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THE IMPACT OF ADAPTIVE APERTURE TECHNIQUES ON HEL SYSTEM EFFECT--ETC(U)
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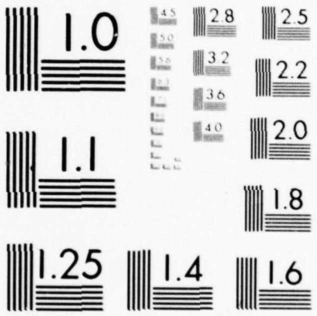

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THE IMPACT OF ADAPTIVE APERTURE TECHNIQUES
ON
HEL SYSTEM EFFECTIVENESS

NOVEMBER 1973

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Science Applications, Incorporated
1701 N. Ft. Myer Drive, Suite 908, Arlington, Virginia 22209

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THE IMPACT OF ADAPTIVE APERTURE TECHNIQUES
ON
HEL SYSTEM EFFECTIVENESS

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(10) J. I. Connolly, Jr.
D. E. Yansen
J. Wallace ~~Consultant~~

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FOREWORD

This report is a summary of a viewgraph presentation delivered by Science Applications, Incorporated (SAI) at the Naval Ordnance Laboratory on 21 September 1973.

The briefing describes and discusses alternative components for a generic adaptive aperture system, outlines and analyzes qualitatively the many phenomena which suppress the far-field intensity of a laser system, and explains the potential of adaptive aperture techniques for restoring near-diffraction-limited intensity.

IMPACT OF ADAPTIVE APERTURE TECHNIQUES ON HEL SYSTEM EFFECTIVENESS

- NEAR-TERM/ULTIMATE TECHNOLOGY
- FUNCTION OF LASER WAVELENGTH
- FUNCTION OF DEVICE TYPE

The impact of adaptive aperture techniques on HEL system effectiveness can vary greatly depending on technology advancement, laser wavelength, and even, at a given wavelength, whether the device is a gas-dynamic, electric, or chemical laser. For example, in the near term it may be feasible to correct for relatively low spatial and temporal frequency variations in phase across the wavefront. Higher frequency variations will require more advanced technology. A second factor depends on how the system is interrogated in order to determine what phase (and intensity) corrections must be applied. If one must "close the loop" to the target to assess turbulence structure in real time, the technology required will be more advanced than that necessary to interrogate the outgoing wave in the near field. Having to close the loop to the target draws attention to a wavelength dependence, specifically the difference in near-term adaptive aperture utility for DF and CO_2 systems. Under many conditions the target intensity in the DF case will be turbulence limited. Thus effective adaptive aperture techniques for DF systems must await relatively advanced technology. These examples given above are discussed in more detail later in this briefing.

Although the variation of adaptive effectiveness with device type is less important, the variation is nevertheless real. One can in principle have 3.8μ lasing from gas-dynamic* and electric as well as from chemical lasers. In each case the cavity conditions, and hence the phase and intensity distortions to the wavefront, will be different.

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*Efficient gas-dynamic lasing at 3.8μ would require elevated ($\leq 4000^\circ K$) plenum temperatures for efficient thermal excitation of the upper states and hence is unlikely.

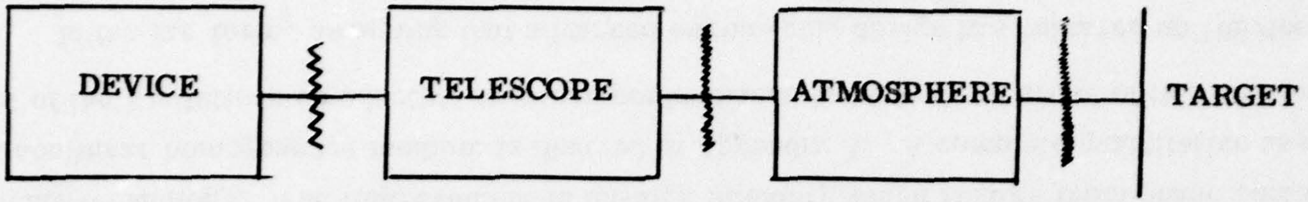
EMERGING CONCLUSIONS

- IMPACT OF ULTIMATE TECHNOLOGY IS TO "PERFECT" ALL HEL SYSTEMS EXCEPT UNDER SEVERE ATMOSPHERIC CONDITIONS
- NEAR-TERM IMPACT MUCH GREATER AT CO_2 THAN AT DF WAVELENGTHS
- FAR-TERM IMPACT APPEARS GREATER FOR CO_2 SYSTEMS
- ATMOSPHERIC PHENOMENA ARE THE PRINCIPAL CULPRITS, PARTICULARLY FOR ADVANCED SYSTEMS

Advanced adaptive aperture techniques appear capable of restoring virtually diffraction-limited performance to all high-energy laser systems, under a wide range of conditions. This statement can be made without qualification with respect to the perturbations introduced by the device and telescope. With respect to atmospheric induced degradations, however, even the ultimate technology appears to be limited. The first limitation concerns the Coherent Optical Adaptive Techniques (COAT) used to interrogate the atmosphere by closing the loop through to the target. These techniques (discussed later) depend on the return beam being coherent. Sufficiently severe atmospheric distortions (turbulence or blooming) will so degrade beam coherence that the system will fail to operate. In a moderately severe distortion environment the ultimate system will correct turbulence introduced perturbations almost completely, although as diffraction-limited performance is approached the system signal-to-noise ratio approaches zero, invoking a practical limitation somewhat short of the diffraction limit. The second limitation to adaptive aperture performance is that thermal lensing cannot be corrected completely, even by ultimate technology. The improvement in on-axis intensity which results from phase contouring in a nonlinear homogeneous medium is derived in Appendix A. A complete quantitative assessment of the limitations on adaptive aperture performance is beyond the scope of this briefing.

In the far term, assuming that advanced engineering design has "cleared up" device and telescope performance, atmospheric phenomena emerge as the driving reason to pursue adaptive techniques. System considerations, however, may provide added emphasis, e.g., one might eliminate the very heavy strongback which maintains alignment in the optical train and use an adaptive aperture system to compensate for the additional phase perturbations.

PERTURBATIONS TO WAVEFRONT REDUCE FAR-FIELD ON-AXIS INTENSITY

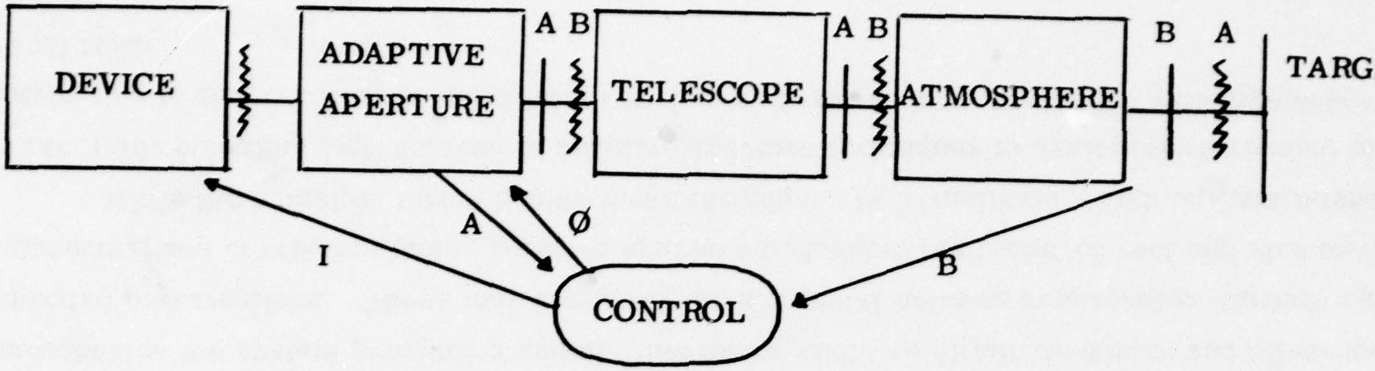


- PHASE AND INTENSITY FLUCTUATIONS
  - Wide range in spatial and temporal frequencies
  - Function of wavelength
- CONTROLLABLE VERSUS "UNCONTROLLABLE" PERTURBATIONS
  - Almost all perturbations can be suppressed
  - Tradeoff between suppression and correction
- ADAPTIVE APERTURE TECHNIQUES CONTROL NEAR-FIELD PHASE AND INTENSITY TO
  - Maximize far-field intensity
  - Provide "inertia-less" fine tracking
  - Contribute to autoalignment

Phase and intensity perturbations which lead to a decrease in on-axis intensity in the far field arise primarily from three sources. Of these three only the atmosphere is immune to the effects of advanced engineering techniques and hence emerges as the principal reason for developing adaptive aperture technology. One should remember, however, that once developed to counteract atmospherics the system provides a useful "fine tuning knob" to eliminate device and telescope generated perturbations. There may frequently be a tradeoff between suppression (through advanced engineering) and correction (using adaptive aperture techniques) in terms of cost and size and weight.

While the principal thrust behind these techniques is to maintain a high on-axis intensity in the far field, potential contributions of adaptive aperture techniques to system performance include contributing to fine tracking in the pointer-tracker system and assisting in the autoalignment of the optical train.

ADAPTIVE APERTURE SYSTEM



- CRITERION IS INTENSITY AT TARGET
- INTERROGATION CAN OCCUR - INITIALLY (needs tuning)
  - PREDICTIVELY
  - AT TELESCOPE
  - AT TARGET (ultimate)

An adaptive aperture (or active optic or snythetic aperture as it is sometimes called) is a mirror in the optical train which can undergo distortions to compensate for phase changes introduced into the wavefront by other parts of the laser system or by the atmosphere. Which mirror in the optical train is adaptive is somewhat arbitrary, although definite tradeoffs are present. On the one hand one would prefer the relatively complicated adaptive aperture to appear early in the optical train where the mirror diameter is small. For the unstable resonator configuration, however, this implies an intense thermal loading. For the MOPA design, one could eliminate cooling requirements in the adaptive optic by placing it before the power amplifier.

One, of course, would like to interrogate the outgoing wave as late in the mirror train as possible in order to include perturbations from as much of the device as possible. This interrogation need not occur at the adaptive optic. Interrogation of the outgoing wave somewhere in the optical train represents a relatively near-term level of technology. Interrogating the return wave reflected from the target represents added complexity, where advanced technology certainly will be required before a high-power system can be fielded.

Inital interrogation means measuring the positon of, e.g., a shock structure within the cavity and "permanently" contouring a mirror surface. As the device is used these patterns tend to shift slightly so that the "permanent" contouring must be tuned slightly. Thus a truly permanent contouring of a mirror surface would be only marginally acceptable. Predictive interrogation refers to that which can be used to correct substantially for thermal blooming, where a knowledge of expected transverse wind along the beam, humidity, temperature, range, and aperture size allows one to estimate the nature of the blooming,and hence the optimal near-field corrections, quite accurately. This discussion is expanded later in the briefing.

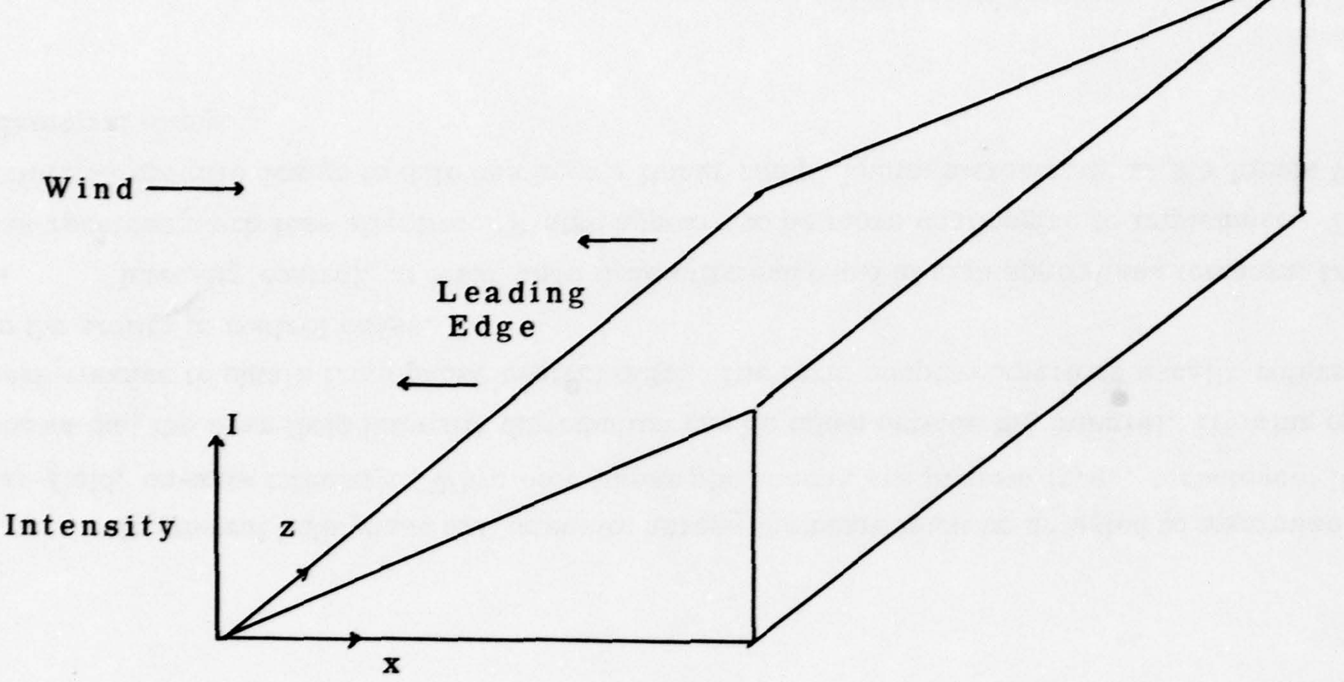
PHASE VERSUS INTENSITY CONTROL

- OPTIMAL SYSTEM INCORPORATES BOTH CONTROLS
- PHASE CONTROL ALONE VALID FOR TURBULENCE (DF)
- PRINCIPAL INTENSITY CONTROL HAS BEEN JAMES WALLACE MEMORIAL RAMP

In general both phase and intensity across the beam must be adjusted to maximize the far-field, on-axis intensity. When only linear phenomena are present (e.g., turbulence) it can be shown that the near-field intensity distribution can be taken outside the integral, allowing optimal performance to obtain from phase control only. The term adaptive aperture usually refers only to the ability to control phase.

Intensity control, at least when done efficiently and at high spatial and temporal frequencies, has received much less attention. It also appears to be more challenging to implement. The principal specific design to date has been a linear ramp, known historically as the James Wallace Memorial Ramp.

CLASSIC NEAR-FIELD INTENSITY
CONTOURING
THE JAMES WALLACE MEMORIAL RAMP



This viewgraph portrays the historic Memorial Ramp in action. The low-intensity edge of the ramp should always point "into the wind" or in the direction of sluing for maximum effectiveness. An intuitive explanation of the ramp's effect is: the low-intensity portion does very little heating of the path through which the higher intensity portion of the beam must pass. Thus less of the energy in the intense part of the beam is diverted out of the desired focal region.

It appears that the ramp profile can be generated by modifications within the HEL cavity. In addition concepts exist for rapidly rotating the beam to keep the low intensity in the direction of sluing. Intensity enhancements of over one order-of-magnitude under severe thermal blooming conditions have been demonstrated in scaled experiments, using this technique in conjunction with phase correction. Optimal use of the Memorial Ramp requires that a cylindrical mirror be used concomitantly for phase shaping. This should not be a serious complication.

DEVICE PERTURBATIONS

- $\Delta \rho/\rho$
  - shocks
  - natural turbulence
  - wakes, boundary layers, etc.
- WINDOW
  - aerodynamic (steady state)
  - material (f[t])
- INTERNAL OPTICS
  - thermal loading
  - vibration
  - misalignment

The many device sources of wavefront perturbations are listed. The relative importance of many of these vary with device type and with the level of engineering sophistication. One notes that from the output window the phase distortion would be principally steady-state in the aerodynamic window case. These distortions result from density gradients established when the aerodynamic window flow is initiated, prior to device turn on. For a material window, however, the distortion is generated by absorption in the window. This distortion could have significant time-dependent features.

EXTERNAL OPTICAL TRAIN

- THERMAL LOADING (principally defocus for symmetric beams)
- HIGH PRESSURE COOLANT DISTORTIONS
- VIBRATION
- THERMAL LENSING IN CONFINED SPACES

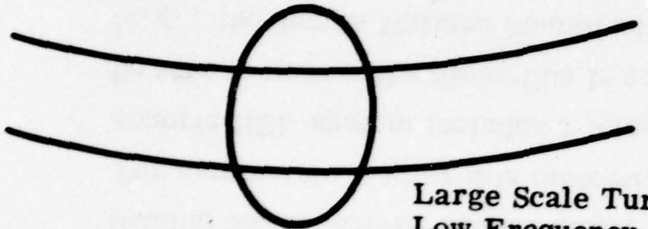
There are several sources of phase perturbations within the external optical train. As for the device these perturbations can in principle be suppressed by careful engineering. Thermal loading on the mirror causes distortions, typical thermal relaxation times being tens of milliseconds. For symmetric loading this distortion can be corrected almost completely by refocussing. Since a generic HEL system includes a telescope this distortion causes no inconvenience, although one must be able to assess the distortion in advance in order to refocus correctly. For asymmetric beams (e.g., the James Wallace Memorial Ramp introduced deliberately to ameliorate thermal blooming), however, the effect of the distortion could not be corrected by refocussing. Under these conditions an adaptive aperture *system could be useful.*

Most advanced mirror designs include a high pressure coolant system. The forces which the coolant lines impart to the mirror surface can be significant in view of the stringent mirror figure requirements, even at IR wavelengths. Adaptive aperture techniques could be used to correct for this and for vibration-induced mirror surface displacement.

A problem which has proven particularly serious for the AFL (Air Force TSL), and which has received considerable attention at the XLD-1 site, is the heating and consequent distortion which results in confined spaces between the output window of the laser cavity and the outside world. Frequently, this distortion will be too serious to rely on adaptive aperture techniques alone. After direct methods, e.g., creating a cross wind or flushing with dry nitrogen, have been invoked, adaptive aperture techniques could handle the residual distortion.

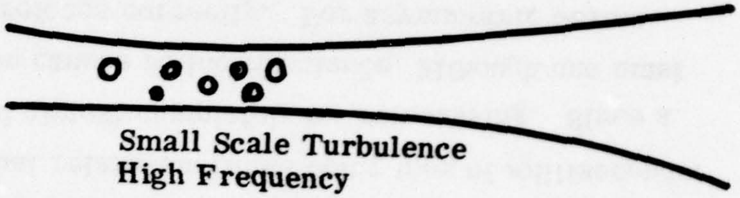
ATMOSPHERE

- THERMAL LENSING
- TURBULENCE
  - beam wander
  - beam spread



Large Scale Turbulence
Low Frequency

MORE AMENABLE TO AAT



Small Scale Turbulence
High Frequency

LESS AMENABLE TO AAT

Atmospheric-induced distortions are the driving force behind the development of adaptive aperture techniques. These are the remaining distortions not susceptible to sophisticated engineering techniques. At 10.6μ, and at other relatively highly absorbing wavelengths, thermal lensing is the principal degrading phenomenon. The magnitude of this effect depends on relative humidity, temperature, and relative wind, all quantitities which are sensibly constant, or which vary predictably over typical engagement ranges (1-3 km). Thus by measuring these quantities at the transmitter we can correct for thermal lensing predictively at least to first order.

For high-energy laser systems operating at wavelengths of relatively low absorption turbulence broadening is frequently the most threatening atmospheric phenomenon. While one can predict the time average decrease in far-field intensity reasonably well (neglecting intermittencies) by measuring the turbulence strength at the transmitter, one cannot correct for this beam broadening without knowing the (time dependent) integrated optical path shift along each ray. Thus a COAT system is required for satisfactory performance.

It should be noted that some compensation, namely for beam wander, is achievable without COAT. The average transverse gradient in optical path length along the ray, can be inferred by monitoring the wandering of the centroid of the far-field spot. This wandering results from the turbules of scale size larger than a beam diameter. These relatively low-frequency variations can be removed by a responsive pointer-tracker. Instantaneous beam spread, however, requires some type of COAT system for compensation.

ADAPTIVE APERTURE SYSTEM

- WAVEFRONT SENSOR
- CONTROLLABLE OPTIC
- INTERROGATION PHILOSOPHY
  - closed loop through telescope (near term)
  - closed loop to target (farther term)

The three principal components of an adaptive aperture system are listed. The component options one has for these subsystems are discussed in detail in the following viewgraphs along with the differences between the two principal interrogation philosophies.

WAVEFRONT SENSORS

- HETERODYNE INTERFEROMETRY
- LATERAL SHEARING INTERFEROMETRY
- COMMON PATH MACH ZEHNDER INTERFEROMETER
- UNEQUAL PATH MACH ZEHNDER INTERFEROMETER

The wavefront sensor provides the real-time information on the phase distribution across the wavefront which is required for the feedback controls system. The current techniques for wavefront sensing (either outgoing or return wave) are listed in the viewgraph.

All these techniques have been used extensively in the visible spectrum and are therefore very sensitive for 10.6μ use in that they may make available more information than is necessary for the required corrections. Currently this is not an objectionable feature, but for operational systems simpler, less sensitive techniques suffice and may be more reliable.

DETECTORS

- REQUIREMENTS
  - Medium Sensitivity
  - Medium to High Frequency Response - Maximum ~ 2 MHz
  - Spectral Response - Peaked at Laser Probe Wavelength
  - Low Microphonic Output

- ALTERNATIVES
  - Single Element

    IR -

    Thermopile
    Hg:Cd:Te
    Pyroelectric
    Bolometer

    Visible -

    Silicon Diode
    Photomultiplier
  - Two-Dimensional

    Image Dissectors
    Vidicons
    Two-Dimensional Solid-State Arrays

The detectors utilized in the wavefront sensing systems are for the most part off-the-shelf items with no unusual properties. The sensitivity and frequency response requirements are well within those currently available; only the vibration susceptibility for some of the IR infrared detectors is a serious limitation. Of all the IR detectors the thermopile is probably the least sensitive to vibration and is a good candidate for low-frequency applications ($f \lesssim 10$ Hz).

Detectors in the visible and near-IR part of the spectrum are quite adequate for the job. Silicon diodes make excellent detectors in either single element or array format. Ruggedized image dissectors and vidicons provide high resolution two-dimensional image detection at very fast response times ($< 1\mu$sec). There are no high-resolution, off-the-shelf, two-dimensional far-IR detectors available at the present time.

ADAPTIVE MIRRORS

- REQUIREMENTS
    - High Reflectivity
    - High Spatial Resolution
    - High Thermal Conductivity
    - Low Mass
- DEFORMABLE MIRROR ADVANTAGES
    - No $n\lambda$ problem
    - No cracks
    - Possibly fewer cooling problems
- SEGMENTED MIRROR ADVANTAGES
    - Simpler Control Task
    - Reduced Force Required
    - COAT Adaptability

Adaptive mirrors for high-energy laser systems fall into two general categories - thin deformable and segmented. For both categories there are a number of desirable general characteristics, or basic requirements. Several of these are listed in the viewgraph. For the deformable mirror a high modulus of elasticity is desirable. This allows high spatial resolution while minimizing crosstalk. The limitations on the minimum deformable mirror element size and the smallest practical mirror segment have not yet been established.

Currently, the deformable mirror is being pursued more than the segmented mirror for one principal reason - its continuous surface. The continuous surface eliminates the radiation seepage, much of the alignment problem, and diffraction from segment edges. This diffraction results in near-field fresnel intensity spikes. These could cause a grid-like pattern in the near field which would divert significant energy from the center of the far-field pattern. The only blooming reduction experiment to date using a controlled segmented mirror incorporated a blooming cell which was near the focal point. Thus, potential deleterious effects from the blooming caused by these near-field fresnel spikes were not assessed.

The segmented mirror has the simplest control problem since adjacent segments are completely independent. There is also reduced force required at least for low frequencies (e.g., $\lesssim$10Hz). For higher frequencies, there may come a point where inertial forces contribute as much as stress. At the present time COAT systems are more rapidly adapted to segmented mirrors.

DEFORMABLE MIRROR TECHNIQUES

● MATERIALS	Molybdenum Copper ....
● COATINGS	99 - 99.8% Reflectivity
● THICKNESS	~ 0.140" (current designs)
● DIAMETER/THICKNESS	~ 75

The materials that have been considered for operational deformable mirrors are: molybdenum, chrome-copper, stainless steel, and various combinations of these. The first choice has been molybdenum for its high heat transfer, high elasticity, high shear strength, and low coefficient of expansion. Recent polishing breakthroughs have made copper an attractive alternative.

Coatings are quoted currently near 99 percent; improved polishing and coating techniques should increase this and thereby reduce cooling system requirements. Presently projected mirror thicknesses are roughly one-eighth of an inch. Thinner mirrors, of course, would place less stress on the actuators. At the same time such a change would lower the resonant frequencies of the mirror and perhaps complicate the control problems at higher frequencies.

CONTROL SUBSYSTEMS

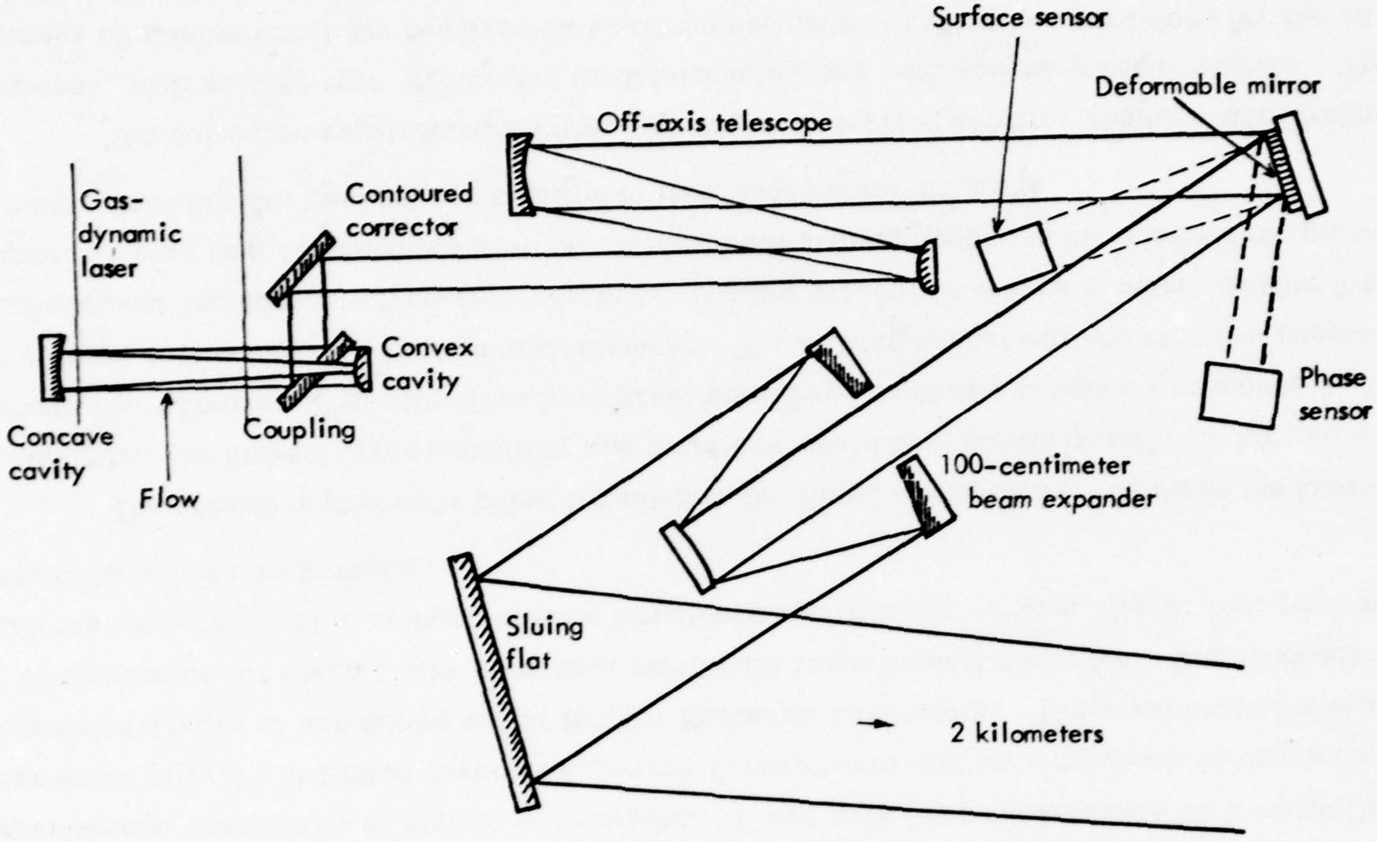
- CONTROL APPROACH
  - Manual - Micrometer, Piezoelectric
  - Automatic - Programmable, Feedback Systems
- ACTUATORS
  - Alternatives
  - - Hydraulic
  - - Piezoelectric
  - - Electromechanical
  - Requirements
  - - Force $\sim$ 10 lbs (typical of current designs)
  - - Displacement $\gtrsim 20\mu$
  - - Bandwidth $\gtrsim$ 1 kHz
- COMPUTER
  - Closed Loop Around Device
    - Memory $\gtrsim$ 8000 Words
    - Process Time $\lesssim 1\mu$second
  - Closed Loop Through Target
    - Significantly Increases Computer Requirements

Experimental work on controlled, adaptive apertures has been confined to low power experiments, principally at visible wavelengths. There have been experiments with manually adjusted segmented mirrors at United Aircraft Research Laboratories and low-frequency feedback controlled segmented arrays at Autonetics and at Hughes Research Laboratory. These experiments were aimed at compensating for thermal blooming with significant improvement observed. The feedback control systems were designed to compensate for turbulence and tracking errors. Here, too, preliminary results have been encouraging.

The actuators presently being considered are listed on the chart. Of these the hydraulic actuator has the highest force capability and therefore would be a strong possibility for use with deformable mirrors. Piezoelectrics have great accuracy, moderate frequency response (~ 2 kHz away from resonance), but limited displacement. The electromechanical actuator has considerable displacement and adequate frequency response, but low force; this makes it more suitable for segmented or very thin deformable mirrors. If sufficient displacement can be achieved the piezoelectric actuator probably has the best combination of desirable characteristics.

The computer requirements vary markedly with desired actuator number, with frequency response, with surface type (segmented or deformable), and with accuracy requirements. The major sources of data on computer requirements are the estimates of various contractors for the 10 Hz, deformable, $\lambda/20$ system requested recently by MIT Lincoln Laboratory for an ARPA-sponsored experiment at the XLD-1. These estimates typically project a standard mini-computer with 8K of core memory and microsecond processing time. Although more advanced systems will require additional computer capability, it does not appear that the requirements in this area will approach the state of the art in computer hardware or software.

OPTICAL TRAIN FOR XLD-1/ADAPTIVE APERTURE EXPERIMENT



NOTE: This figure reprinted through the courtesy of Lincoln Laboratory.

The viewgraph shows the components of the optical train for the XLD-1 Adaptive Aperture Experiment. The adaptive aperture, a thin deformable mirror with 10 Hz response capability, is positioned immediately before the telescope.

This adaptive aperture system will allow phase distortion corrections to be made for thermal blooming and for disturbances originating in the device or optical train. Since it does not interrogate the return wave from the target no turbulence compensation is possible. This is not a serious limitation since the system (XLD-1) with which this device is to be used lases at 10.6μ where turbulence-induced beam spreading should play a minor role.

COHERENT OPTICAL ADAPTIVE TECHNIQUES (COAT)

- APPROACHES
  - PHASE CONJUGATE (Autonetics)
  - MULTIDITHER (Hughes)
  - OTHER
- LIMITATIONS
  - THREATENED BY SEVERE PHASE DISTORTIONS (Incoherence)
  - LIMITED OPERATING RANGE (Not Important)
  - LIMITED TO $\sim 2\lambda/D$ (S/N)
  - VARIABLE GLINT STRUCTURE-PRIOR TO AND AFTER DAMAGE

Coherent Optical Adaptive Techniques (COAT) refer to a variety of techniques which utilize the properties of a coherent return wave from the target to introduce appropriate phase compensations into the outgoing wave. Such appropriate compensation can markedly reduce the turbulence-induced beam spreading in the far field. The principal versions introduced to date have been the phase conjugate approach (Autonetics) and the multidither approach (Hughes). The former measures the phase of the return wave and impresses the conjugate phase across the outgoing wave. In the multidither approach, one establishes a far-field interference pattern between two mirror segments. By dithering (moving sinusoidally) one of the segments at a prescribed frequency one sweeps the maximum in the far-field intensity pattern across the target glint point generating a return signal oscillating at the dither frequency. The dither signals are used to determine those mirror segment positions which maximize far-field intensity. An expanded explanation of the multidither technique is given in Appendix B, along with a discussion of the limitations to COAT performance. Combinations of the above two techniques are possible but have not been explored.

COAT TECHNOLOGY STATUS

- 7-Element Linear Array
- 3-Element Two-Dimensional Array
- Piezoelectrically-Driven Mirror

Both techniques proposed to date have been tried with small, several-element arrays in the lab and over modest outdoor ranges at low power. Although the results have been close enough to theoretical predictions to verify the basic principles involved, implementation of these techniques in full scale, high-power systems is not a near-term prospect. The experiments indicate that these systems focus rapidly, compensate for moderate turbulence, and track in a multiglint field. The multidither system has demonstrated that it can track light edges and dark spaces in addition to glint reflections.

The state of the art in system complexity is on the order of 7 elements in a linear array and 3 elements in a two-dimensional array. In the multidither systems the phase shifting is currently done by piezoelectrically-driven mirror segments. In the phase conjugate system the phase of the return is detected by a heterodyne system using a separate, very stable laser as a local oscillator. After detection the phase of the transmitted beam is modulated to match the conjugate of the return beam using a piezoelectrically-driven mirror. Autonetics has suggested a number of improvements in the modulation and phase detection sections of this system. The maximum bandwidth of existing systems is approximately 100 Hz.

ADAPTIVE APERTURE IMPACT

CO_2 VERSUS DF

CO_2

- Nonlinear spread not receptive to increased power
- Principally blooming/predictive compensation attractive
- Relatively large λ/tolerance relief
- ϕ and I control required for optimal improvement
- Severe (10 λ/D) blooming => 2-3 λ/D at 2km (worse at longer ranges)

LL (ϕ only)	const	V_t	x2	(near future)
	slue		x5	
JW (ϕ + I)	theory		x5	(quasi near future)
	expt		x12	

DF

- Linear spread receptive to power increases
- Turbulence spread => ϕ control alone can be optimal
- Relatively small λ

The overall impact of adaptive aperture techniques on system effectiveness appears to be noticeably greater at 10.6μ than at the low absorbing DF lines, particularly in the near term. There are several reasons which support this conclusion. The first is that the principal beam spreading phenomenon at 10.6μ is thermal blooming while for DF lasers, most of the lines of which have very low molecular absorption coefficients and hence produce little blooming, the principal culprit is turbulence. For turbulence compensation COAT systems (and hence advanced technology) are mandatory whereas for blooming compensation it appears that COAT may be required for vernier corrections only. Secondly, the precision with which the mirror surface must be adjusted for equivalent phase compensation is nearly three times greater at DF- than at CO_2-wavelengths. This difference is less fundamental than the first and may be minimized by advanced engineering techniques. Note that since the index of refraction of air is extremely insensitive to wavelength the total displacement is the same in each case; only the precision differs. A third difference is that turbulence spreading, being a linear phenomenon, can be overcome by increasing the output power, whereas as a method of overcoming blooming, increasing the power is self defeating.

The factors by which increased on-axis intensities have been calculated and demonstrated (lab experiments) are shown on the viewgraph. Lincoln Laboratories (Bradley and Herrmann) have calculated factors of 2 and 5, without and with slue respectively, using phase compensation only.

James Wallace, utilizing his historic Memorial Ramp plus a cylindrical mirror for phase correction, has predicted enhancement by a factor of 5. A scaled experiment at Avco predicted a factor of 12 for the same conditions.

PULSE WAVEFORMS

- NO COMPENSATION FOR PULSED BLOOMING (focussed beam)
- FOR SELF ASSESSMENT - single pulse severely R limited
  (10μ sec, 10%, 500 ft)
  - requires $\geq$ 100 kHz bandwidth
- AUGMENTED ASSESSMENT RELIEVES BOTH REQUIREMENTS

For turbulence compensation of pulse waveforms adaptive aperture techniques appear promising when a precursor pulse is used to interrogate the atmosphere. Over canonical pulse lengths (10 - 100μ seconds), the atmosphere is frozen (there is very little if any turbulence structure at frequencies of 10 kHz and greater). Thus a precursor pulse leading the main pulse by a millisecond or less could accurately assess the instantaneous density field in the atmosphere. An adaptive aperture system with a one kilohertz bandwidth could then adjust the phase pattern for the main pulse. For a multi-pulse system each pulse could act as the precursor for the subsequent pulse, although the canonical rep rates (10 - 200 pps) are low enough to miss some of the high-frequency structure.

Self assessment seems out of the question. First, if an adaptive aperture system were to react by the time 10 percent of the pulse had been transmitted, (which does not seem to be an unreasonable constraint) the bandwidth demands on the mirror would be astronomic (1 MHz for a 10 μsecond pulse). Secondly, a self assessment system would be severely range limited. For a 10 μsecond pulse, allowing 10 percent to be transmitted uncorrected, the maximum system range is 500 feet. An augmented, or precursor assessment system relieves both of these constraints considerably.

For the classic focussed beam (which now appears to be non-optimal) little or no compensation for thermal blooming appears to be achievable through adaptive aperture techniques. The reason for this is that the spot size is initially limited by diffraction; adaptive aperture techniques cannot improve on this. For focussed pulse waveforms the blooming occurs principally in the focal spot (where the acoustic transit time is smallest). Very early in the pulse, density gradients are established in the atmosphere which propagate radially to broaden the beam. Subsequent phase and intensity adjustments at the aperture cannot affect this significantly. It now appears that the impact of single pulse thermal blooming can be relieved considerably by deliberate defocussing. To take full advantage of this, however, requires that the pulse energy increase as the cube of the far-field beam diameter.

APPENDIX A

AMELIORATION OF THERMAL BLOOMING BY PHASE CONTOURING

INTRODUCTION

The objective of this appendix is to evaluate the effects that absorption and consequent heating of the atmosphere have on the focal point irradiance, and the effectiveness of near-field phase contouring for restoring near diffraction limited intensities. Uncompensated refractive effects impose serious constraints in many DoD applications on the average power which may be propagated efficiently. However, recent theoretical and experimental work indicates that substantial increases in far-field irradiances can be achieved by either phase corrections in the external optical train (which tend to compensate for the phase changes introduced by atmospheric heating) or irradiance tailoring which creates only linear or quadratic phase changes. This appendix addresses only the former.

UNCOMPENSATED BLOOMING DEGRADATIONS

The laser beam interacts with the atmosphere through the index of refraction, which has both a real and imaginary part. The imaginary part leads to absorption and phase changes associated with heating of the atmosphere. The equation, in normalized coordinates x/r_m, y/r_m, z/z_f, which describes the complex amplitude is

$$2i\,A_z + \epsilon\,(A_{xx} + A_{yy}) - 2N\left(\int_{-\infty} I(x', y, z)\,dx'\right) A = 0 \qquad \text{(Eq 1)}$$

where

$$\epsilon = z_f/kR_m^{\;2},$$

$$N = k\,z_f\,(\gamma-1)\,(n_\infty-1)\alpha\;I_o R_m/\gamma p_\infty\,U_\infty, \qquad \text{(Eq 2)}$$

and

$$N = \frac{z_f^{\;2}}{R_s}\;\frac{(\gamma-1)\;(n_\infty-1)\alpha\;I_o}{\gamma\;p_\infty\;U_\infty}\;.$$

The terms in Equations 1 and 2 are defined below

A	complex amplitude
I (= AA^*)	irradiance distribution (watts/cm^2)
x, y	coordinates transverse to propagation direction

a	propagation direction
R_m	radius of final mirror of external optical train
r_s	diffraction limited spot size
z_f	distance to focal point
k	wave number
n_∞	index of refraction
γ	ideal gas constant (1.4)
α	absorption coefficient
U_∞	component of velocity transverse to propagation direction
p_∞	atmospheric pressure (0.1 joules/cm^3)

For 10.6μ radiation the absorption coefficient, α, is determined primarily by the partial pressures of CO_2 and H_2O. The expected range of the molecular absorption coefficient varies between 0.1 km^{-1} and 0.3 km^{-1}.

The properties of the governing equation are well known and numerical codes of a complex nature are available for detailed results. The irradiance distribution of an initially circular gaussian beam will distort into a crescent shaped irradiance distribution. The peak irradiance at the focal point will be degraded since the area of the crescent is very much larger than a diffraction limited spot. This degradation has been measured in a scaled experiment; the results are shown in Fig. A-1.

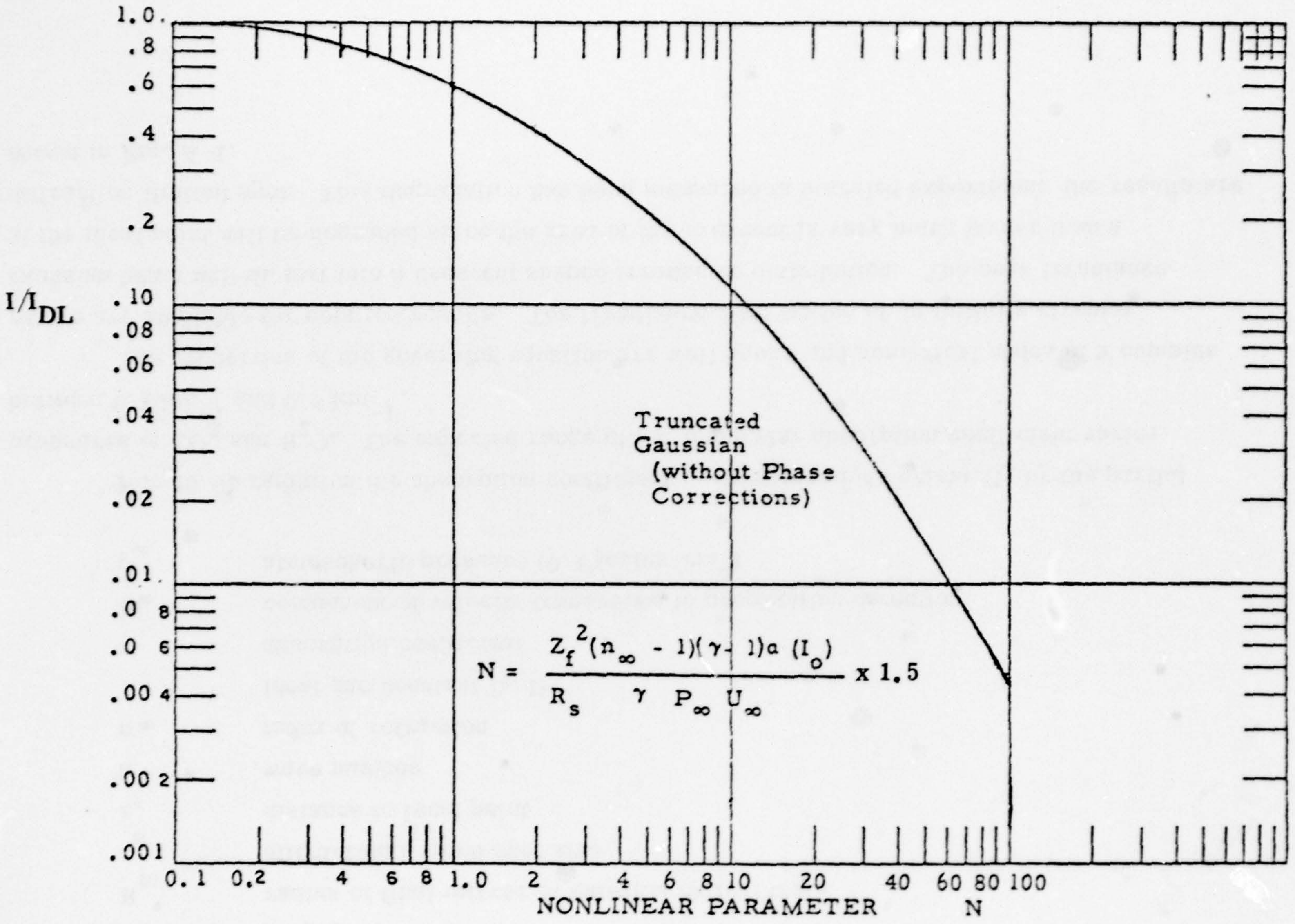


Fig. A-1 Loss of Focal Point Irradiance due to Atmospheric Heating (taken from Gebhardt & Smith UARL report number K921004-8)

This report defines the blooming parameter N, given in Equation 3, which measures the strength of the heating weighted by the effect of the lever arm, z_f.

$$N = \frac{Z_f^2 \, (n_\infty - 1) \, (\gamma - 1) \sigma \, (I_o)}{R_s \quad \gamma \quad P_\infty U_\infty} \qquad \text{(Eq 3)}$$

Larger values of N (i. e., larger focal lengths or smaller transverse velocities) correspond to more severe heating effects. For most sea-level applications, N is greater than 10. As clearly shown in **Figure A-1**, nonlinear refractive effects cause the system to fall considerably short of achieving diffraction limited irradiances.

Physically, the heating term (integral term in Equation 1) creates astigmatic phase changes which depend upon the intensity absorbed by the atmosphere in one transit time, r_m/U_∞, of the beam. Longer focal lengths are clearly worse in terms of the ratio of nonlinear irradiance to the diffraction limited irradiance. The heating effect at a fixed range z_f, with a transverse wind or sluing velocity U_∞, defines an optimum power. If the power is either greater or less than optimal, the far-field brightness at a given range will be lower. For many engagement conditions this optimal power is quite low. It is therefore clear that a special effort must be made to minimize these nonlinear refractive effects to make the optimum device power high enough for DoD applications.

POTENTIAL IMPROVEMENT FROM PHASE CONTOURING

The principal idea behind phase shaping is to introduce by external optics a set of ray trajectories which compensate for the deflection of rays caused by atmospheric effect. Nonlinear propagation theory can be of significant value in predicting the necessary corrections to compensate for atmospheric heating. In particular, present theoretical and experimental conclusions show that an optical train which has the ability to use a cylindrical focus along with a coma correction can achieve considerable enhancement of the far field brightness.

To derive a quantitative estimate of the magnitude of the compensation, let us rewrite Equation 1 in terms of the irradiance, $I = AA^*$, and phase, ψ:

$$\psi_z + 1/2\,(\psi_x{}^2 + \psi_y{}^2) = -\left[R_s/R_m \int I dx \right] + 1/2 \left(\frac{kR_m{}^2}{z_f}\right)^{-2} \frac{\nabla^2 \sqrt{I}}{\sqrt{I}} \qquad \text{(Eq 4)}$$

and

$$\frac{\partial I}{\partial Z} + \nabla(I\nabla\psi) = -\alpha I \qquad \text{(Eq 5)}$$

subject to

$$\psi(x,\ y,\ o) = \psi_o(x\ y);\ I = e^{-2(x^2 + y^2)}\ .$$

Typically, in atmospheric propagation, N is much greater than unity but R_s/R_m is of the order of unity, and is wavelength independent. The initial phase front distortion $\psi_o(x, y)$ is chosen to maximize the brightness at the focal point.

For severe heating the nonlinear refractive term in the phase equation dominates the diffraction term. This breakpoint, sometimes called N_{crit}, occurs physically when the integrated phase shift caused by heating is equal to or greater than π. This occurs, for an absorption coefficient of 0.2 km^{-1}, R_m = 35 cm, z_f = 2 km and v = 10 M/sec, for a total power in the beam of 150 kw. For this case, analysis by Lincoln Laboratory has shown that phase contouring using a cylindrical mirror plus a coma correction gives nearly a diffraction limited beam. For powers which exceed 150 kw (N > 10 in Figure A-1) the assumption that the beam propagates undistorted in the near field is no longer valid and the atmosphere must be regarded as a thick lens. This calculation must now take into account the change in irradiance in the near field. To our knowledge, calculations of this nature have not yet been performed and the true extent of the improvement is therefore open to speculation.

The basic idea involved with these more complicated calculations (taking into account the change in the irradiance in the near field) is to integrate the ray equations for an arbitrary distribution of ray angles at the mirror surface, determine the effect of a changing irradiance with propagation distance on phase front distortion, and adjust the initial ray angles until the focal spot diameter is minimized. This analysis is straightforward and can, in principle, yield a considerably improved focal point distribution. Based on our experience, improvements of a factor of 10 are very possible if the "thick lens" nature of the atmosphere is appropriately compensated for.

Shown in Figure A-2 is an estimate of the improved brightness expected by phase contouring. This estimate was prepared in the following manner. Phase changes for $1<N\leq 10$ do not cause significant change in the shape of the irradiance in the near field. Thus in this region, the thin lens analysis is appropriate and we can expect nearly diffraction limited results. For $10\leq N\leq 100$, preliminary analysis which compensates for the "thick lens" aspect of atmospheric propagation shows that factors of 10 improvement are very clearly within the state of the art.

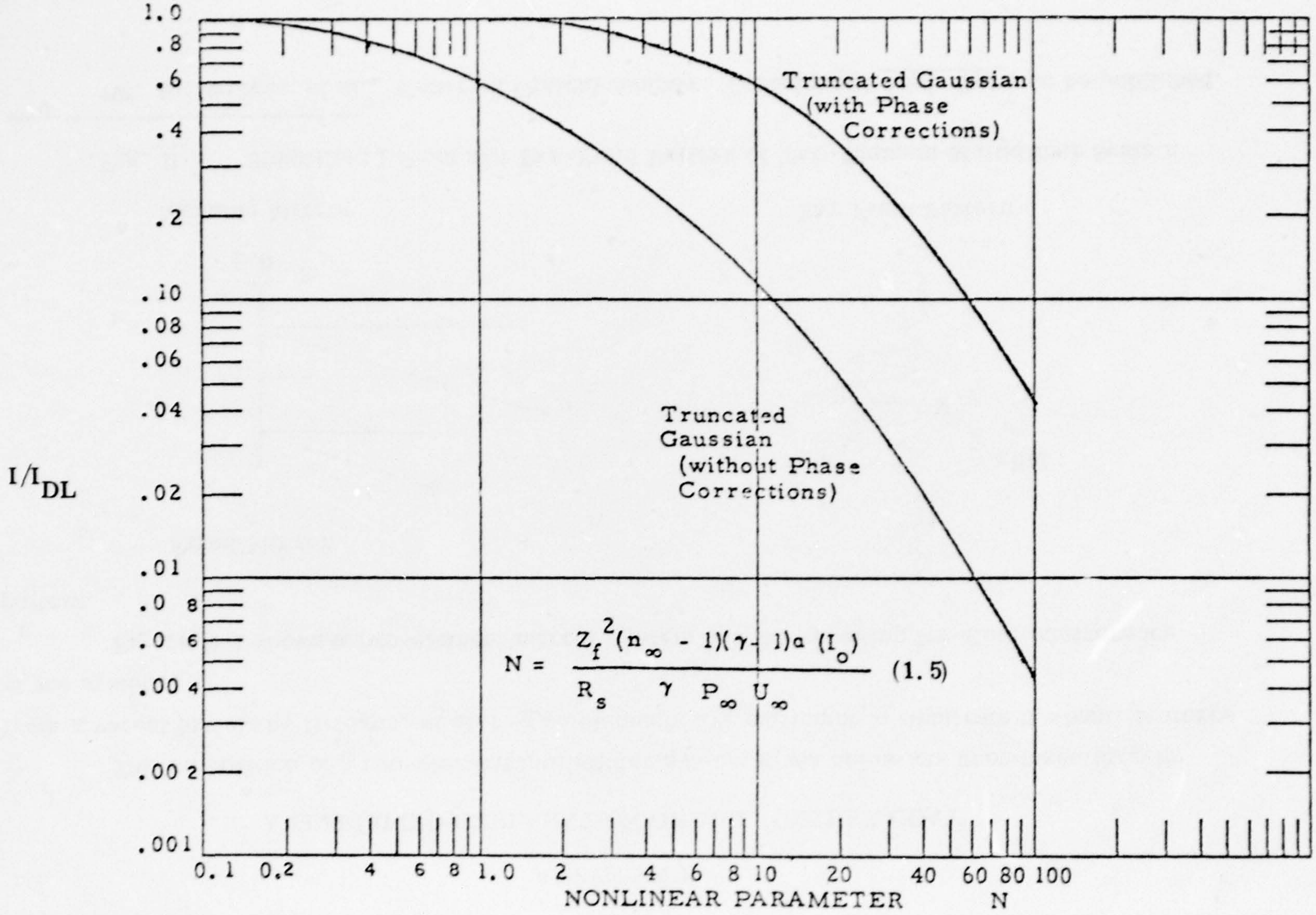


Fig. A-2 Expected Improvement in Focal Point Irradiance due to Phase Contouring (taken from Gebhardt & Smith UARL report number K921004-8)

APPENDIX B

A SIMPLIFIED EXPLANATION OF MULTIDITHER COAT

The explanation of a two-element multidither system given below has been taken largely from a recent article by Bridges, et al.* Two elements are sufficient to illustrate the basic features of the system.

Figure B-1 shows a two-element mirror system and the resulting far-field interference pattern.

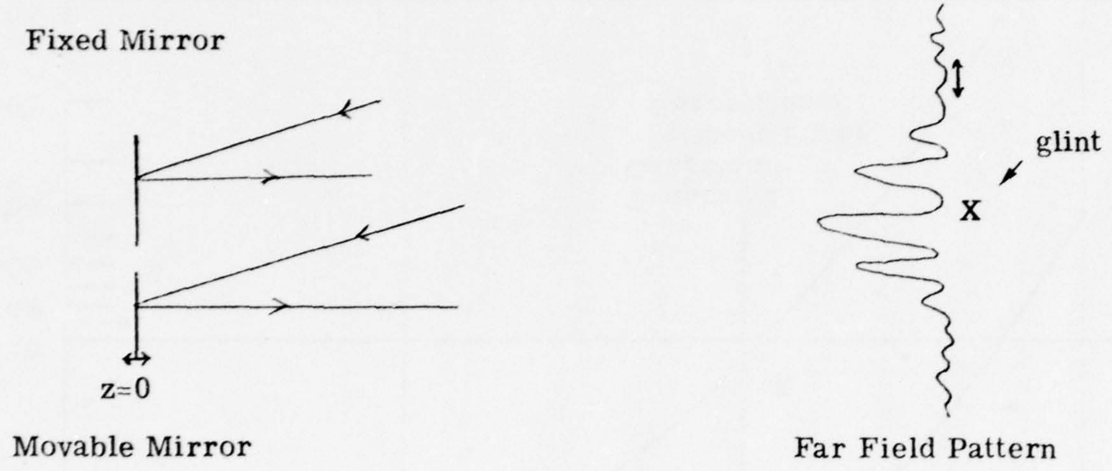


Fig. B-1 Simplified Layout and Far-Field Pattern of Two-Element Multidither System

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*W. B. Bridges, et al.; "Coherent Optical Adaptive Techniques" Appl. Opt., to be published.

The first step is to look at the far-field diffraction pattern of the two mirror segments with both segments held stationary. Assuming a relatively coherent illumination beam, the pattern is the well known two-slit interference pattern sketched at the right side of Figure B-1.

The second step is to move one of the mirrors a small fraction of a wavelength along the optical axis. The displacement of one of the mirrors has the effect of shifting the entire far-field diffraction pattern laterally, i. e., normal to the optical axis. Moving one of the mirrors is therefore a way of scanning the diffraction pattern across a target. If there is a glint on the target within the bounds of the diffraction pattern, the light reflected back to the transmitter will be modulated when the diffraction pattern is shifted. Since there is just one most intense maximum in the diffraction pattern, the movable mirror can be adjusted until the return signal is maximum. The beam is then centered on the glint. This process can be repeated for as many elements and dither frequencies as desired. A feedback system connecting the receiver and transmitter directs the average mirror position.

This system can be adjusted to lock onto a number of different object characteristics. Bright edges, dark holes, dark edges, and the brightest glint in a multiglint field are a few which have been demonstrated.

Although prototype COAT systems have demonstrated excellent atmospheric turbulence correction and promising target tracking capability, there still remain some unresolved questions regarding their ultimate capability.

One question regards the required bandwidth of the detector-feedback system. For the stationary target/severe turbulence case the bandwidth of the detector-feedback system needs to be well above the bandwidth of the temporal disturbances in the transmitted beam path, in particular above the bandwidth of the temporal disturbances which are uncorrelated between beam segments. If this requirement is not met then the detector starts to see a somewhat time averaged far-field interference pattern which would be lower in visibility (i. e., lower S/N) than for the non time averaged case. This may not be a severe requirement since the bandwidth required is ~ 1KHz. The cases of fine tracking a fast moving target and compensation for thermal blooming are more severe and at this time not so well understood quantitatively as is the stationary turbulence case.

A related problem could arise with diatomic lasers which lase at several lines, each line being temporally incoherent with respect to the others. The total far-field interference pattern would have lower visibility than the pattern resulting from one line. This could be circumvented if there were enough intensity at one line to operate the COAT system.

A second, although less important, limitation is the operating range due to the finite speed of light. Since the atmosphere can change at frequencies up to kilohertz, COAT systems begin to degrade for ranges through the sensible atmosphere of more than several tens of kilometers. The photons are simply not fast enough to warn the outgoing wave of what lies ahead. One should note that this degradation with range is gradual in that much of the important variation lies at the lower frequencies. Also there are few paths through the sensible atmosphere which are more than several tens of kilometers long, so this range limitation is not important in practice.

The variable glint structure would seem to be a serious threat to effective adaptive aperture system performance. Any significant change in glint structure could cause the beam to jump from the previously strongest glint to the new one. In principle, such jumping can be suppressed by a phased-array system which offsets the beam. In practice, however, it is not clear that sufficiently precise imaging information will be available.