flip over the wrong way on the shuttle's first attempt to face the retroreflector at the ground site. NASA corrected the problem, however, and on the second attempt the space shuttle was oriented properly and we successfully compensated the retroreflected beam.

The experiment with the space shuttle did not involve compensating an outgoing beam. To demonstrate such compensation, we conducted experiments with four instrumented sounding rockets. These rockets, developed for us by Sandia [15], were launched from Barking Sands on the island of Kauai, Hawaii, and reached altitudes of about 600 km as they went by Maui (Figure 13). Each rocket carried a retroreflector, which we illuminated to serve as a beacon, and a linear array of detectors to measure the outgoing beam. Figure 14 shows a time exposure of the ACE laser beams going through the sky; the bright streak at the top of the photograph is the return from the retroreflector. Figure 15, which contains data from one of the rocket tests, clearly shows a dramatic increase in irradiance when the beam is compensated. The ACE tests were the first to demonstrate atmospheric compensation of a beam propagating from the ground to space.

Short-Wavelength Adaptive Techniques (SWAT)

At the same time we were conducting the ACE cooperative compensation experiments, we began a new program called Short-Wavelength Adaptive Techniques (SWAT) to explore uncooperative atmospheric compensation. The first SWAT experiment, conducted at the White Sands Missile Range in New Mexico, is discussed in Reference 16 and in the article by Humphreys et al. [5] in this issue. Strictly speaking, this experiment was not a phase-compensation experiment but only a phase-measurement experiment: we generated a synthetic beacon in the mesospheric sodium layer and compared the phase measured from the beacon to the phase measured from a star in the same direction (Figure 16). The experiment was the first to demonstrate that atmospheric phase distortions could be measured with a synthetic beacon in the mesospheric sodium layer.

The main SWAT experiment used a 241-channel adaptive optics system. The system's mirror, built by Itek, used discrete lead-magnesium-niobate (PMN) actuators [17]. The phase sensor, which is discussed in the article by Herbert T. Barclay et al. [18] in this issue, was a Hartmann design that used advanced charge-coupled device (CCD) focal planes [19]. Both the phase sensor and the CCD focal planes were developed by Lincoln Laboratory. The wavefront re-

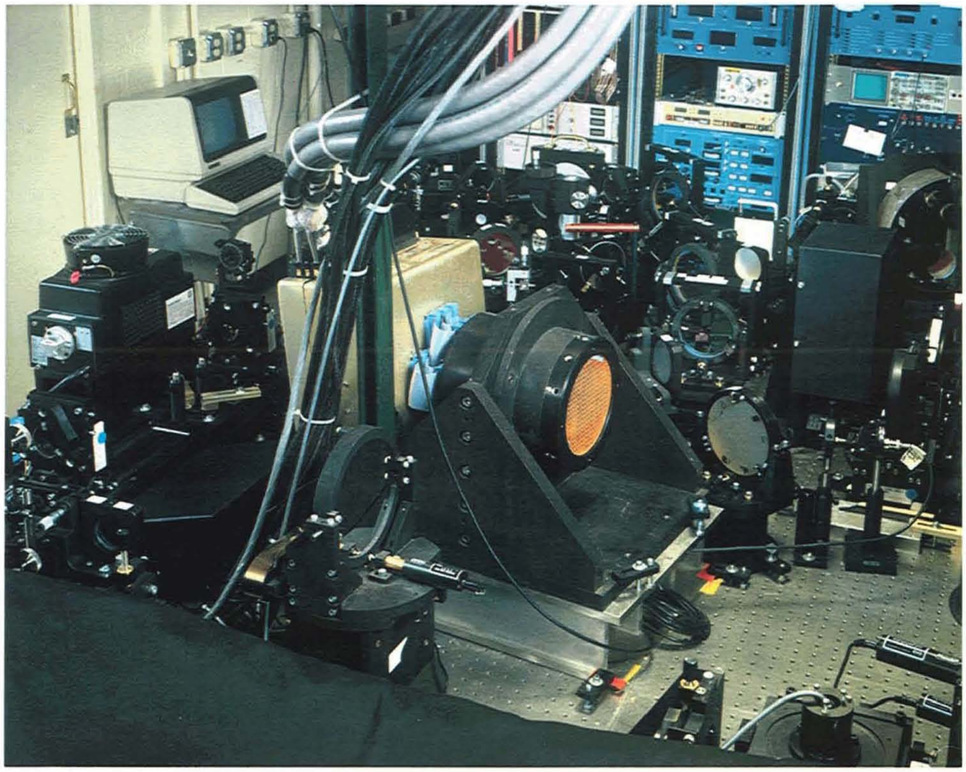


FIGURE 17. SWAT optical bench (1988). The photograph shows a portion of the main SWAT optical bench as installed at the AMOS facility on Maui. The 241-channel deformable mirror is in the center of the photograph. In the rear of the photograph are three of the 24 electronics racks used to control the SWAT adaptive optics system and to record and process data.

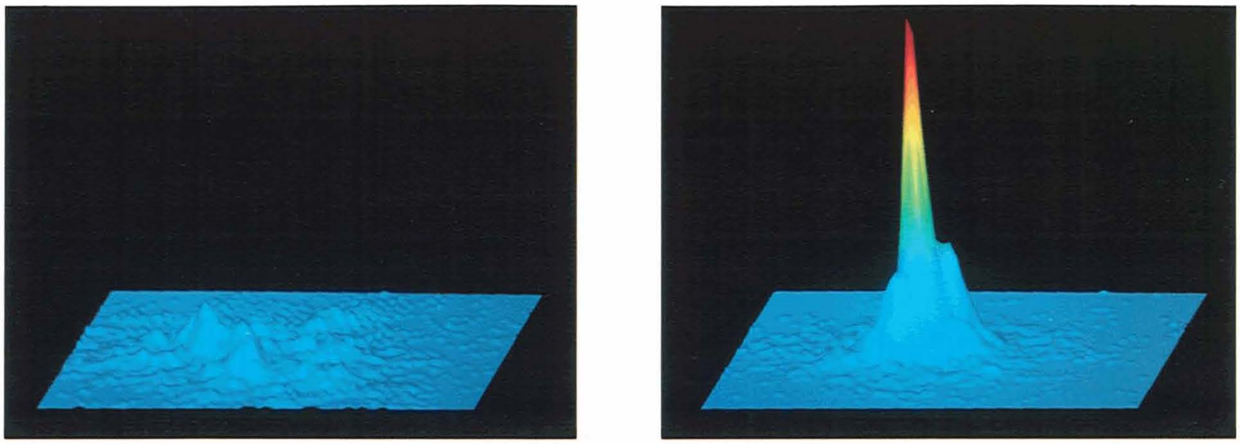


FIGURE 18. SWAT stellar-image compensation using a synthetic beacon. In August 1988 we performed the first ever atmospheric compensation with a synthetic beacon. This figure, which is from a later experiment, shows (left) uncompensated and (right) compensated images of the star Procyon. The compensated image has a peak intensity more than an order of magnitude larger than that of the uncompensated image, and a width at half maximum intensity that is essentially diffraction limited.

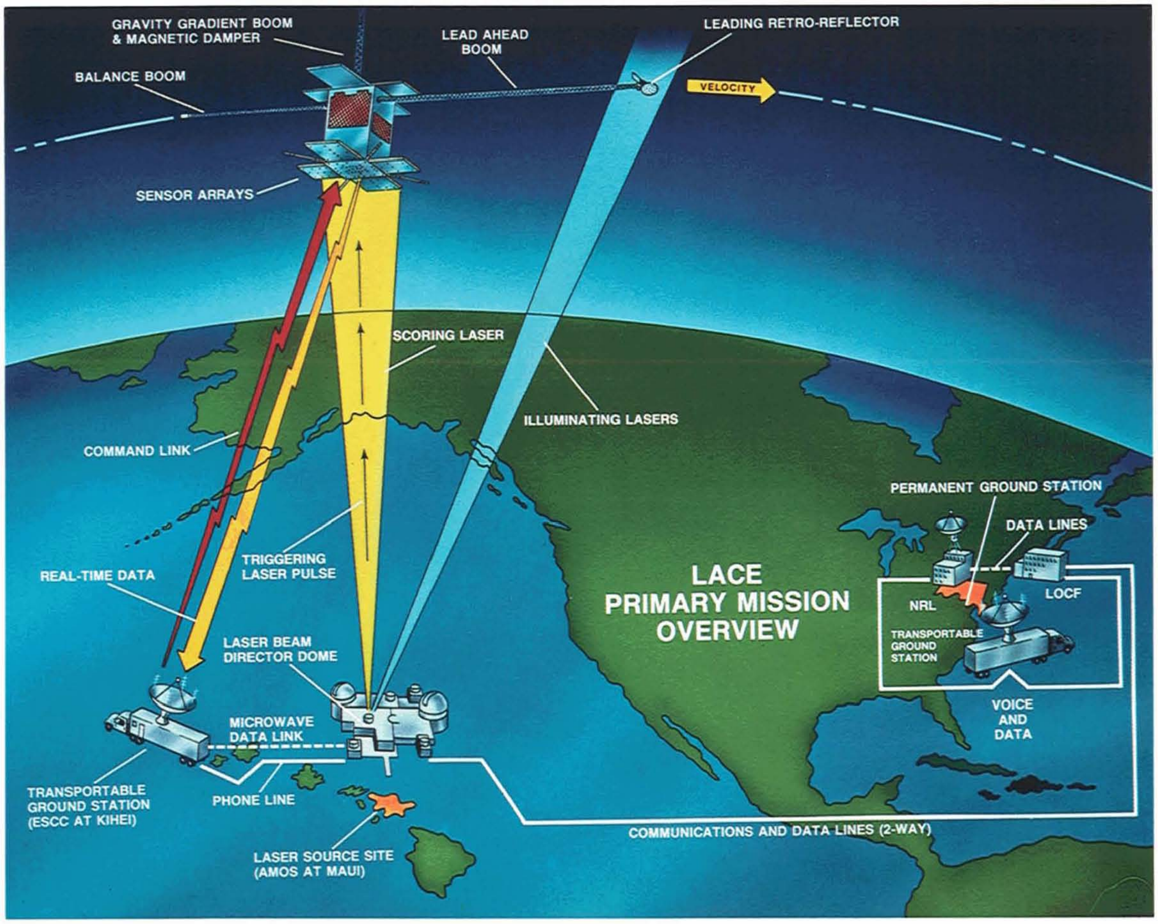


FIGURE 19. SWAT experiments to the Low-Power Atmospheric-Compensation Experiment (LACE) satellite. Developed by the Naval Research Laboratory (NRL), the LACE satellite was launched on 14 February 1990. Later that year we used LACE to perform the first experiments to compensate a laser beam propagating to a satellite target. In these experiments, a laser illuminated the lead-ahead retroreflector on the satellite boom to generate a beacon for the ground site. A compensated scoring beam was then sent to the two-dimensional detector array on the satellite body.

constructor [20], also developed by Lincoln Laboratory, used an all-digital matrix-multiplication technique. The entire system was designed to operate in many different modes. It could either operate in an astronomical-imaging mode, or it could compensate an outgoing laser beam propagated to a satellite. The system could operate either in a cooperative mode with a real beacon or in an uncooperative mode with a single synthetic beacon or multiple synthetic beacons. In the synthetic-beacon mode, the system could make a single phase measurement and drive the deformable mirror to correct for the measured phase error, all in less than 1 msec.

In February 1988 the SWAT system was shipped to Maui and installed on the same 60-cm beam director that had been used for the ACE experiments. Figure 17 shows the SWAT deformable mirror and other optical equipment installed on the main optical bench at the Maui site.

Over the next three years the SWAT experiments achieved four major milestones in atmospheric compensation. In August 1988 we used the SWAT system to perform the first ever atmospheric-compensation experiment with a synthetic beacon (discussed in Reference 21 and the article by Byron G. Zollars [22] in this issue). This experiment used a single Rayleigh beacon generated by a dye laser, and imaged a bright star to diagnose the degree of correction. Figure 18 shows compensated and uncompensated star images for a synthetic-beacon experiment.

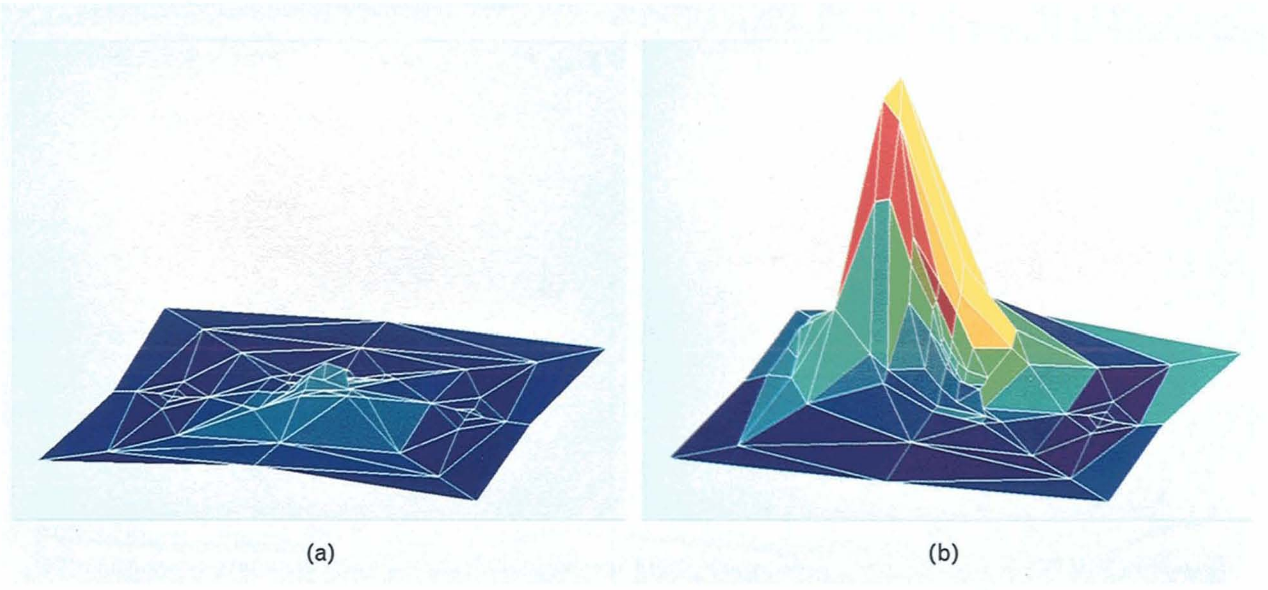


FIGURE 20. SWAT compensation experiments to the LACE satellite (1990): (a) uncompensated beam and (b) compensated beam, as seen by the LACE detector array. The grid intersections are the locations of the 85 detectors on the satellite; the color-coded heights represent the beam intensity at each detector.

In February 1990 the Low-Power Atmospheric-Compensation Experiment (LACE) instrumented satellite, developed by the Naval Research Laboratory (NRL) primarily for SWAT experiments, was launched [23, 24]. Over the next 15 months we conducted an extensive series of tests with the LACE satellite (discussed in the article by Daniel V. Murphy [25] in this issue). Figure 19 gives an overview of the SWAT/LACE test configuration. In the summer of 1990 we performed the first cooperative atmospheric compensation of a laser beam propagating to a satellite target and later the first uncooperative synthetic-beacon atmospheric compensation of a laser beam propagating to a satellite target. A picture of uncompensated and compensated beams at the LACE satellite for a cooperative test is shown in Figure 20.

We performed the first ever multiple-synthetic-beacon experiment [26] as the final major SWAT milestone in October 1990. In this experiment, measurements from two synthetic beacons were stitched together to compensate the image of a star.

Compensation of High-Energy Lasers

The ACE and SWAT experiments convincingly demonstrated atmospheric compensation for the distor-

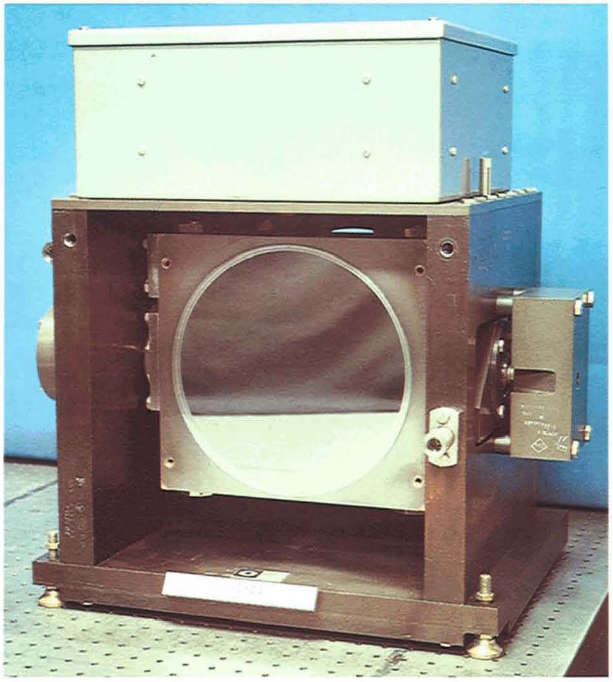


FIGURE 21. Cooled 69-channel deformable mirror. In 1987 we used this mirror, built by United Technologies and named HICLAS, to perform adaptive optics experiments with the high-energy deuterium-fluoride (DF) Mid-Infrared Advanced Chemical Laser (MIRACL) located at the White Sands Missile Range.

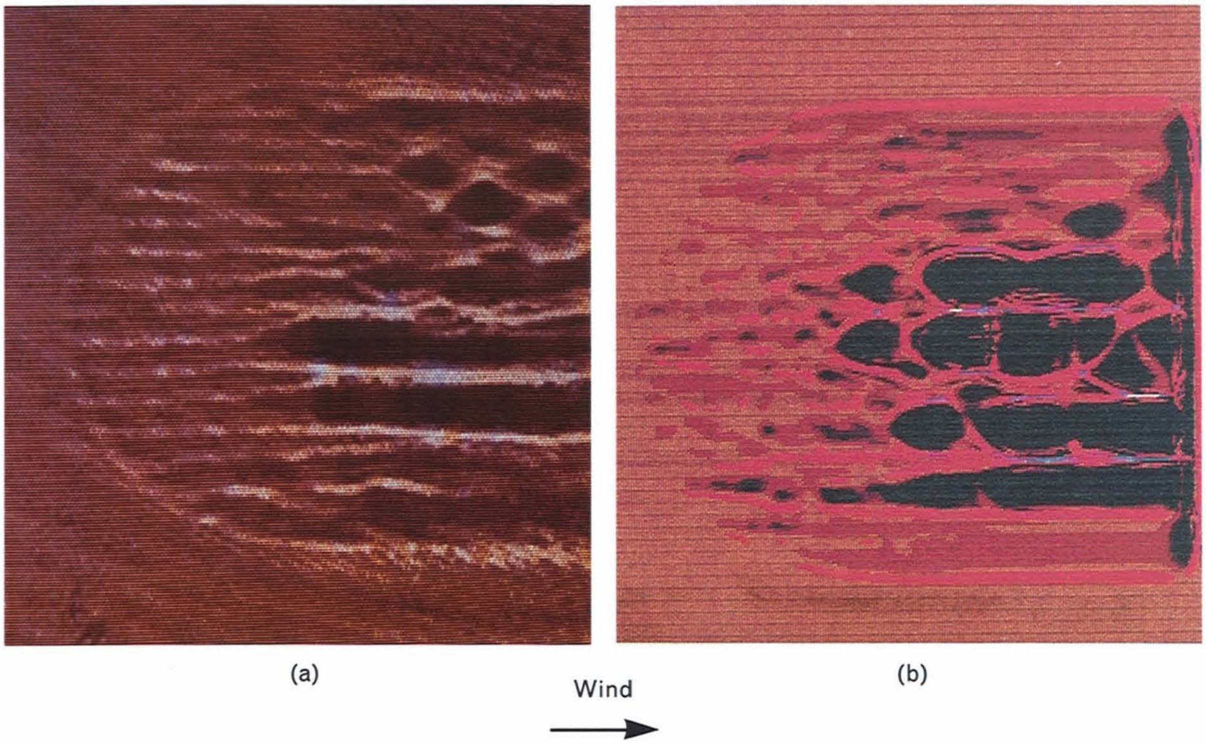


FIGURE 22. Comparison of laboratory measurement and MOLLY simulation for compensation of strong thermal blooming (1990): (a) measurement of the received beacon beam at the deformable mirror, and (b) simulation using MOLLY, a time-dependent-propagation code. The photographs are in red because a red helium-neon laser beam was used as the beacon. Both experimental measurement and simulation show two characteristic signatures of the phenomenon known as phase-compensation instability (PCI): (1) intensity streaks along the wind direction and (2) a honeycomb structure of intensity variation that corresponds to the actuator pattern of the deformable mirror.

tions introduced by turbulence, but because only low-power beams were used the experiments did not address high-power effects. Thus, to complement the ACE and SWAT experiments, in the mid-1980s we began several high-power efforts—one to address laser-device correction and the other to address thermal blooming.

From 1986 through 1987 Lincoln Laboratory developed and tested a local-loop compensation system to correct device aberrations for the Mid-Infrared Advanced Chemical Laser (MIRACL) [27]: a high-energy DF laser at 3.6 to 4.2 μm installed at the White Sands Missile Range. The adaptive optics system that we developed used a cooled 69-channel deformable mirror (Figure 21) and a multidither sensing technique. Using this system we demonstrated a significant improvement in the beam brightness of the MIRACL. Although local-loop compensation had been accomplished earlier, these tests demonstrated that compensation could be done at power levels of interest to the military.

With the formation of SDIO in 1984, Lincoln Laboratory returned to research on thermal blooming, with the objective of determining whether the ultrahigh powers required for ballistic-missile defense could be successfully propagated through the atmosphere. From the mid-1980s through 1991 we conducted a multistage thermal-blooming research program that involved propagation-code development, laboratory experiments, and field experiments.

We developed a new four-dimensional (three spatial dimensions and time) propagation code named MOLLY, which is discussed in the article by Jonathan Schonfeld [28] in this issue. The code includes simulations of combined turbulence and thermal blooming and realistic treatment of adaptive optics hardware. With MOLLY we have been able to simulate scenarios involving full ballistic-missile-defense power levels and to watch for the development of phase-compensation instability (PCI).

To verify the propagation-code predictions and to examine PCI further, we conducted a two-phase laboratory experiment on thermal blooming (discussed in the article by Bernadette Johnson [29] in this issue). In Phase I we used the ACE 69-channel adaptive optics system, which had been returned from Maui. By seeding phase-compensation instability with an initial intensity perturbation, we obtained the first experimental evidence of the instability [30]. For Phase II we constructed a new 241-channel adaptive optics system. With the larger system we were able to obtain the first experimental evidence of PCI growing spontaneously from noise [31]. Figure 22, which compares MOLLY code predictions with laboratory results, vividly illustrates phase-compensation instability.

Although the laboratory experiments verified the predicted PCI and benchmarked the MOLLY code predictions, they did not include a number of real atmospheric effects, such as fluctuations in the wind velocity. Thus, we proceeded to develop field experiments, called Scaled Atmospheric Blooming Experiments (SABLE), to address thermal-blooming compensation in the real atmosphere [32]. We propagated a 10-kW, 2.7-μm HF chemical laser [33] over a 400-m horizontal path at the TRW test site in San Juan Capistrano, Calif. (Figure 23). Because 2.7-μm radiation is highly absorbed in the atmosphere, the laser simulated the thermal blooming of a much higher-powered laser tuned to an atmospheric-transmission window. The adaptive optics system for SABLE used two cooled deformable mirrors—one with 69 actuators and the other with 241 actuators—in a woofer-tweeter arrangement. The recently com-

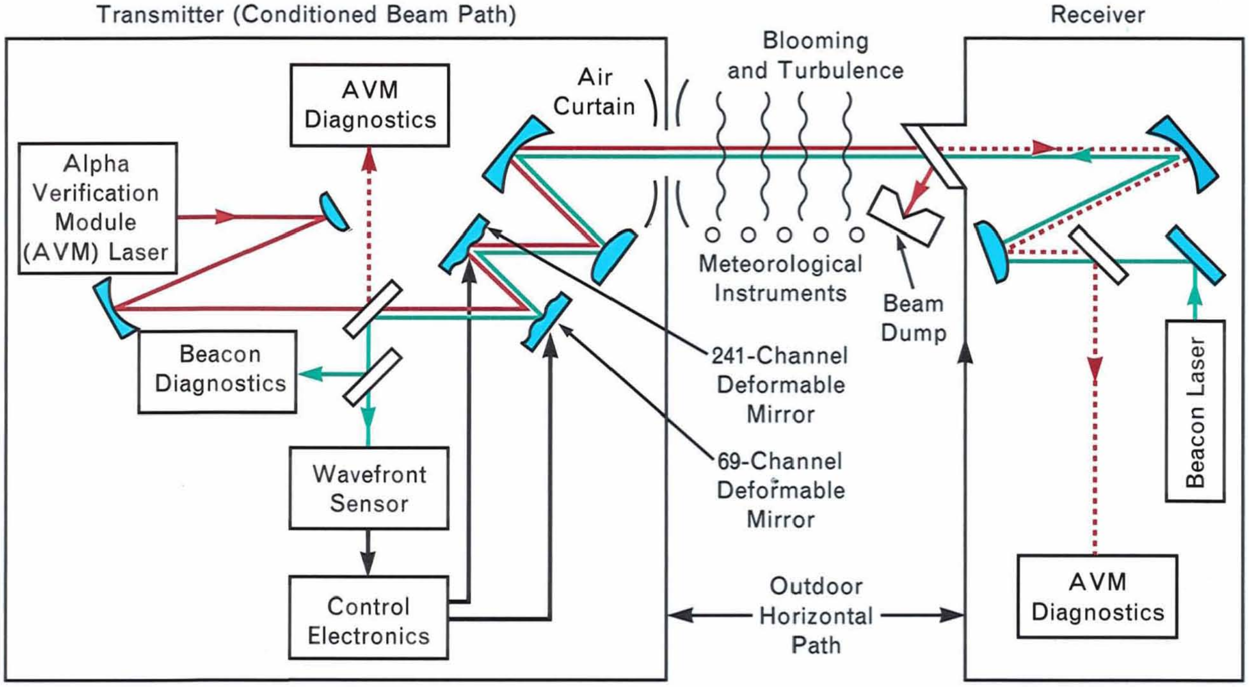


FIGURE 23. Schematic of Scaled Atmospheric Blooming Experiments (SABLE) (1991). We performed these thermal-blooming-compensation experiments with a 2.7-μm HF laser at the TRW test site at San Juan Capistrano, Calif. The transmitter section in the left of the figure shows the adaptive optics system with its 69- and 241-channel deformable mirrors. At the center of the figure is the instrumented 400-m horizontal-propagation range. The right of the figure shows the beacon laser and diagnostics equipment in the receiver trailer.

pleted SABLE experiments demonstrated that PCI can be considerably mitigated by real-world atmospheric effects such as wind shear and wind fluctuations.

Summary

We have briefly reviewed some of the highlights of 20 years of adaptive optics research at Lincoln Laboratory. In the past two decades Lincoln Laboratory has taken adaptive optics from a vague conceptual possibility to a stage where the capabilities of this technology have been convincingly demonstrated in field experiments. We hope that by the end of the next two decades adaptive optics will be routinely employed in a number of practical applications.

Acknowledgments

Over the past two decades several hundred people have contributed significantly to the adaptive optics research program at Lincoln Laboratory. The large number involved makes it impractical to list every contributor, but the authors are grateful to each and every person.

It is appropriate to single out one individual—Louis C. Marquet—for special mention. Lou initiated the adaptive optics program at Lincoln Laboratory and directed it with an infectious enthusiasm. Even during the second decade of the program, after Lou had left for a government job in Washington, D.C., the enthusiasm that he had instilled in those of us who had worked for him continued to energize the program.

From the beginning of the program through 1984 most of the funding for this research was provided by the Defense Advanced Research Projects Agency (DARPA). From 1985 to the present, funding was principally provided by the Strategic Defense Initiative Organization (SDIO). Additional funding was provided by the Air Force, the Army, and the Navy.

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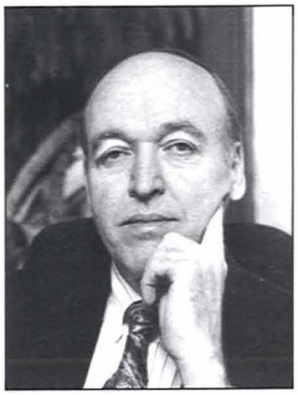

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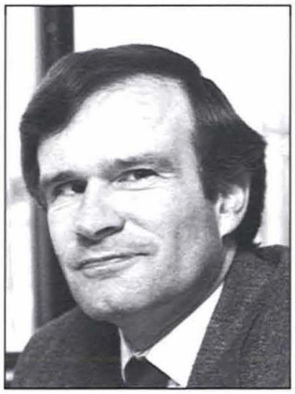

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He joined Lincoln Laboratory in 1975 as a member of the technical staff. For the past 17 years he has been involved in research on laser propagation, adaptive optics, and atmospheric compensation. In 1985 he was promoted to his present position as leader of the High-Energy-Laser Beam Control and Propagation Group.

As a counterbalance to his high-technology professional interests, he divides his free time between skiing (winter) and sailing his J-24 (summer).