AERO-OPTICS OVERVIEW

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Introduction

The advent of the laser in 1960 brought with it the revolutionary concept of a radiation transport weapon system. Advantages of this novel system vis-a-vis conventional momentum transport weaponry (e.g., bullets, missiles, etc.) include:

(1) Zero time-of-flight

(2) Large angular coverage (i.e., lasers are low inertia systems)

(3) Meticulous, not mass destruction

Disadvantages of laser weapons, shared to some extent by their more traditional counterparts, include:

(1) Weather constraints - lasers are sometimes dubbed "fair weather friends."

(2) Range limitation - system lethality scales at least as the inverse square of the range.

(3) Countermeasure susceptibility. Lasers generally affect a kill by melting or vaporizing into the target. Sometimes relatively simple, lightweight target alterations (e.g., paint removal, insulation of vulnerable innards, etc.) can dramatically harden them to laser radiation. Laser weapon systems have been proposed for a plethora of military applications covering land to sea to air. Each system has its unique set of advantages and constraints.

All laser weapon systems have these basic components:

• Photon source

• Beam transport system - means to get energy from device to telescope

- Pointing and tracking system

- Environmental factors - the particular milieu through which the energy must propagate.

- Target

Figure 1 depicts this photon odyssey and the effect it can have on far field beam quality and, hence, weapon system lethality. The challenge to the optical engineer is to ferret out the various error sources and to quantify their contributions to overall system performance.

Aero-optics is that portion of the error budget due to interaction of the airborne platform and the atmosphere. These effects manifest themselves both as mirror vibration and optical path phase distortions. Jitter arises from buffetting effects on the aircraft and its laser turret assembly. This same interaction with the surrounding flow field produces boundary layers, shear layers and separated flow regimes as well as potential flow and local shocks. Optical losses from these latter phenomena are due to index of refraction fluctuations within the flow field. In general, the convolution of the above aero-optical effects produces a reduction in far field intensity, or power in the bucket. Understanding these various aero-optical effects, and how each is effected by aircraft performance parameters for a particular laser turret geometry, is the central challenge of aero-optics.

The field of aero-optics has experienced dramatic growth in the last several years. Early flying observers performing "ocular" imaging experiments through aircraft boundary layers saw negligible degradation due to the small apertures involved (pupil diameter is of order 2 millimeters). The first known quantitative observation of aero-optical degradations was Project

Press, a mid-1960's test series which involved a star-imaging shearing interferometer mounted onboard an Air Force KC-135 aircraft. The perplexing discovery was that celestial images observed in clear air at 30-40 KFT altitudes and high subsonic Mach numbers frequently had blurring or image spreads of 5 to 15 microradians, levels frequently exceeding ground observations! Lincoln Laboratory, the principal investigator, attributed this inflight degradation to the aircraft turbulent boundary layer.

Lethality of a laser system is proportional to the amount of energy one can deliver within a given bucket size at some specified range. Two common lethality figures of merit are peak and average intensity, the latter being defined as the power delivered within some bucket of area A,

$$(1) \qquad \bar{I} \quad = \quad \frac{P}{A}$$

Diffraction theory limits the peak intensity deliverable by a perfect laser device and beam control system (sans atmosphere) to

$$(2) \qquad I_p \quad = \quad \frac{K \; P_0 \; D^2}{\lambda^2 \; R^2}$$

With P_0 = laser power output

D = diameter of telescope primary optic

λ = laser wavelength

R = range

K = dependent on laser beam mode and limiting apertures, but having order unity.

This equation provides a first-order prescription for increasing system lethality; the lure of a shorter wavelength system is obvious. Actually, however, nature combines risk with reward. As the wavelength decreases, turbulence and optical train degradations generally grow to partially offset this advantage. A more accurate description of the important physics is:

$$(3) \quad I_p = \frac{P_o}{R^2} \; \frac{1}{(\frac{\lambda}{D}) + \theta_j^2 + \theta_{Bw}^2 + \theta_{Bs}^2} \; \gamma e^{-\frac{4\pi^2}{\lambda^2}(\sigma_{opt}^2 + \sigma_F^2)}$$

With θ_j = System mechanical jitter

θ_{Bw} = Atmospheric beam jitter

θ_{Bs} = Atmospheric beam wander

σ_{opt} = rms phase variance of optics

σ_F = rms phase variance of platform-induced atmospherics

γ = Everything else

The form of this relationship is sketched in figure 2, showing there is an optimal wavelength for system lethality which depends primarily on the degree of system phase aberrations. In the absence of the thermal blooming, this optical wavelenth for propagation is

$$(4) \qquad \lambda^* = 2\sqrt{\pi(\sigma_{opt}^2 + \sigma_F^2)}$$

Description of Aero-Optical Phenomena

The prospect of airborne high energy laser weapons poses a really scintillating challenge. In general, a laser beam must be generated within the aircraft, propagated efficiently to the exit telescope, and then through the aircraft-induced and natural turbulence fields. Such is a veritable photon odyssey. Aero-optics is the study of laser optical degradations

accruing from aircraft-induced flow fields. Figure 3 depicts a high energy laser error budget, showing at each stop the parameters implicit in determining far-field intensity, or system lethality.

A laser beam exiting from a fast-moving aircraft is susceptible to several compressibility effects induced in the surrounding flow field. These losses are due to changes in index of refraction directly related to density fluctuations via the Gladstone-Dale relationship

$$(4) \qquad\qquad n' = G\rho'$$

Where n' = Index of refraction fluctuations

   ρ' = Density fluctuations

   G = Gladstone-Dale constant

Viscous effects manifest themselves as aircraft boundary layers or shear layers which exist near the aircraft surface. These viscous layers are typically fully turbulent with randomly fluctuating air density, and scale sizes of order 10 percent of the thickness of the layer. Because the boundary-layer scale sizes are typically small compared with the laser beam diameter, energy is scattered at wide angles. This leads to a decrease in far-field peak intensity. When these random flows depart the fuselage they become separated flow regions. Because they can present long optical paths for certain aft look angles, these can be the source of severe optical degradations.

The second aero-optical source of loss is inviscid flow fields surrounding the aircraft due to airflow around protuberances such as laser turret

assemblies. These flow fields yield spatially steady density variations which act effectively as an aberrated lens to the beam.

The final aero-optical loss mechanisms are shocks, established whenever local flow exceeds Mach one. For typical cylindrical turret geometries these conditions exist for aircraft Mach numbers in the 0.5 to 0.6 regime. The strong density gradients associated with these shocks generally both refract and disperse the laser beam. The convolution of these effects imposes a near-field phase aberration on the beam with a concomitant reduction in lethality or far-field intensity. The challenge of aero-optics is to quantify this far-field degradation for a particular airborne laser system.

Interaction of a laser beam with a turbulent boundary layer is described in figure 4. The important physical parameters describing the interaction are the unsteady density fluctuations ρ', the propagation direction coherence length ℓ_z associated with the turbules, and the total path length through the disturbance.

In general, the system far-field performance is limited by the telescope diffraction angle

$$(5) \qquad\qquad \theta_D \approx \lambda/D$$

With λ = laser wavelength

         D = telescope diameter

The turbs, on the other hand, scatter radiation at a relative wide angle,

$$(6) \qquad\qquad \theta_\ell = \frac{\lambda}{\ell}$$

The net far-field pattern is a central spot reduced in intensity but having a spot size defined only by the laser and beam transfer optics convoluted

with a turbulence-generated halo. If the beam diameter is large compared with the turbulence coherence length $(D \gg \ell)$, then the reduction in on-axis intensity (Strehl ratio) is approximately

$$(7) \qquad I/I_0 = e^{-K^2 \sigma^2}$$

Where K = wavevector $(2\pi/\lambda)$

σ = rms phase variance

The phase variance can be calculated by integrating through the disturbance along the optical axis

$$(8) \qquad \sigma^2 = 2 G^2 \int_0^L \langle \rho' \rangle^2 \, \ell_z \, dz$$

With G = Gladstone-Dale constant

ρ' = Unsteady density

Armed with these tools one can make an aerodynamic estimate of the Strehl ratio I/I_0 via equations (7) and (8). Then an integrated path optical technique such as a Modulation Transfer Function or a Line Spread Function measurement provides a comparison measurement. Recent experiments on relatively thick (L 30 cm) aircraft boundary layers have produced good correlations between these aerodynamic and optical measurements.

Separated flow is established behind aerodynamic bodies such as wings or turrets or aircraft themselves. The aircraft boundary layer separates from the surface at some point and spreads to form a turbulent wake. This flow is generally fully turbulent, and has scale sizes of the order of the body itself. The total optical degradation through such a disturbance can

also be estimated from equations (7) and (8). Even though the unsteady density fluctuations are usually smaller than those associated with fuselage boundary layers and shear layers, the larger coherence lengths and longer paths for aft look angles more than compensate. In short, aircraft separated flows can act as a major constraint to airborne laser weapon systems.

Potential flow regions are established outside the boundary layer, and occur due to flow around aerodynamic postuberances. The flow in these regions is both inviscid and approximately incompressible. The rudiments of a potential flow field are depicted in figure 5. The density changes through this regime are estimated by using compressibility corrections to the potential flow. This region acts as an aberrated lens with approximate focal length

$$(9) \qquad f = R \frac{\rho_1}{\rho_1 - \rho_0}$$

With   R = radius of curvature of flow

   ρ_1 = characteristic density within flow

   ρ_0 = free-stream density

The potential flow field of a one meter diameter hemispherically capped circular cylinder has been calculated numerically for a range of high subsonic Mach numbers. The density variations in the flow were inferred from compressibility corrections applied to the potential flow model. The optical effects of this flow field were found to produce primarily a defocus, with

secondary astigmatic effects. The effective focal length of this negative aerodynamic lens was a few kilometers. Though the dominant effect of the flow field was defocusing, which is correctable via the system telescope, there is no reason to believe that higher-order aberrations will be negligible for different laser turret geometries.

A shock wave is formed whenever local flow velocities around turrets exceed Mach one. This can occur for common geometries at relatively low aircraft Mach numbers (e.g., cylinder turret M $\geq$0.55). A laser beam traversing this shock will generally be both refracted and dispersed (the reflected component at the shock interface is negligible). Maximum refractive angles are typically of order one milliradian, when dispersion depends on details of the shock geometry. Because optical refraction is essentially wavelength independent, if the high energy laser tracker shares the optical axis then shock-induced beam deflection will not be a source of optical degradation.

Aerodynamic-induced beam jitter is generally a major source of airborne laser degradation. This jitter arises from an interaction of aerodynamic structures with the natural turbulent medium through which it is flying. The aerodynamic buffeting manifests itself as optical train mechanical jitter; the far-field result is an increased effective spot size on target with a concomitant reduction in system lethality.

Figure 6 depicts the aero-loading problem. This aerodynamic-induced jitter spectrum has two major components. Energy coupled into the airframe and laser turret assembly causes the whole structure to respond, with a resultant (indirect) response of the optics. These components have characteristic frequencies

$$\nu_0 \sim V/d$$

With   V = aircraft velocity relative to airstream

      d = size of protuberance

Too, in the event of a windowless turret, the telescope can be loaded directly. These unsteady pressures produce both a jitter and a torque. Both these phenomena tax the ability of the beam control system to hold the spot on the target.

Aerodynamic-induced jitter is a primary source of far field degradation for today's 10.6μm airborne high energy laser (HEL) systems. Moreover, as shorter wavelength HEL airborne systems emerge, enabling one presumably to engage harder target at longer ranges, the premier challenge for beam control will be to keep net system jitter less than or of the order of the intrinsic diffraction angle; i.e.,

$$\theta_j \ \lesssim \ \frac{\lambda}{D}$$

To date little has been done to aerodynamically ameliorate turret buffeting. Fairing assemblies offer some relief, as they offer a degree of insulation against the mainflow. However, these ploys generally limit the laser field of view. Aerodynamic flow control is another possiblity, as by suctioning or diverting. Future wind-tunnel efforts should plumb the efficiency of these techniques. Most of the investments to date have been toward measuring the torque and bandwidth capabilities of trackers to compensate for aero-loading. Clearly a combination of techniques is needed to meet and solve the general problem.

The field of aero-optics has matured dramatically over the past half-decade. This monograph hopefully describes this maturation.

Early experiments were conducted in wind tunnels, which provided a cost-effective simulation tool for some airborne aero-optical phenomena as well as a development laboratory for essential aerodynamic and optical instrumentation. In spite of spiraling operation costs, wind tunnels are a much more benign and efficient laboratory for research than are airborne platforms. Large wind-tunnel tests mainly broached the aero-loading problem. As we shall see, these experiments found great success in simulating airborne unsteady pressure fields (i.e., the driving function) but less success in simulating the vehicle response (i.e., jitter) to this forcing function.

Similarly, techniques to infer unsteady density and correlation lengths within boundary layers and shear layers were developed in Air Force sponsored wind-tunnel experiments. Corresponding nascent optical techniques yielded corroborative integrated path measurements of optical degradation. A recent airborne flight test program plumbed aircraft turbulent boundary layer/shear layer degradations via both aerodynamic and optical instrumentation. Good correlations were shown between these two independent techniques of inferring optical Strehl loss I/I_o.

Little definitive work has been done on laser propagation through separated flows, though the investigative techniques are similar to those developed for boundary layers and shear layers. The importance of understanding separated flow effects for rear-looking laser missions cannot be overstressed.

One article describes a wind-tunnel investigation of laser potential flow-induced degradation. Though these effects have a frequency bandwidth of only a few hertz, the potential laser optical degradation is significant. No

known work has been done on the effect of aircraft-induced shocks on airborne laser systems.

Flight tests are clearly essential as a "proof of principle." Only via flying laboratory experiments can one examine real world random flows, potential flows and aero-loading effects essential to an evaluation of airborne high energy laser weapon potential.

Though the consensus status of aero-optics has reached an impressive quantum level of maturity, eminent challenges remain. These include (1) aero-optical design optimization of laser turret systems, or, turretology. As shorter wavelength laser systems emerge, the contributions of turret-induced jitter and optical degradation to the system error budget will grow. Techniques such as flow separation control, potential flow tailoring, and unsteady pressure amelioration must be nurtured in wind tunnels and brought to airborne testing fruition over the next decade.

(2) Adaptive optic system development. Residual aero-optical degradations may be amenable to advanced beam control techniques. In particular, several of the low bandwidth phenomena such as potential flow, shocks, and certain aspects of wake turbulence effects may be correctable via adaptive optic technology.

(3) Generalized analyses of aero-optical degradations must be developed. The majority of experiments accomplished to date have examined only beam propagation normal to relatively simple shear layers or boundary layers. Furthermore, laser turret geometries have generally been rudimentary. Certainly some experiments with more interesting configurations must be accomplished. Analytical techniques must be developed to extrapolate these results to more generalized aircraft turret configurations. Included should

be the ability to handle the observed inhomogenious, anisotropic random flow density fluctuations.

The generalized challenge to laser turret optimization can be sketched as follows. First a mission profile is defined, which sets a Mach number regime, field of view requirements and a laser telescope diameter. A useful aero-optical figure of merit is then:

$$\gamma_i = \frac{e^{-\phi_i^2}}{(\lambda/D)^2 + \theta_i^2}$$

Where ϕ_i = optical phase variance associated with the 1th set of mission parameters

    θ_i = aero-optical jitter associated with i[th] mission point

The objective then is to design a turret which maximizes the various γ_i subject, of course, to the condition that aircraft performance must be preserved!
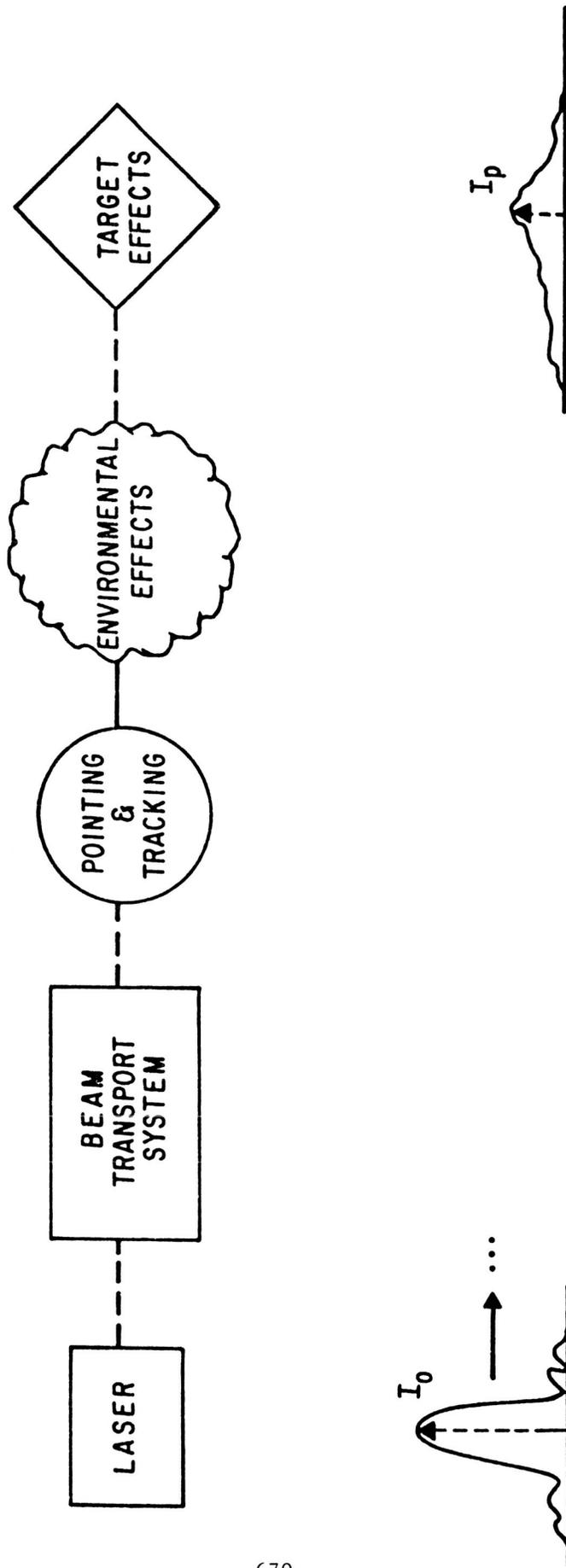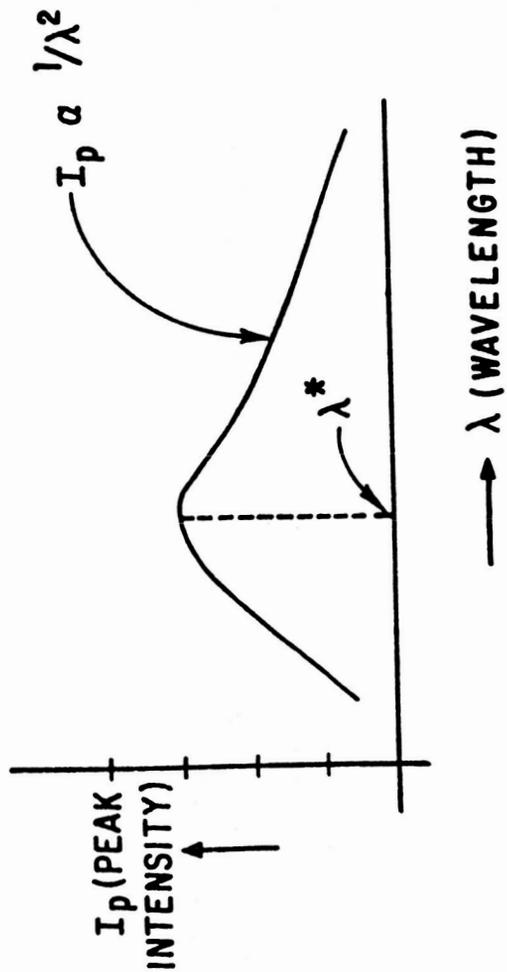
Fig. 1. Elements of Laser Weapon System.

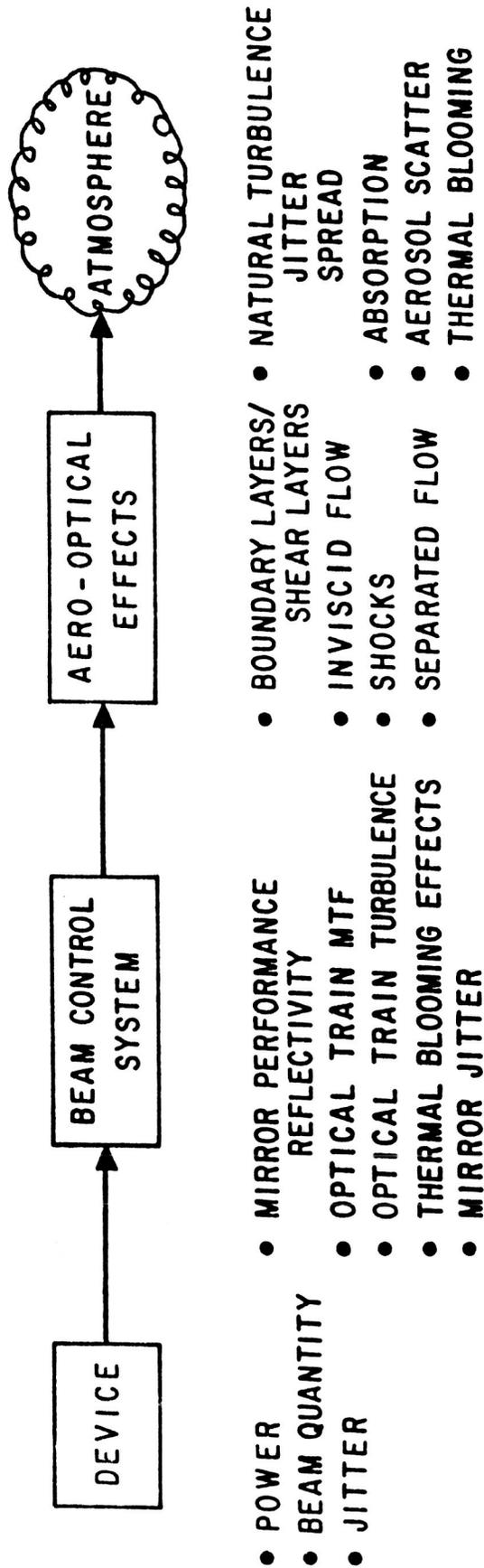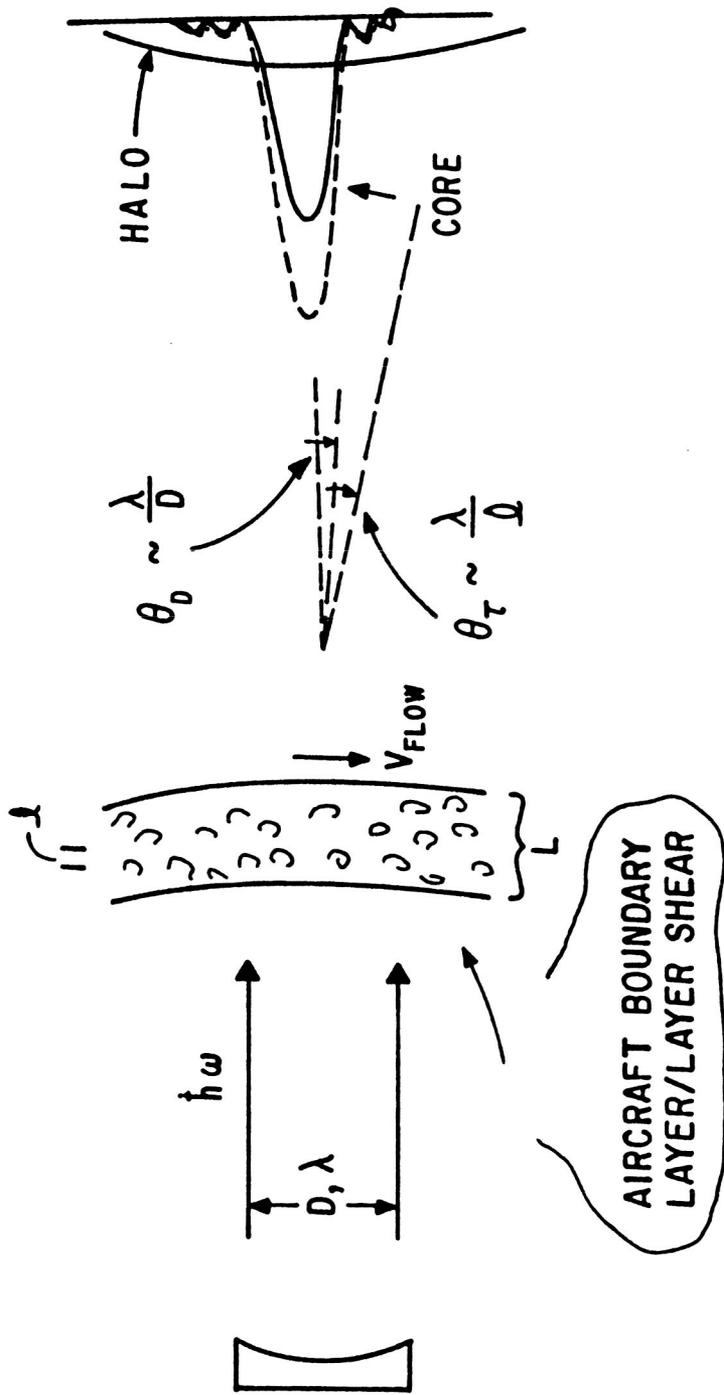Fig. 2. Wavelength Scaling of Laser System Lethality.

Fig. 3 Error Budget.

HALO

CORE

$\theta_D \sim \dfrac{\lambda}{D}$

$\theta_\tau \sim \dfrac{\lambda}{\ell}$

V_{FLOW}

$\hbar\omega$

D, λ

L

ℓ

AIRCRAFT BOUNDARY
LAYER/LAYER SHEAR

$\theta_D \sim \dfrac{\lambda}{D}$, D = TELESCOPE DIAMETER

$\theta_T \sim \dfrac{\lambda}{\ell}$, ℓ = TURBULENCE SCALE

$I/I_0 \sim e^{-k^2\sigma^2}$ $\quad (D/\ell \gtrsim 5)$

$k = 2\pi/\lambda$

$\sigma^2 = 2G^2 \displaystyle\int_0^L <\rho'>^2 \ell_z \, d_z$

- SYSTEM DIFFRACTION ANGLE

- TURBULENCE SCATTER ANGLE

- BOUNDARY LAYER-INDUCED
  STREHL LOSS

Fig. 4   Interaction of Laser Beam with Aircraft Random Flow Regions.

FREE STREAM

ρ_0

$\hbar\omega$

ρ_1

LASER TURRET

$\hbar\omega$
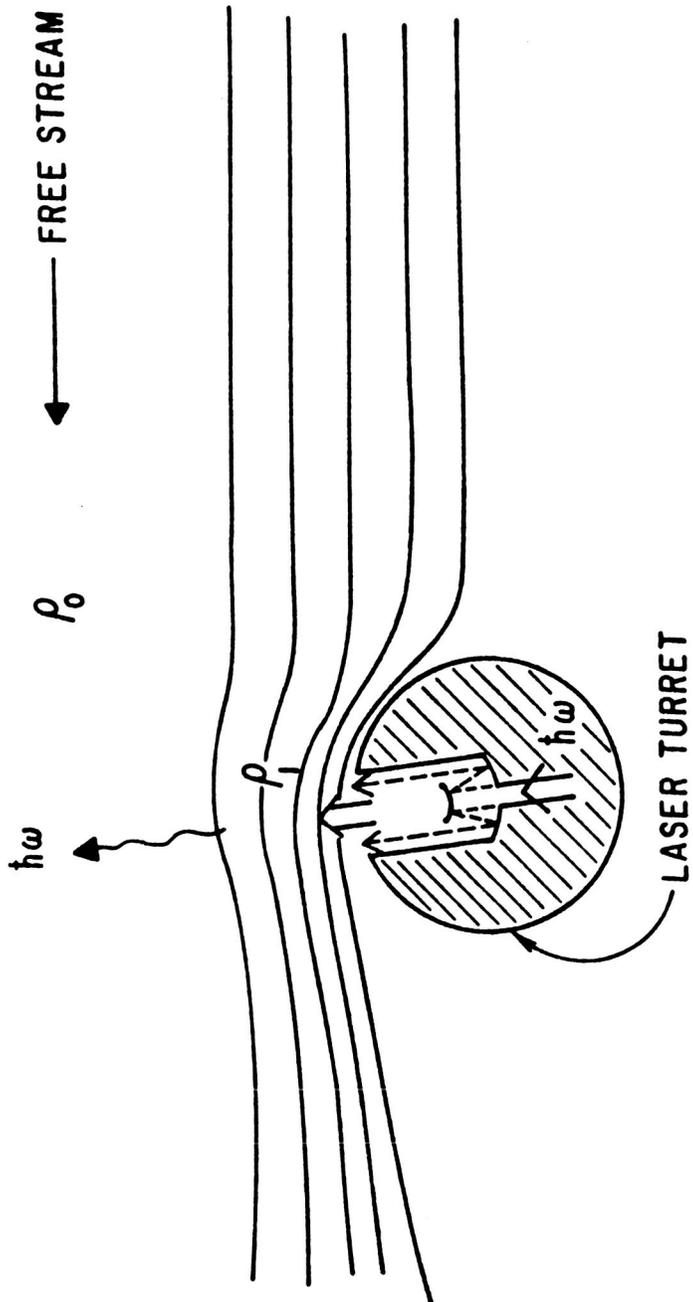
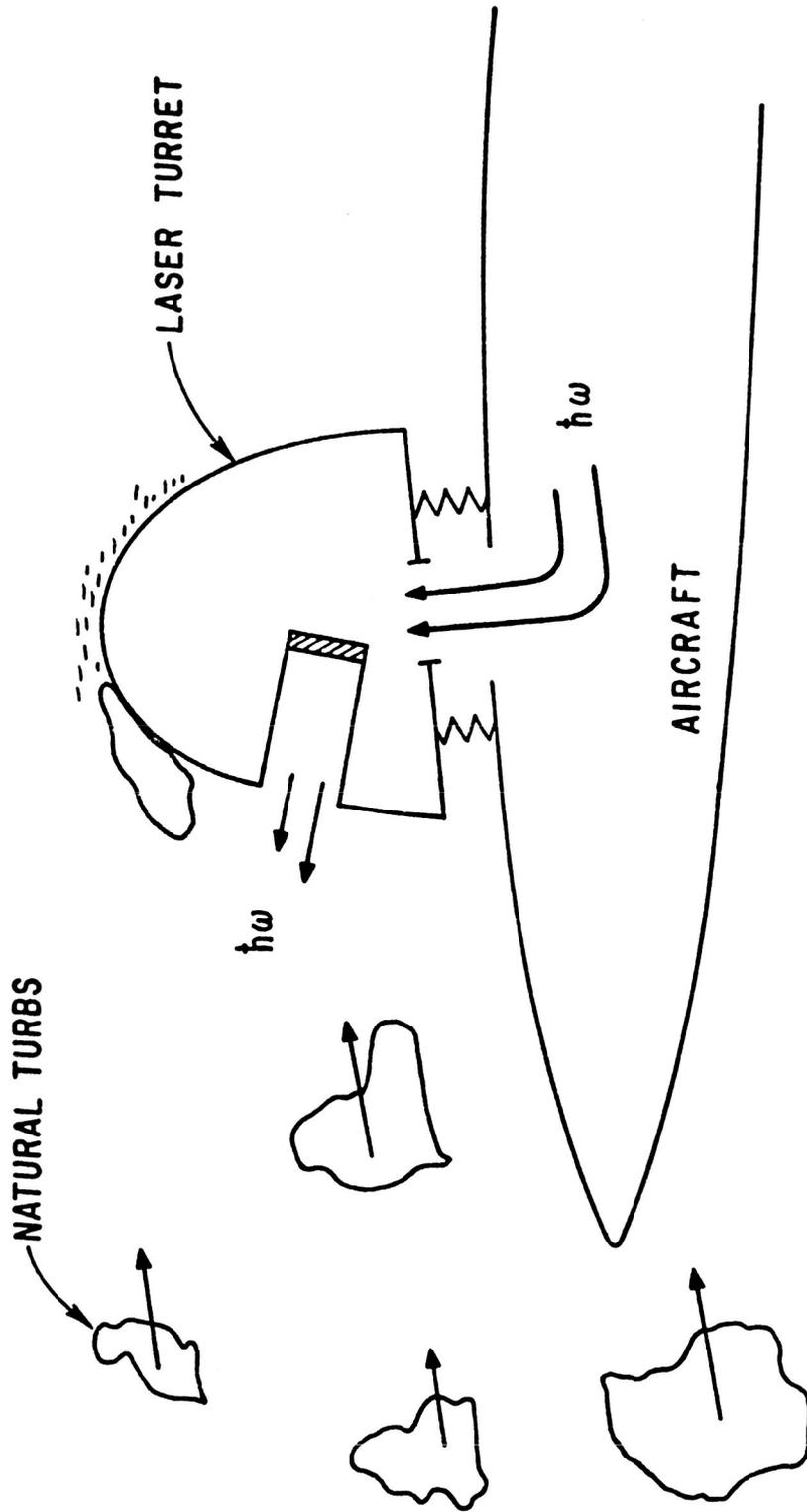R = CURVATURE OF FLOW

Fig. 5   Interaction of Laser Beam with Aircraft Potential Flow Field.

Fig. 6 Aerodynamic Loading Phenomena.

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