PROCEEDINGS OF THE SOCIETY OF PHOTO-OPTICAL INSTRUMENTATION ENGINEERS

Volume 141

Adaptive

Optical Components

March 30 - 31, 1978

Proceedings of the Society of Photo-Optical Instrumentation Engineers

Volume 141

Adaptive Optical Components

March 30-31, 1978, Washington, D.C.

[illegible]ly, Major Lawrence James
Editors

Presented By
The Society of Photo-Optical Instrumentation Engineers

ISBN 0-89252-168-6

Printed in the United States of America.

Seminar Committee

ADAPTIVE OPTICAL COMPONENTS

Volume 141

Chairman
Sandor Holly
Rockwell International

Co-Chairman
Lawrence James
Air Force Weapons Laboratory

Chairman Session 1 — Adaptive Optical Components
Sandor Holly
Rockwell International

Chairman Session 2 — Adaptive Optical Systems
Lawrence James
Air Force Weapons Laboratory

Chairman Session 3 — Instrumentation and A/O Systems Diagnostics
Sandor Holly
Rockwell International

Chairman Session 4 — Miscellaneous Topics
Lawrence James
Air Force Weapons Laboratory

ADAPTIVE OPTICAL COMPONENTS

Volume 141

INTRODUCTION

Recent advances in adaptive optical control techniques have resulted in the development of a wide variety of high-performance components. Although most of these devices were designed initially for defense purposes, many have been applied to commercial areas. The principal object of this seminar was to explore in-depth hardware results of recent research and development efforts in unclassified military and commercial applications. Optical quality, performance characteristics and limitations associated with these components were of particular interest.

ADAPTIVE OPTICAL COMPONENTS

Volume 141

CONTENTS

ADAPTIVE OPTICAL COMPONENTS

Volume 141

SESSION 1

ADAPTIVE OPTICAL COMPONENTS

Session Chairman
Sandor Holly
Rockwell International

HISTORICAL REVIEW OF ADAPTIVE OPTICS TECHNOLOGY*

Louis C. Marquet
Massachusetts Institute of Technology
Lincoln Laboratory
Lexington, Massachusetts 02173

and

John Hardy
Itek Corporation
Lexington, Massachusetts 02173

Abstract

The history of adaptive optics is outlined from the concepts of 25 years ago to the many forms in which it is being applied today. Several independent paths of development are traced, leading to the emergence of a new technology that combines the disciplines of optics and electronics. Speculations are made on possible directions for the future.

Introduction

When we look at the recent rapid development of adaptive optics, the question that springs to mind is why did it take so long? The most remarkable fact about the history of adaptive optics is that it is so short – 25 years at the most. Optics as a science has been around much longer than electronics – the first telescopes were built 300 years before the first radio receiver – and yet optical engineers are only now starting to use techniques that have been commonplace in electronics for over 20 years.

The contrast is even more startling when we realize that most animals, including man, possess adaptive optical faculties that have evolved through natural selection: the eye is a very sophisticated optical device capable of tracking and autofocusing. Nature's model was known for centuries, but was never copied.

Looking at a historical time scale (Fig. 1) one might conjecture that the reason for the late development of active optics is the lack of any real need for it until recently. But as early as 1704 Newton complained about the havoc that the earth's atmosphere was playing with his telescope images. In 1953, Babcock first suggested a practical method for real-time compensation of atmospheric seeing, but it was 20 years before this became a reality.

The development of large astronomical telescopes practically came to a standstill with the completion of the Hale 200-inch mirror in 1947. Astronomers can always use more light-gathering power, but larger monolithic mirrors are exceedingly difficult to make; it is only the advent of active optics that now allows us to conceive of segmented mirrors of almost unlimited size.

The evolution of high energy laser systems within the last 10 years has provided a significant impetus to the development of adaptive optics. However, we suspect that there is another reason for adpative optics' short history: it is an interdisciplinary science of prime use in high-performance optical systems but drawing heavily on electronics technology and requiring the development of new devices such as wavefront sensors and wavefront correctors that fall between the established fields of optics and electronics.

The prehistory of adaptive optics is legendary. The first reference to Archimedes' attempt to set fire to the Roman fleet at Syracuse in 212 B.C. using an array of burning mirrors was set down 700 years after the event – there are no contemporary accounts. Although lenses came into general use in the 13th century, the reason why they worked remained unknown for another 300 years. In the 18th and 19th centuries, opticians were concerned with reducing the systematic optical aberrations (chromatic, spherical and coma) rather than compensating for random external effects. It was not until large telescope mirrors were built that effects such as gravity and temperature changes needed attention.

The history of adaptive optics over the last 25 years has developed along several quite distinct paths that are now beginning to coalesce as the technology matures. (Fig. 2)

*This work was sponsored by the Defense Advanced Research Projects Agency.

First, we have the optically low-grade but technically valuable "light buckets" which have been used since the 1950's for collecting radiation from distant astronomical objects and are now coming into use for large-scale solar energy collection.

Secondly there are the figure-control systems for large primary telescope mirrors, pioneered by NASA for space applications in the 1960's and now leading to concepts such as the 25-meter aperture optical "Next Generation Telescope" being studied by Kitt Peak National Observatory.

Next, we have the atmospheric compensation concept stemming from Babcock's original idea of 1953, which has now led to systems such as RTAC (Real-Time Atmospheric Compensation) and Image Sharpening.

And finally, there is the adaptive antenna concept first developed for microwave radar in the early 1960's and which consciously or not forms the bases of present-day COAT (Coherent Optical Adaptive Technique), employed for optimizing the propagation of laser systems.

We shall now explore in more detail the technology of these four general areas of adaptive optics outlined above.

Light Buckets (Incoherent Systems)

Large segmented mirrors have been used for many years to collect the light from skies. In fact, the earliest mention of such a system in the reference to Archimedes legendary "burning glass", in 212 B.C. More recent applications of this concept are in the area of solar furnaces, in which arrays of moving mirrors are used to capture the sun's radiation. The first large scale system developed at the U.S. Army Natick Lab in 1957, utilized 180 separate elements mounted in a square array occupying 710 square feet, and yielded an output power of about 30 KW. The largest such system currently is the solar furnace of the French National Center for Scientific Research at Odeillo in the Pyrenees which has been in operation since 1970. An array of 63 flat mirrors with a total area of 2592 square meters tracks the sun and directs the radiation to a large fixed parabolic mirror which concentrates the power, normally amounting to 1000 kilowatts, into a furnace in which temperatures of 3800°C have been obtained. (Fig. 3)

The principle of using moving mirrors to capture the sun's radiation is of considerable importance in these energy-conscious times. The U.S. Energy Resources Development Agency ERDA) is working on an experimental steam generating plant near Albuquerque, N.M., using a field of mirrors that track the sun and direct the energy to a central boiler mounted on a tower. Plans have recently been announced for a dimilar installation at Barstow, California which will have 10 megawatts of electrical generating capacity.

Astronomers have also used large segmented mirror systems to increase stellar irradiation on their sensors. In 1962, a 6.5 meter diameter array of mirrors was built at Narrabri, Australia, and used in Hanbury Brown's intensity interferometer measurements. In this system, the elements were pre-aligned to a reference axis and designed to hold this alignment during use.

In a more recent version of the same idea (Fig. 4) is the IR interferometer built by Chevillard and Connes at Meudon, France. In this system, active control is used, in that such of the elements is aligned in tip, tilt, and focus by a servo system, using a star as a reference.

These examples of multi-mirror systems are non-coherent; no attempt is made to match the phases of the wavefronts reflected from the individual elements. The size of the final image is governed by the size and quality of the individual mirrors; its intensity is equal to the sum of the individual intensities.

Figure Control (Coherent Systems)

This next class of adaptive optics systems differs from the previous in that the individual elements are controlled in such a way as to maintain the spatial coherence over the entire aperture.

A multi-mirror telescope for the collection of radiation from distant astronomical objects is under construction at the University of Arizona. This telescope consists of a ring of six circular mirrors on a steerable mount, each mirror 1.8 meters in diameter, with a total light-gathering capacity equivalent to a single telescope of 4.5-meter diameter. This instrument may be regarded as transitional between a non-coherent "light-bucket" and a fully coherent synthetic aperture. Its prime use will be at IR wavelengths in the range from 10 to 20 micrometers, where the alignment precision of the individual mirrors allows coherent addition of the wavfronts to provide an angular resolution of 0.5 arc-second. At visible wavelengths the instrument will function as six parallel telescopes, giving a sixfold improvement in the light-gathering power but no improvement in resolving power over a single element. (Fig. 5)

Looking ahead, coherent segmented arrays are being considered for the "Next Generation Telescope," which will be a ground based system with an effective aperture of 25 meters. Of course, the resolution of this system will be limited by atmospheric seeing conditions imposed by turbulence; it will be unlikely that the full coherence diameter will be reached, even in the IR.

In space, however, where the atmospheric limitation does not apply, such a system holds enormous promise. Recognizing this fact, NASA in the early 1960's investigated the possibility of mounting large astronomical telescopes in earth orbit. The first approach was to use a segmented mirror, as described by Robertson et al. in 1966, with each segment controlled in two axes of tilt and one of focus by three actuators. Because of the difficulty of manufacturing the large number of individual off-axis aspheric mirror segments required for an astronomical reflecting telescope, attention was directed to the use of thin continuous deformable mirrors. A 76-centimeter, f/3 spherical mirror with 61 force actuators evenly spaced over the rear of the mirror was developed at Perkin-Elmer in 1970. Control system concepts and the practical problems associated with actuators for large active mirrors also received considerable attention at this time for a multi-actuator deformable mirror system. A representative figure control system is shown schematically in Fig. 6.

Atmospheric Compensation for Imaging

The possibility of compensating for the wavefront distortion due to the earth's atmosphere which is a major limitation to ground-based astronomy, was discussed in 1953 both by Horace Babcock and by James G. Baker. Baker pointed out that when observing a single star, compensation for the telescope aberrations and for the atmosphere near the telescope aperture could be made with a single wavefront corrector. He suggested the use of a Foucault test with a bank of photocell receivers to generate the necessary correction signals. When dealing with a wider field of view, covering several stars, the atmospheric correction required is different in each direction and a signle corrector cannot be used. Baker proposed solving this problem by re-imaging the entire turbulent atmospheric path within the otpical system of the telescope and passing the beam through a refracrive gas cell using lateral ultrasonic transducers to introduce density variations along the cell that would compensate for the effects of the phase disturbances at conjugate locations in the propagation path. A digital computer would be used to calculate the required corrections in real time.

Babcock originally proposed the use of an arbitrarily deformable optical element with feedback from a wavefront sensor, suggesting the use of an Eidophor in which the thickness of an oil film on the surface of a mirror is controlled by electrostatic charges deposited by a scanned beam from an electron gun, thereby producing controlled optical phase shifts in the reflected light. A letter published by Babcock in 1958 suggested an improved form of mirror consisting of a flexible reflecting film with an array of target elements on which the electrostatic charge is deposited, thereby producing local bending of the film. There is no record of either of these proposals having been implemented.

In 1956, a first-order active optics system for compensation of image motion in astronomical telescopes was described by Leighton. This system, which used an electromagnetically operated tip-tilt mirror with a bandwidth of 5 Hz, was used on the 60-inch reflecting telescope at Mount Wilson Observatory, with the aperture stopped down to 20 inches. Some spectacular planetary photographs, characterized as the best obtained up to that time, were obtained.

When imaging distant objects such as stars through the atmosphere, the object radiance itself must be used as the reference source. Such sources emit a broad spectrum, necessitating measurement and compensation of optical path length ~~rather~~ than phase angle. Because of the rapid fluctuations of the earth's atmosphere, wavefront measurements must be made at a rate of about 200 Hz. To optimize the signal-to-noise of the wavefront measurements, the largest possible number of photons must be detected; it is therefore necessary to use optically efficient wavefront sensors that make full use of the spectral bandwidth of the reference source.

The first successful system of this type was developed at Itek in 1973. This real-time atmospheric compensation (RTAC) system used in ac white-light lateral-shear interferometer, a parallel analog computer, and a 21-element monolithic piezoelectric mirror. Because of its parallel architecture, the performance of this approach, as measured by the residual wavefront error for a given reference source stellar magnitude, is virtually independent of the number of corrected subapertures), for a given subaperture size.

RTAC test data were obtained using a low-power HeNe laser as a reference source both in the laboratory using simulated turbulence and over an outdoor horizontal propagation range. Two frames from a 16-millimeter movie showing operation with moderate atmospheric turbulence over a 300-meter horizontal path are shown in Fig. 7, (a) being the uncorrected image of the laser source and (b) the image obtained with the RTAC switched on. The telescope aperture used was 30 centimeters in diameter with each of the 21 subapertures measuring 6 x 6 centimeters.

The concept involved in the RTAC monolithic active mirror involves the use of a mirror substrate which is homogeneous block of material in which local deformations can be induced and controlled by external means. In effect, the functions of the faceplate, actuators, and backplate are all combined in one monolith.

Devices of this type can be expected to have good mechanical properties such as stiffness, stability and shock resistance, making them more tolerant to an operational environment than conventional active devices assembled out of a multiplicity of parts.

The construction of the MPM is based upon a circular slab of lead zirconate titanate (PZT) titanate (PZT) piezoelectric ceramic typically 5 to 10 centimeters in diameter and 1.2 to 2.5 centimeters thick. An array of electrodes is located at the top surface to each of which is applied a control voltage, using the electrode at the base of the slabe is common reference. A thin glass bonded to the top surface is optically polished and aluminized to form the reflecting surface.

The frequency response of MPM devices is extremely good, being limited primarily by the natural modes of the PZT block, which because of its large thickness-to-diameter ratio, occur at high frequencies. Typical devices have a flat response to over 10 kHz and have been operated at discrete frequencies as high as 60 kHz, although such frequencies can excite resonant modes. Experimental MPM's have been built with 300 active elements within a 75-millimeter diameter.

Other techniques have been developed to achieve the wavefront correction required for real-time atmospheric compensation. We have already mentioned the continuous deformable mirror concept first developed by Perkin-Elmer for a space telescope. If high frequency actuators, such as obtainable with piezoelectric stacks, are used in conjunction with a fast servo system, such an element could provide the dynamic capability required.

Another possibility is a membrane mirror. A membrane is distinguished from a thin plate by having no inherent stiffness so that tension must be applied to maintain flatness; relatively small forces are required to obtain the deflections necessary for optical wavefront correction. The simplest type of membrane mirror is the "varifocal" mirror in which a reflectively coated membrane is acoustically coupled to a piston (in practice a loud speaker) producing changes in the radius of curvature and therefore the focal length of the mirror.

The use of membranes as high bandwidth, high-order active mirrors has been pioneered at Perkin-Elmer. The metal membrane is typically 0.5 to 1.0 micrometer thick and is positioned between a transparent electrode carrying a bias voltage V_B and an array of electrodes, to each of whichis applied the bias voltage plus a signal voltage V_S. The membrane is at ground potential, and experiences no net force so long as $V_S = 0$. When a signal voltage is applied to one actuator, a deflection is produced, centered around that actuator. The membrane is operated at low air pressure (2 torr) to obtain a favorable compromise between sensitivity (which is maximized in vacuum) and membrane resonant freouency (which is at a minimum in vacuum). The incident light beam passes through a sealing window and the transparent electrode before being reflected off the membrane.

The control system for the Itek 21 element RTAC system, as mentioned above, is based on parallel processing of the 21 channels. The basic concept is to track the wavefront tilt from each element, thereby obtaining a measure of the local phase gradient. The simplest method for doing this involves using a Hartmann plate and an array of quad-cell trackers. The wavefront gradients can then be integrated in real time to develop the wavefront error, from which control signals to the actuators are derived.

In fact, the Itek system is somewhat more sophisticated than this. It utilizes two rotating gratings as trackers in such a way that the detectors are used as simple photon counters.

Other control techniques have been suggested and developed, chief among which is an image sharpening concept first described in 1974 by Muller and Buffington. Trial phase perturbutions are applied to the aperture in such a way that the required correction can be computed from the image sharpness function, and applied to the corrector element via a servo feedback loop.

Transmitted Wave Adaptive Systems

The objective of transmitted wave optical systems is to optimize the power density arriving at some target plane. In the present context, we normally think in terms of the propagation of laser beams, but this concept also applies to microwave and radar systems. It should not be surprising, therefore, that the basic system concepts in the area were all first considered by radar engineers. Only recently have we opticians developed the components required to implement these concepts.

Dynamic optical phase correction offers considerable promise in compensating a host of optical aberrations for laser systems. These aberrations include optical element imperfections, index of refraction variations of the medium within the optical train, mount and jitter, imperfection in the laser wavefront and, most importantly, aberrations which arise in the atmosphere due to turbulence and thermal blooming in the case of high power applications.

By way of introduction we shall expalin just how one may compensate for atmospheric induced phase aberrations in a projected laser beam. Clearly a closed-loop system based upon feedback representing the nature of the beam at the target is required. This feedback may either be sensed remotely, back at the aperture of the laser system, say, or locally at the target and relayed via a telementry link bank to the control system. In the former case, one generally speaks of a "glint" or feature on the target which sends a strong reflection back to the aperture. (A retroreflector is an ideal glint.) The strength of the glint, as sensed at the aperture, is a relative measure of the intensity of the laser beam incident upon the glint.

There are two generic techniques proposed for utilizing this glint return in an adaptive optics servo control system, shown schematically in Fig. 8. In the phase conjugate technique the glint is considered to be a point source, launching a spherical wave which is sensed at the system aperture. The phase aberration acquired by this initially spherical wave is a measure of the atmospheric degradation. In fact, if the conjugate of this wave is projected back through the aperture to the target, the initial phase aberration would be just that required to offset the phase effects of atmosphere and, by reciprocity, the beam would arrive as a converging spherical wave, unaberrated. (This ignores amplitude effects.) This phase conjugation can be achieved by driving a wavefront corrector element in such a way as to eliminate the phase aberration in the received beam. In this respect, the return wave phase conjugate technique is analogous to the image compensation technique discussed in the previous section.

The alternative approach, called "outgoing wave multi-dither," involves tagging the projected beam with a small phase dither and synchronously detecting the glint return to derive an error signal which is applied by a hill-climbing servo system to the corrector element. This phase dither can be applied either zonally (in which case each sub-zone of the wavefront is tagged at a different frequency, and the demodulated detector signal is used to develop an error signal which is applied to the corresponding zone on the corrector mirror) or in a modal fashion, for example, using Zernike functions.

One important distinction between the return wave phase conjugate and the outgoing wave multidither approach is thatthe latter automatically compensates for all phase aberrations (within its spatial and temporal bandwidth limitations) in the laser system, whereas the former makes no correction for any aberrations occuring prior the beam splitter.

The simplest form of modal control is tilt correction, which will compensate for both system jitter and the so-called turbulence induced beam wander. It will also correct for the non-linear beam steering associated with thermal blooming of a high power laser beam. If the two axes are dithered at the same frequency but 90° out of phase, this technique amounts to nothing more than what radar technologists call "conical scan." The demodulated signal from the glint return drives a tilt corrector to keep the peak of the beam on the glint.

The basic techniques of adaptive control over electromagnetic wavefronts were first developed in the early 1960's for use in microwave systems. The self-phasing array antenna described by Skolnik and King is the direct forerunner, at microwave frequencies, of the phase conjugate active optical system. The principle of beam tagging in adaptive antenna systems was described by Adams in 1964, who noted that "the beam tagging process optimizes the received signal at the point where the tagging modulation is analyzed."

These similarities of system concept do not extend to the actual hardware because of the difference of about 10^4 between the optical and microwave frequencies, and the greatly differing effect of physical factors on the propagation path. Thus, the development of active optics systems has been paced mainly by the development of suitable hardware rather than by the need to develop system concepts. The main area of commonality is in the information-processing functions.

The development of the phase conjugate COAT (Coherent Adaptive Optical Technique) was pioneered at Rockwell International Corporation, in 1970, using a 10.6 μm CO_2 laser. Successful operation of a 7 element phase conjugate system tracking glints over a 1-km turbulent path has been recently reported by Hayes et al.

For the outgoing wave concept, the approach first proposed in 1971 by O'Meara and described by Bridges et al. in 1974 uses the principle of measuring the intensity of the radiation returned from a target glint while making trial perturbations of the transmitting aperture, each section of which is tagged with an identifiable signature. A multi-dither COAT system of this type using an 18-element phase corrector was described by Pearson et al. in 1976. Each controlled element was identified by modulating or "dithering" the phase by about ±30 degrees at a different temporal frequency, within the range from 8 kHz to 32 kHz.

The experiments, reported by Pearson, were conducted on a horizontal propagation range about 100 meters in length across a rooftop. Target glints were simulated by 3-millimeter-diameter retroreflectors, which were unresolved by the transmitted beam. The power received by each glint was directly measured by a detector located behind the retroreflector.

Using the power received by a single glint under condition of low turbulence with the COAT system on as a reference (=1.0), the relative glint power with strong turbulence was 0.15 with the COAT system off and 0.44 with the COAT system on. Figure 9 shows corresponding beam with profiles, showing a reduction of beam width by a factor of about 5.

Conclusion

In conclusion, it is fair to say that the technology of adaptive optics has experienced an enormous growth over the past several decades. The gap between the optical and microwave regions of the spectrum has closed with the advent of sophisticated optical componetry. Insofar as compensation for atmosphereic turbulence now appears to be in hand, we might say that the sky is no longer the limit!

The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the United States Government.

Major Events in the History of Optics

Archimedes burning mirror?	212 B.C.	
First eyeglasses	1285	
Invention of telescope	1606	
First reflecting telescope	1663	
Isaac Newton's "Opticks"	1704	
Fizeau Velocity of Light	1849	
	1864	Maxwell's equations
	1888	Hertzian waves
100-inch reflector	1916	
	1935	Radar experiments
200-inch reflector	1947	
Babcock "seeing" compensation	1953	
	1958	Adaptive antennas
Invention of Laser	1960	
Active mirror figure control	1966	
Phase conjugate COAT (Rockwell)	1968	
Multi-dither COAT (Hughes)	1970	
Predetection image compensation (Itek)	1973	
Next generation telescope	?	
Laser fusion	?	

Fig. 1. Major Events in the history of optics.

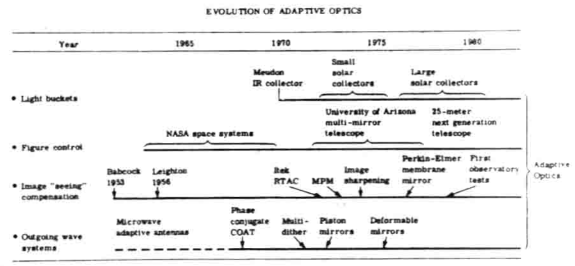


Fig. 2. Evolution of adaptive optics.

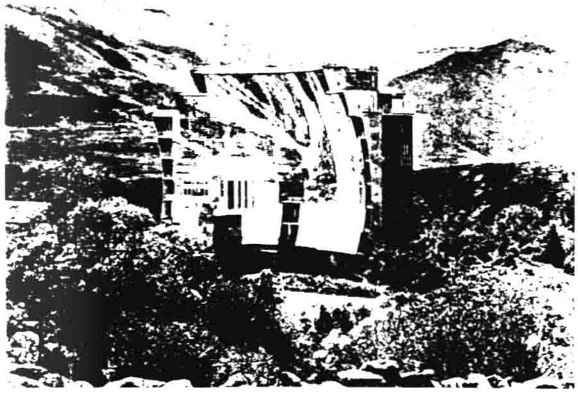


Fig. 3. Parabolic Reflector Concentrator and Focal Building of CNRS 1000 kW Solar Furnace.

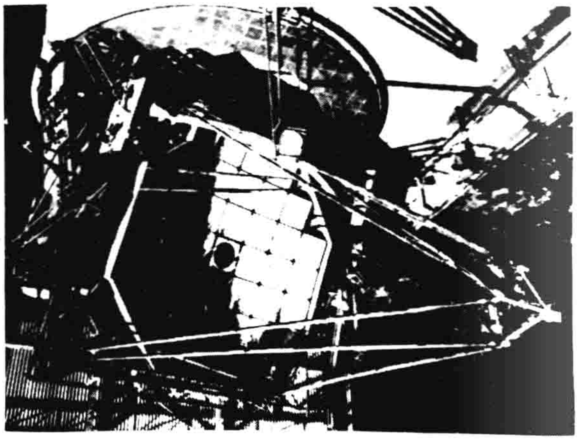


Fig. 4. Collector for stellar IR interferometer at Meudon.

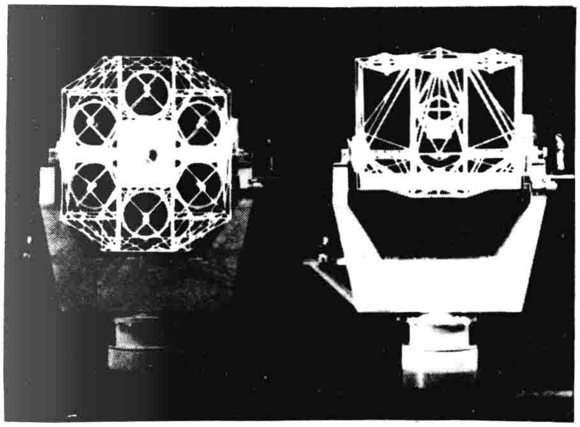


Fig. 5. Model of 6 element, 4.8 meter University of Arizona/Smithsonian Telescope.

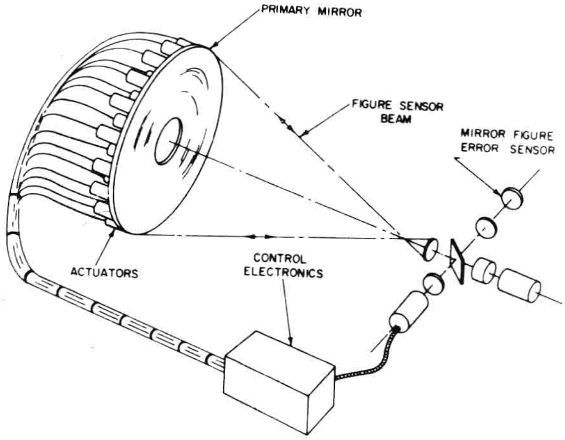
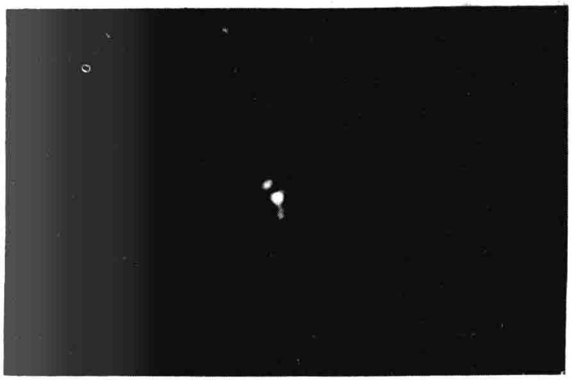
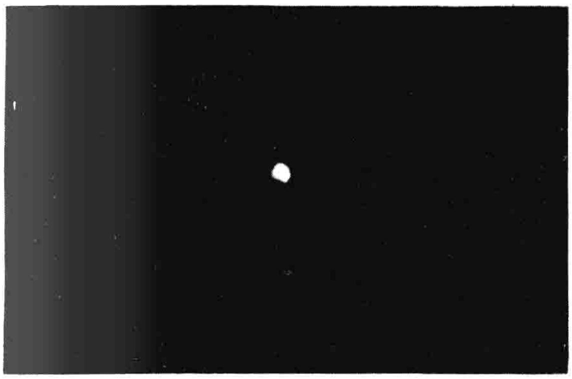


Fig. 6. Schematic of representative figure control system for multi-actuator deformable mirror.



(A)



(B)

Fig. 7. Turbulence degraded image of laser source propagated over 300m ground path, collected by 30 cm telescope. a) RTAC off, b) RTAC on.

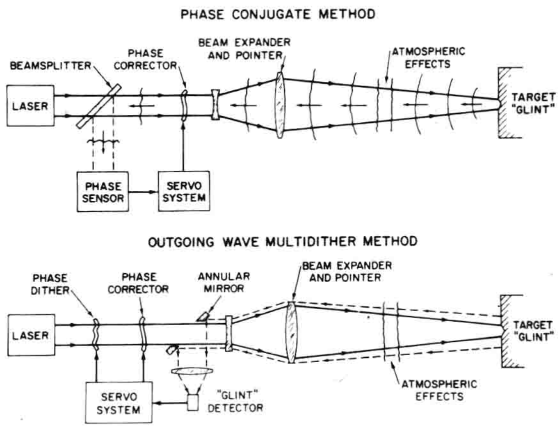


Fig. 8. Techniques for adaptive optics compensation of atmospheric aberrations for a projected laser beam, using glint return.

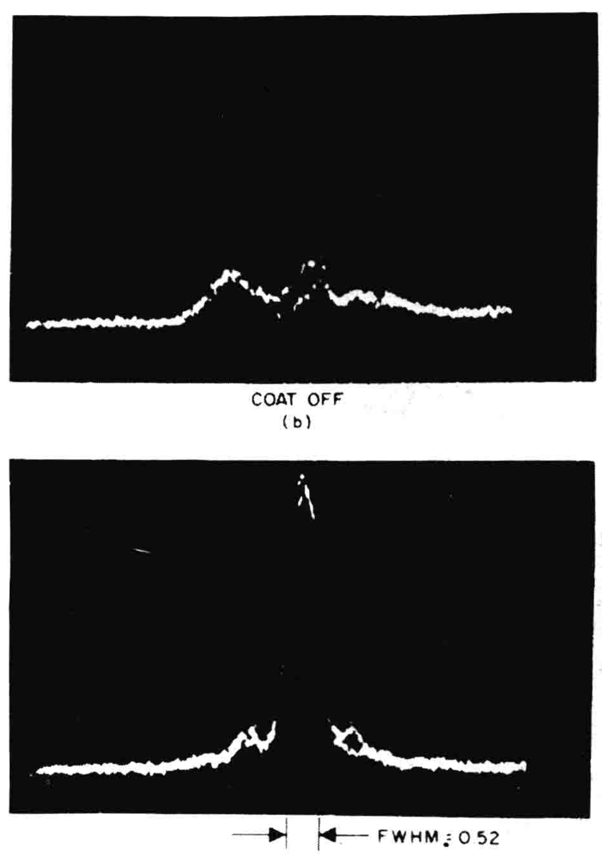


Fig. 9. Focal spot scan through image of a laser beam projected through 100m of turbulent atmosphere. a) COAT off; b) COAT on.