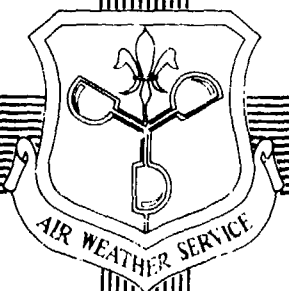


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ATMOSPHERIC SENSITIVITIES OF HIGH ENERGY LASERS

Thomas H. Pries, Lt Col, USAFR

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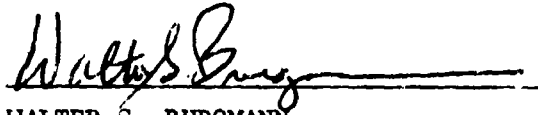
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TABLE OF CONTENTS

	Page
INTRODUCTION.	1
HIGH ENERGY LASER SYSTEMS	1
ATMOSPHERIC SENSITIVITIES	1
LINEAR EFFECTS.	2
Absorption and Scattering	2
Gas Effects	3
Aerosol Effects	4
Clouds.	4
Precipitation	5
Battlefield-Induced Contaminants.	5
Optical Turbulence.	6
NONLINEAR EFFECTS	11
Thermal Effects	11
Other Nonlinear Effects	12
CONCLUSIONS	12
REFERENCES	13

LIST OF ILLUSTRATIONS

Figure 1	Atmospheric Effects on HEL Beam Propagation	2
Figure 2	Effects of Refractive Index Variations.	6
Figure 3	Effects of Eddies on Beam Propagation	7
	a. Wander Due to Eddies Larger than Beam Diameter	
	b. Spread Due to Eddies Smaller than Beam Diameter	
	c. Degradation Due to Scintillation	
Figure 4	Average Optical Turbulence Taken Over the Desert.	8
Figure 5	Average Daytime Optical Turbulence as a Function of Height.	9
Figure 6	Vertical Path Modulation Transfer Function.	10
Figure 7	Thermal Blooming Intensity Change With Time	11

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ATMOSPHERIC SENSITIVITIES OF HIGH ENERGY LASERS

INTRODUCTION

The United States has a large directed-energy technology program which includes high energy lasers (HEL), charged-particle beams and high power microwave technology. Of these, the high energy laser technology is most advanced. High energy laser beams, both continuous wave (CW) and repetitively pulsed (RP) are propagation limited in the atmosphere. In general, the atmosphere attenuates and defocuses the laser beam which reduces the energy density on a target. The significance of the various atmospheric effects depends upon the type of laser and the scenario to which it is applied; therefore, the individual atmospheric parameters must be considered as a part of a laser-atmosphere-target system. It can be misleading to evaluate any component separately. The purpose of this note is to identify the sensitivities of HEL propagation to atmospheric effects in preparation for operational HEL systems.

HIGH ENERGY LASER SYSTEMS (HELs)

Proposed HEL weapons systems consist of a transmitter to propagate HEL radiation to a target and of various subsystems (e.g., television, imaging infrared, search and detection radar, and tracking and fire control radar) to detect, acquire, and point and track the target. Although each subsystem has its unique sensitivities, only weather sensitivities associated with the transmission of HEL radiation will be addressed. Many of the weather sensitivities of the other devices are discussed in the AWS Electro-Optical Handbook.¹

HEL propagation has been demonstrated at several wavelengths using gas dynamic lasers (9.3 μm , 9.6 μm , and 10.6 μm), electric discharge lasers (4.8-6.2 μm , 10.6 μm) and chemical lasers (2.5-3.0 μm , 3.7-4.1 μm). Many wavelength dependent tradeoffs as well as temporal modes of operation (e.g., CW or RP) are possible depending upon anticipated atmospheric propagation characteristics and the relative importance of each wavelength dependent sensitivity. Two candidates at this time are the carbon dioxide (CO_2) and deuterium fluoride (DF) systems, and the gas dynamic and chemical lasers, respectively.

All three services have HEL programs, the Air Force having the largest. To centralize HEL technology and avoid unnecessary duplication, a National High Energy Laser Test Range (NHELTR) is being established at the White Sands Missile Range, NM, for proposed weapons applications demonstrations. The Army Atmospheric Sciences Laboratory has been designated as the lead laboratory to establish data bases for atmospheric characterization, to develop predictive techniques for mission decisions and the diffusion and transport of effluents, to develop tailored measurement systems, and to perform operational test support.

ATMOSPHERIC SENSITIVITIES

An HEL beam propagating through the atmosphere suffers all the linear effects that a low energy beam would encounter, while creating nonlinear effects of its own by changing the atmosphere through

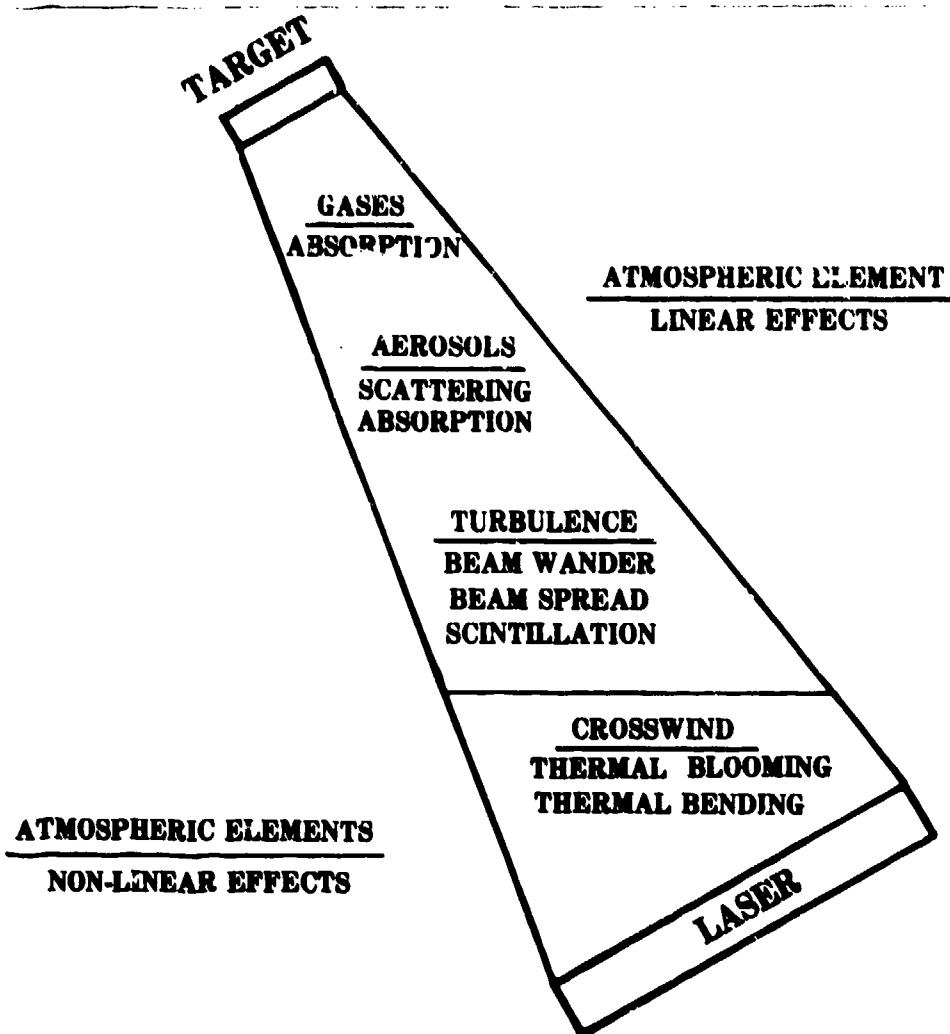


Figure 1. Atmospheric Effects on HEL Beam Propagation.

which it is propagating. An understanding of the various linear and nonlinear atmospheric effects on HEL propagation is necessary before any assessment of the impact of the myriad of "real-world" weather conditions on HEL operations can be made. Linear effects include attenuation due to molecular and aerosol absorption and scattering, and beam spreading, wander, and distortion due to optical turbulence. Nonlinear effects include thermal blooming from atmospheric absorption of beam energy and attenuation resulting from gas breakdown at high optical intensities² (Figure 1).

LINEAR EFFECTS

Absorption and Scattering

Energy in a laser beam is attenuated by both absorption and scattering effects due to natural atmospheric gases and aerosols. This can be greatly complicated by the addition of dust, smoke, precipitation, fog, clouds, and battlefield-induced contaminants. Even though HEL wavelengths are

chosen in regions of low atmospheric absorption, appreciable atmospheric absorption can and does occur depending upon the wavelength. The concentration of each absorber varies both in time and space. The sum of the scattering and absorption coefficients is called the extinction coefficient, κ . The transmittance, τ , is therefore given by

$$\tau = e^{-\kappa x}$$

in which $\kappa = \kappa_a + \kappa_s$, where κ_a = absorption coefficient, κ_s = scattering coefficient, and x = pathlength in the atmosphere. The scattering of laser radiation may be classified as either Rayleigh (for particle diameters \ll Wavelength) or Mie (for larger diameter particles).

Absorption of HEL radiation also leads to thermal blooming, i.e., a heating of the air that spreads, distorts, and bends the beam which is discussed in the section "Nonlinear Effects."

Gas Effects. Molecular absorption depends on the concentration of the absorbing gases, the ambient temperature and pressure, and the path length. An investigation of HEL sensitivities to gaseous absorption was made by Flowers, et al.³ A summary of significant absorption by maximum expected quantities of atmospheric gases for DF (at 3.8 μm) and CO₂ (at 10.6 μm) lasers is shown in Table 1. Optical depth = $\int_0^L \kappa_a \rho dx$ from Beers law where κ_a represents the absorption coefficient, ρ represents the density of the absorbing medium, and L the pathlength. A major stumbling block to obtaining useable modeling predictions for HELS is lack of an accurate data base for molecular absorption, particularly the water vapor continuum absorption. Pressure dependence of the continuum

Table 1. Significant Absorption by Atmospheric Gases on Propagation of Certain Lasers (from Flowers et al.³).

<u>Gases/Laser</u>	<u>DF</u>	<u>CO₂</u>
H ₂ O	X	XXX
H ₂ O Continuum	XX	XXX
CO ₂	X	XX
O ₃	---	X
CH ₄	X	--
HDO	X	--
N ₂ Continuum	XX	--
N ₂ O	XXX	--

where XXX \geq 0.2 km⁻¹ effect

XX = 0.1 km⁻¹ effect

X = 0.01 km⁻¹ effect

-- = no effect

absorption, which was measured by Watkins, et al.,⁴ can be used to infer contributions from both absorption-line-far wing and aggregate-water-molecule (i.e., water dimers or clusters) type absorptions. The absorption depends not only on the pressure or amount of water vapor present but also on the pressure of the other gases. A measure of the effect of the foreign gases on the absorption is the foreign-gas-broadening to self-broadening ratio. It was found that the average value of this ratio is 0.011 in the 3.5-4 μm region, frequency dependent, and an order of magnitude smaller than the value formerly used in models which were derived from measurements at higher temperatures. White⁵ discusses difficulties with physical models for the water vapor absorption (continuum or anomalous) in the 3-5 μm and 8-12 μm regions. Before an accurate assessment can be made, temperature dependence of the models must be determined.

Aerosol Effects. Aerosol absorption depends on the particulate size distribution, number density, chemical composition, and pathlength. Mie scattering theory can be used to calculate the scattering and absorption properties of an aerosol particle using the complex index of refraction. The theory assumes that the particle is spherical in shape. Radiative transfer theory uses the results of the Mie calculations to compute the transfer of electromagnetic radiation through a medium containing an ensemble of aerosol particles. In very turbid atmospheres where multiple scattering occurs the equations become very complex and can often not be solved analytically. It is then necessary to solve the equations numerically or to use Monte Carlo methods to estimate the transfer of radiation. In one such study, Bucher⁶ found that the effective extinction of a beam of light was less than that indicated by the scattering coefficient. This was due to the forward scattering of some of the energy which allowed it to remain in the beam.

A comprehensive study was made by Jennings et al.,⁷ using Mie theory to determine the effect of realistic variations in values of real and imaginary parts of the complex index of refraction on volume extinction and absorption coefficients. Generally, it was found that absorption is less dependent on size distribution than is extinction and is not linear with the imaginary index, especially for broad particle distributions. The complications caused by the presence of irregular particles or particles of mixed composition on interpretation of measurements is discussed in a later article by Jennings, et al.⁸ Scattering losses are minimal for particles smaller than the radiation wavelength.

In the past absorption was always inferred from measurement of extinction and scattering. Recently Bruce and Pinnick⁹ have made direct measurements of aerosol absorption using a CW laser spectrophone. The spectrophone holds promise for making these measurements more directly, bypassing altogether measurements of particle shape, size, and complex refractive index. Absorption results obtained this way compare well with theory.

In absence of clouds and precipitation, the total aerosol extinction tends to be comparable to or larger than the molecular absorption at 3.8 μm , while at 10.6 μm it is almost always smaller than the molecular absorption.

Clouds. The propagation of HEL radiation through clouds will probably be limited to thin clouds and involves "boring holes" through the cloud by vaporizing water droplets and ice particles in order to illuminate targets within or beyond the clouds. The heated hydrosols will evaporate and

conduct heat to the atmosphere. Initial size distribution information and complete optical characterization (i.e., type and shapes of the particles and the complex index of refraction) are required to determine the rate of conduction and evaporation/vaporization of the particles and the scattering losses. Any relative movement of the HEL beam through the cloud beam due to beam slewing (rotation), cloud translation, cloud microdynamic motions, etc., introduce even more processes into modeling HEL propagation in clouds.

Precipitation. The attenuation and scattering of laser beams by rain, fog, and snow were calculated and measured at 0.63, 3.5, and 10.6 μm by Chu and Hogg¹⁰. It was concluded that prediction of attenuation of laser beams by precipitation in the atmosphere is hampered by the uncertainty of particle size distribution. However, they found that the attenuation by rain decreases slowly from millimeter to visible wavelengths primarily because of strong forward scattering by raindrops in the visible region.

While attenuation by fog can be much greater than that of rain (particularly at visible wavelengths), Jiusto¹¹ recognizes that fog properties vary considerably from one geographic area to another, and also at a given location depending upon numerous microphysical to synoptic scale conditions. The extinction (or scattering) coefficient can vary over three orders of magnitude. Pinnick et al.,¹² analyzed vertical measurements of fog and haze taken in West Germany during wintertime. It was found that extinction was approximately proportional of $1/\lambda$ for haze but nearly independent for fog. There exists a size-distribution-independent linear relationship between particle extinction coefficient and liquid water content at 10 μm . Pinnick et al.,¹³ verified a linear relation, independent of the form of the size distribution, between extinction at 11 μm and liquid water content of fog within a factor of 2 for different fog and haze distributions under a variety of meteorological conditions.

According to Mason¹⁴ the major effect of snowfall on propagation in the visible and infrared regions is scattering. The variety of snow types and the presence of fog during snowfall complicates description of the attenuation. The effects on laser propagation by snow can be described as a function of either light attenuation or of visibility. Both methods are discussed by Mason who concludes that attenuation will be greater when snow is drier (colder).

Detailed line codes such as by McClatchey et al.,¹⁵ have been formulated to predict transmission properties, but for field use transmission must be related to meteorological parameters which can be observed on the spot. Mason and Hoidale¹⁶ assessed the utility of visibility as an indicator of transmittance in the infrared based on scattering effect only. Estimations using models depicting haze, fog, smoke, and dust showed that visibility was not a very reliable estimator.

Battlefield-Induced Contaminants. Tests like Graf I and II in Grafenwoehr, FRG and Dusty Infrared Tests (DIRT I and II) at the White Sands Missile Range, NM were designed to assess battlefield obscuration at visible, infrared, and millimeter wavelengths. Only preliminary results are available but indications are that tactical-size explosions can seriously obscure infrared propagation for periods of several minutes.¹⁷

Optical Turbulence

Refractive index fluctuations in the atmosphere lead to such propagation phenomena as beam spread, beam wander, and beam distortion. These fluctuations are primarily short duration small-scale temperature fluctuations or eddies which cause optical turbulence. Optical turbulence causes objects viewed through a telescope to move, distant lights and stars to twinkle, and objects viewed over hot asphalt surfaces in the summertime to shimmer. The primary measure of refractive index fluctuations is through the refractive index structure coefficient, C_n^2 , which Tatarski¹⁸ defined by

$$\overline{[N(\vec{r}_1) - N(\vec{r}_2)]^2} = C_n^2 r^{2/3}$$

where N is the index of refraction and r is the scalar separation distance between the position vectors \vec{r}_1 and \vec{r}_2 . C_n^2 can be measured with fast response spatial temperature sensors or optical scintillometers. The effect of refractive index variations is shown in Figure 2 where part of a coherent laser beam encounters a warm eddy and is refracted towards the cooler or more dense medium resulting in phase and amplitude distortions of the beam. The temperature eddies or refractive index fluctuations act as an optical lens suspended in the atmosphere causing light rays to converge or diverge with constructive and destructive interference patterns. Figure 3a illustrates that a beam can be totally deflected off target or caused to wander by eddy sizes larger than the diameter of the beam. Figure 3b shows how a beam spreads and scintillates when the eddy sizes are smaller than the beam diameter depending upon the random arrangement of the eddies. Figure 3c illustrates that the power density of a beam can be degraded by beam spread and scintillation. A power density profile is depicted at the right. Average measurements of C_n^2 at the 8-m level over a 2-week period at White Sands Missile Range, NM, are shown in Figure 4.¹⁹ Minima can be observed at sunrise and sunset. Strong turbulence, as defined by Gebhardt² as $C_n^2 \geq 10^{-14} \text{ m}^{-2/3}$, which can severely degrade the HEL beam, is prevalent during the daytime and sometimes at night. During the daytime, C_n^2 decreases with height on the average to the $-4/3$ power in the lower half of the convective boundary layer as shown in Figure 5. However, the height of the boundary layer can change from day to day and large horizontal variations in C_n^2 can be present as shown by the standard deviation at the 10-m and 100-m levels. These factors can cause an individual profile to vary markedly from the mean

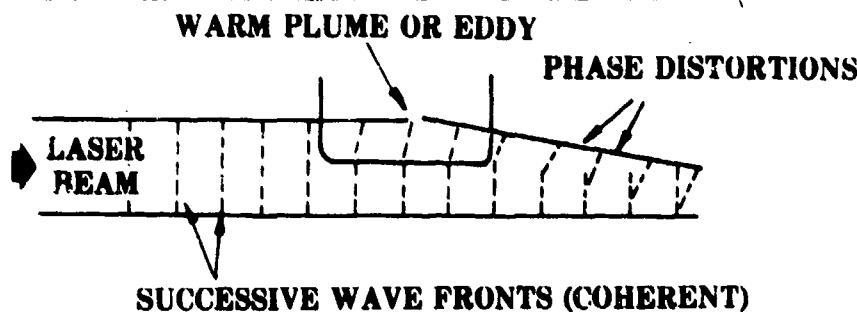


Figure 2. Effect of Refractive Index Variations.

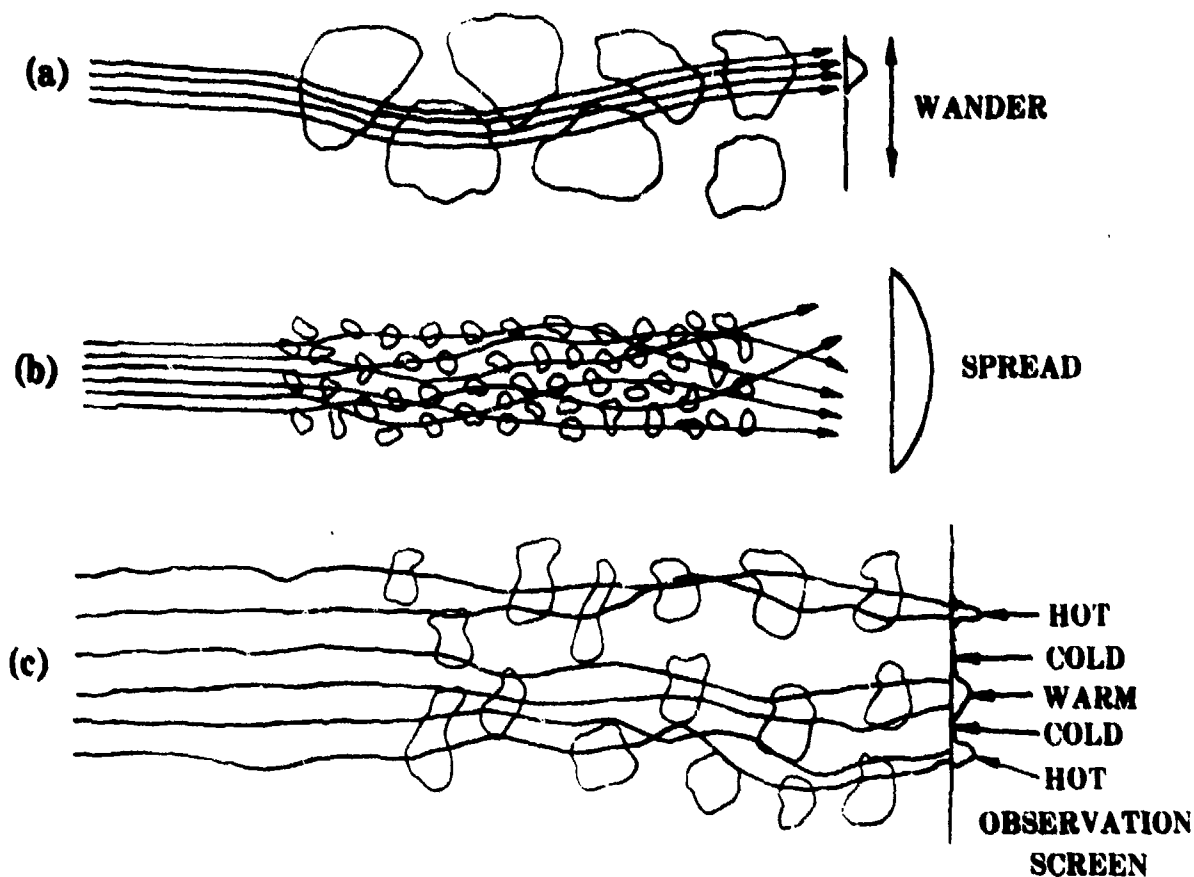


Figure 3. Effects of Eddies on Beam Propagation.

- a. Wander Due to Eddies Larger than Beam Diameter.
- b. Spread Due to Eddies Smaller than Beam Diameter.
- c. Degradation Due to Scintillation.

behavior shown. Walters et al.,²⁰ measured the integrated path modulation transfer function (MTF) (which quantifies the average propagation quality of the atmosphere) by using stars as point sources. Their measurements have shown a diurnal variation (Figure 6) with opposite behavior to C_n^2 shown in Figure 4. The transverse coherence length, r_0 , is a measure of the ability of the atmosphere to maintain a tightly focused beam and may be interpreted as an effective aperture size. The figure shows that the best propagation periods would be at sunrise and sunset. A model at Van Zandt²¹ predicting C_n^2 above the surface boundary layer from radiosonde flights is being evaluated. Some of the effects of optical turbulence on the HEL can be compensated for by using adaptive optics²² to instantly compensate for phase distortions.

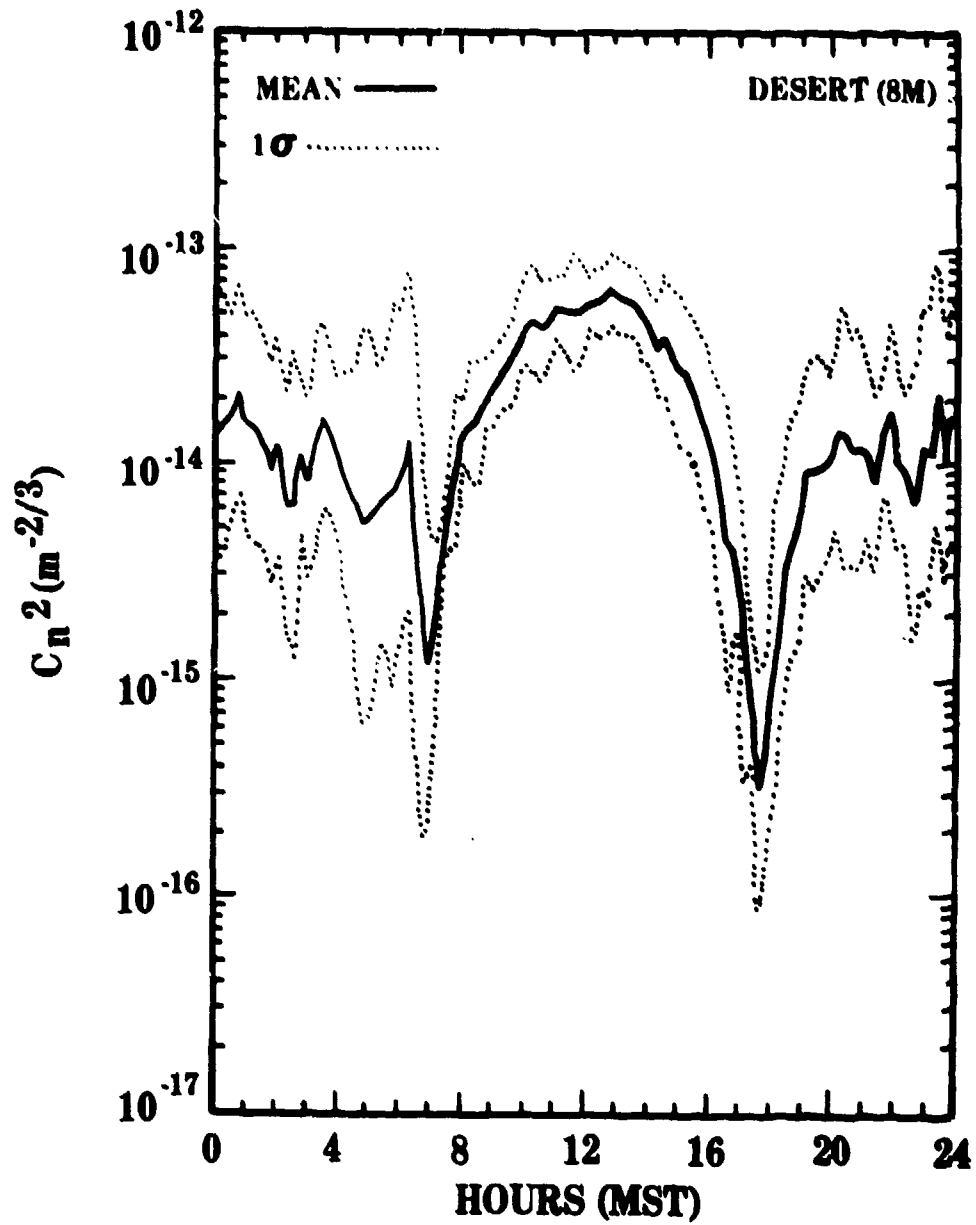


Figure 4. Average Optical Turbulence Taken Over the Desert (one standard deviation added).

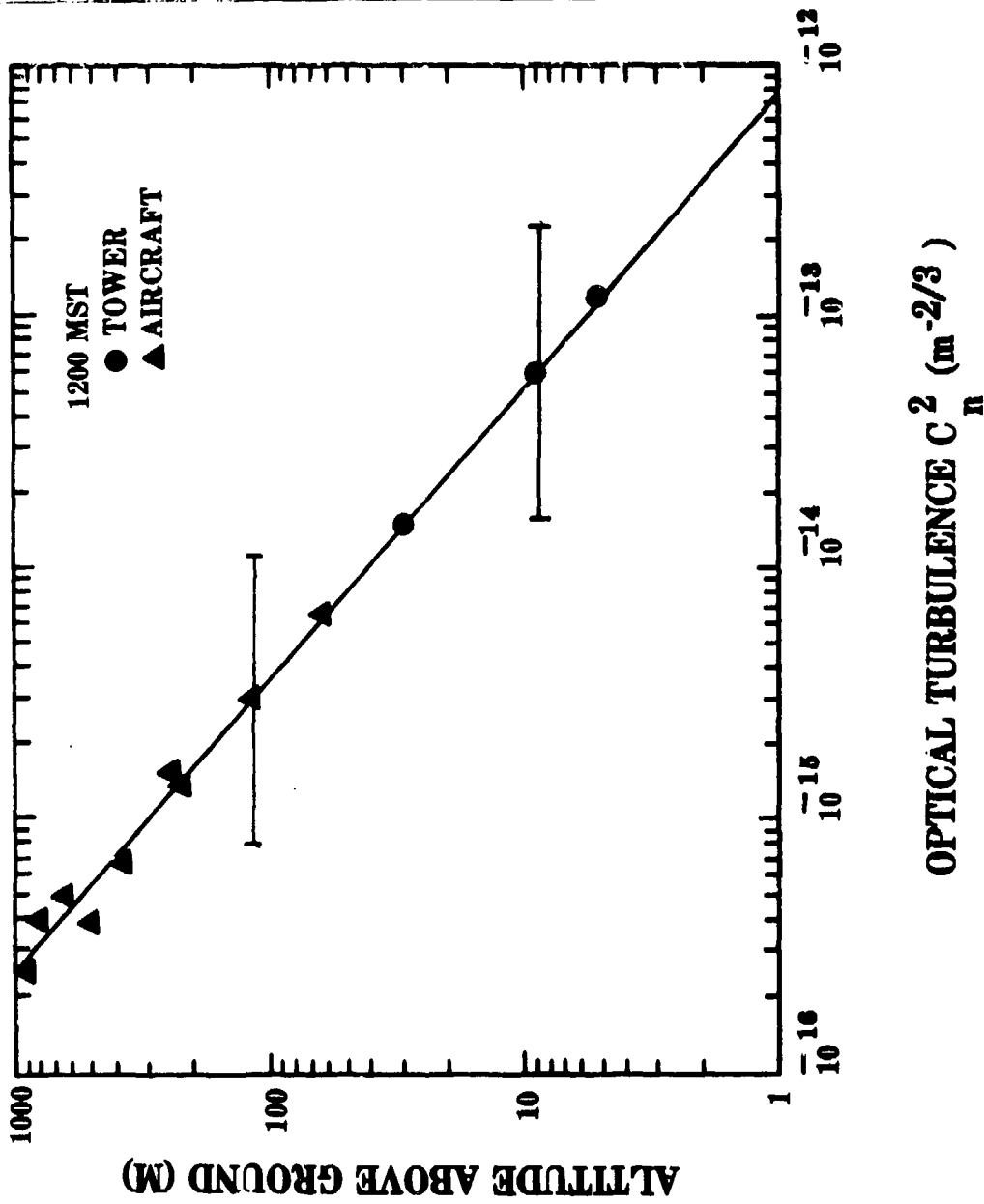


Figure 5. Average Daytime Optical Turbulence (C_n^2) as a Function of Height (one standard deviation shown at the 10-m and 100-m levels).

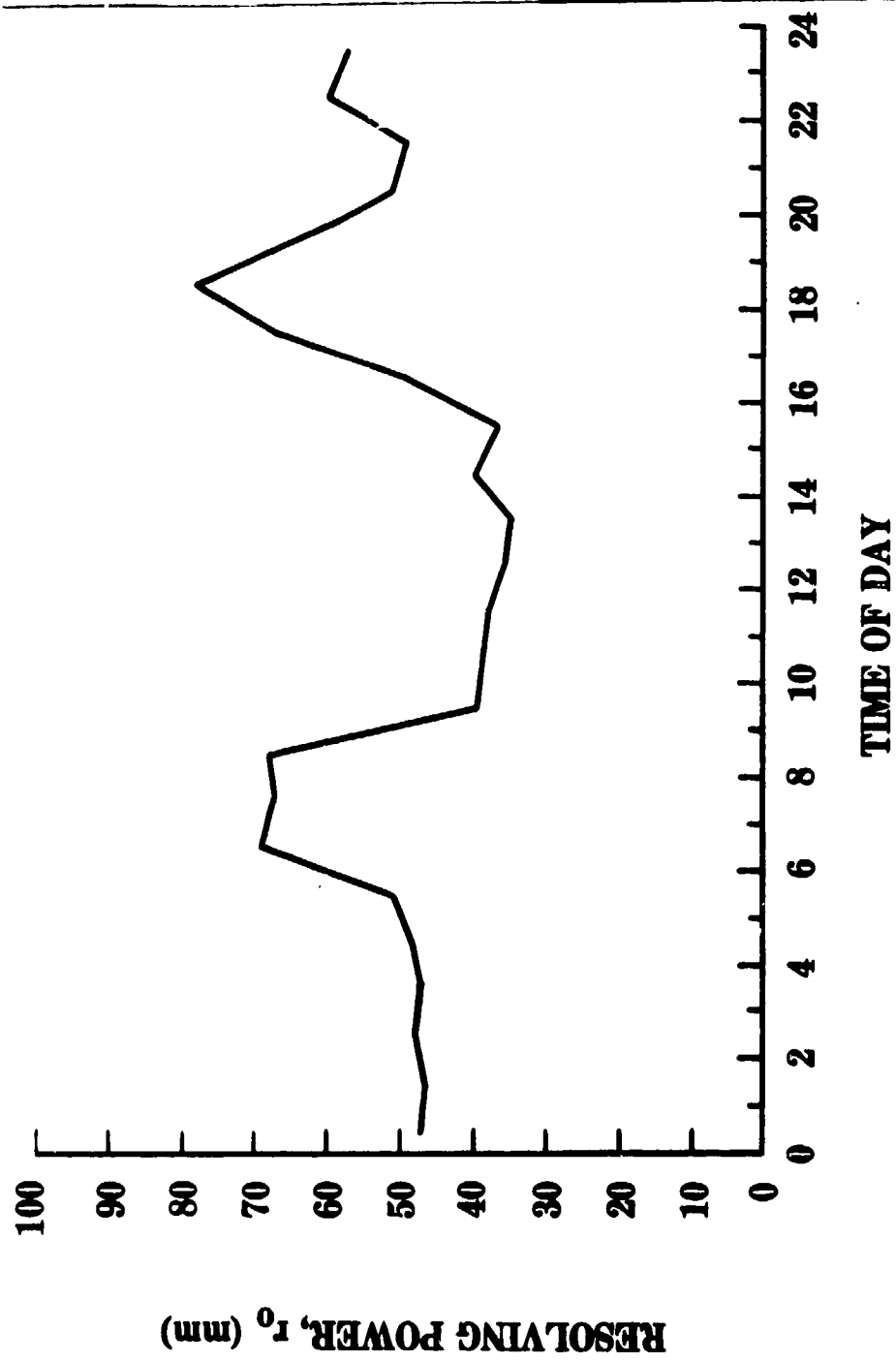


Figure 6. Vertical Path Modulation Transfer Function (MTF).

NONLINEAR EFFECTS

Thermal Effects

Thermal blooming and thermal bending refer to the self-induced spreading, distortion, and bending of a HEL beam that results when the energy absorbed by molecular and aerosol constituents in the atmosphere heats the air causing density or refractive index gradients which distort and degrade the beam. Thermal blooming and bending processes usually act as a divergent lens on HEL beams causing the beams to become defocused and/or deflected from their original beam axis. Figure 7 illustrates how, in the no-wind case, a Gaussian irradiation distribution is redistributed toward a donut-shaped intensity distribution with little or no energy on the beam axis (which can be considered the aim point of the beam). When wind is present, the beam is refracted into the wind or into the unheated, more dense air.

An HEL beam will experience thermal blooming unless it is sufficiently ventilated so that all the heated air is immediately displaced by unheated air. This ventilation is achieved either through natural winds or by slewing the beam through the atmosphere. However, a slewed beam can be degraded by thermal blooming within a stagnation zone which is a point along the beam where the wind vector and the radial slewing velocity add to zero; this causes no effective ventilation. A significant reduction in thermal blooming can be achieved at higher altitudes where water vapor and aerosol absorption is reduced, and in the case of the airborne laser, ventilation is increased.

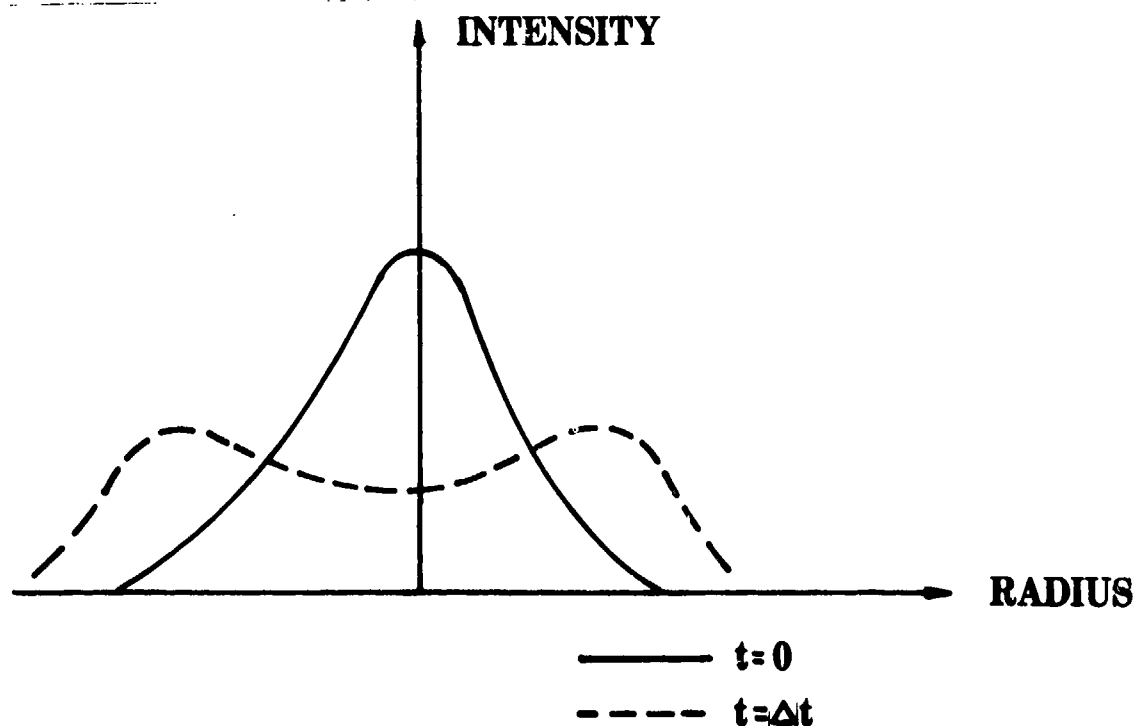


Figure 7. Thermal Blooming Intensity Change with Time.

Experimental and theoretical evidence shows that for a given beam size, target range, and set of atmospheric conditions, there is a critical power level at which the peak irradiance reaches a maximum value and beyond which it begins to decrease. Thermal blooming is a serious potential limitation for HEL applications and unlike linear propagation losses, it cannot be overcome by simply increasing the laser power.

Other Nonlinear Effects

Several other nonlinear atmospheric effects may degrade HEL propagation. HEL-induced thermal shock waves in the atmosphere propagate away from the beam at the speed of sound. These shock waves may degrade a slewed beam at the point where its radial velocity is Mach 1. In addition, gas breakdown in the atmosphere, particularly when using pulsed HEL beams, blocks propagation beyond the region of gas breakdown. However, carbon dioxide absorption can become saturated (i.e., does not increase with increasing power) at high 10.6 μm HEL power level. Also, aerosol heating can cause saturation due to particle vaporization.

CONCLUSIONS

The basic features of the propagation of HEL beams through the atmosphere and the fact that any HEL system is quite weather sensitive are reasonably well understood. Even though much work remains to be done to improve the HEL propagation models and to make them more accurate, most of the models given various atmospheric and device parameters have been either validated to some degree or formulated in theory. However, no methods currently exist which adequately assess the potential natural environmental effects on proposed HEL applications. Meteorological assessment and forecasting techniques and the means for integrating the results produced by those techniques into decision processes must be developed if informed decisions are to be made in optimizing the design of HEL weapons, and in maximizing the probability of success for operational HEL missions.

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