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AN INVESTIGATION OF ATMOSPHERIC EFFECTS ON LASER PROPAGATION AND THE IMPACT ON EYE SAFETY

Walter F. Dabberdt

Stanford Research Institute

Prepared for:

School of Aerospace Medicine

June 1972

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Final Report

AN INVESTIGATION OF ATMOSPHERIC EFFECTS ON LASER PROPAGATION AND THE IMPACT ON EYE SAFETY

BY: WALTER F. DABBERDT

Prepared for:

UNITED STATES AIR FORCE SCHOOL OF AEROSPACE MEDICINE AEROSPACE MEDICAL DIVISION (AFSC) BROOKS AIR FORCE BASE, TEXAS

CONTRACT F41609-71-C-0029



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AN INVESTIGATION OF ATMOSPHERIC EFFECTS ON LASER PROPAGATION AND THE IMPACT ON EYE SAFETY

Errata

1. Page 54: Equation (28) should be

$$\sigma_{\rm m} = \frac{\sigma_{\rm t}}{1 + \alpha \sigma_{\rm t}}^{\rm B}$$

- 2. Page 64: Paragraph two, line twelve should read "....about half those...."
- 3. Page 91: Example 3, γ (Step 13) should be 5×10^{-2} .

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ESCRIPTIVE NOTES (Type of report and inclusive dates)		<u></u>				
Final Report June 1971 - Octob	er 1972					
.UTHOR(\$) (First name, middle initial, last name)						
Walter F. Dabberdt						
EPORT DATE	78. TOTAL NO. OF PAGES	75. NO. OF REFS				
June 1572	117	22				
CONTRACT OR GRANT NO.	DE ORIGINATOR'S REPORT	NUMBER(5)				
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Approved for public release; d:	istribution unlimited.					
SUPPLEMENTARY NOTES	12. SPONSORING MILITARY A	CTIVITY				
	USAF School of A	rospace Medicine				
	Aerospace Medical	Division (AFSC)				

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Eye Safety						
Light Scintillation						
Atmospheric Turbulence						
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Final Report

June 1972

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Prepared for:

UNITED STATES AIR FORCE SCHOOL OF AEROSPACE MEDICINE AEROSPACE MEDICAL DIVISION (AFSC) BROOKS AIR FORCE BASE, TEXAS

CONTRACT F41609-71-C-0029

SRI Project 1341

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FOREWORD

This research program was sponsored by the U.S. Air Force School of Aerospace Medicine, Aerospace Medical Division, Brooks Air Force Base, Texas, under Contract No. F41609-71-C-0029. The project technical monitors were Captain P. D. Walker and Captain Donald Marston. The research was directed by Dr. Walter F. Dabberdt of Stanford Research Institute, under the supervision of Mr. R. T. H. Collis, Director of the Atmospheric Sciences Laboratory.

Publication of this report does not constitute U.S. Air Force approval of its findings and conclusions.

The author appreciates the help of Mr. B. Tupper and Mr. N. Nielsen in the experimental work; Mr. E. Ottoboni, Mr. L. Gasiorek, Mr. N. Nielsen, Mr. L. Salas, and Mr. A. Imada in the data processing; Mr. H. Shigeishi in the computer programming; and Mrs. M. Kucinski in the typing. The field support of Dr. J. Jobst, Mr. D. Frick, Mr. C. Hix, Mr. J. Doyle, and Mr. E. Selbac of EG&G, Las Vegas, is also gratefully acknowledged.

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I INTRODUCTION

The rapid proliferation of laser systems for civilian and military applications urgently requires the development of suitable guidelines to ensure safety in their use. In the absence of appropriate and realistic guidelines, excessively conservative "safety factors" may be proposed that could unduly restrict the use of laser systems. 1.1.1

The U.S. Air Force is actively conducting and sponsoring research studies to: (1) determine threshold levels for laser eye damage (Vassiliadis et al., 1969)^{*} and (2) determine the effects of atmospheric thermal turbulence on eye-damage probabilities. The latter is the objective of our present work and the subject of this report. Three previous reports (Johnson et al., 1968, 1970, and Dabberdt and Johnson, 1971) described the results of the earlier research.

Atmospheric temperature inhomogeneities increase eye-damage probabilities through the breakup of the propagating laser beam. To a viewer, this appears as scintillation (fluctuations in intensity). The "hot spots," or areas of localized beam intensification, typically have intensities that are tens or hundreds of times the average beam intensity. Thus, as the state of the atmosphere changes from a thermally "quiet" situation (no scintillation) to one of increasing thermal turbulence and scintillation, the probability of laser eye damage increases drastically.

Substantial progress has been made toward clarifying and parameterizing the effects of atmospheric thermal turbulence on laser propagation and on the associated eye-damage probabilities. It was determined experimentally that the amplitude probability distribution of the laser inten-

*References are listed at the end of the report.

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sity measured by a 5-mm aperture detector is well described by a lognormal distribution, in accordance with Tatarski's (1961) theory. The results demonstrated that although the observed probability distributions departed somewhat from log normal at the extreme upper end of the distribution (possibly because of the finite laser power), the assumption of a log-normal distribution gave safe (conservative) eye-damage probability estimates. These analyses were carried out to probabilities approaching 10^{-7} , almost three orders of magnitude lower than previously available.

With the use of the log-normal model, a preliminary set of laser safety guidelines for atmospheric effects was developed. These guidelines are based upon readily available, conventional weather observations. A number of approximations, however, had to be made in developing the initial guidelines, because of the basic lack of information. Additional experiments were conducted to clarify certain unresolved propagation effects and to extend the guidelines to a broader range of laser system use in terms of wavelength, path geometry, nature of the platform, and turbulence conditions. Our results indicated the presence of a supersaturation region of optical scintillations along a horizontal path in which the scintillation magnitude decreases with increasing range and thermal turbulence level. The eye-safety guidelines were revised to incorporate this effect as well as the results of our initial scintillation measurements along a slant path. Additional experimental work was carried out to investigate slant-path propagation and the wavelength dependence of scintillation. The results of this research were also incorporated into the eye-safety guidelines.

During the past year, further experimental work was carried out to investigate in greater detail the nature of the scintillation for a slant propagation path. Measurements were made simultaneously along identical

ground-to-air and air-to-ground paths. Concurrent vertical profiles of thermal turbulence (i.e., the refractive index structure function, C_{1}) were also obtained and have been used to parameterize atmospheric effects. The results of the study indicate the onset of scintillation saturation at long ranges, low elevation angles, and high thermal turbulence. A significant finding of our experimental work has been the heretofore unobserved dependence of the scintillation pattern on the scale of atmospheric thermal turbulence, in addition to the widely recognized dependence on range, path geometry, and the vertical profile of the refractive index structure function. More specifically, when the slantpath scintillation (σ_{+}) predicted by the classical theory of Tatarski (1961 and 1971) is taken as the scaling factor for range, geometry, and the vertical profile of C, the observed scintillation shows evidence of saturation at σ_1 -values that are about a factor of two larger during unstable (lapse) atmospheric conditions than during stable (inversion) conditions. The pattern is similar for both paths, although the observed scintillation at saturation is slightly larger (about 1.3 dB) for the ground-to-air path. These results and the incorporation of this information into the eye-safety guidelines are described in the main body of this report.

Additionally, we have developed a simplified eye-safety evaluation procedure for the estimation of the worst-case probability of eye damage. The worst-case estimate is made using only the laser and operational characteristics, while the atmospheric effects are treated implicitly in the procedure. This worst-case guide is intended for use when operational restrictions prohibit the use of the more detailed, general guidelines.

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II PROGRAM SUMMARY

A. Background

Classical optical propagation theory (Tatarski, 1961 and 1971) predicts that the scintillation magnitude for a near-ground, horizontal propagation path is directly proportional to the refractive index structure function (C_n), approximately directly proportional to the range (R), and approximately inversely proportional to the square root of the optical wavelength (λ); the exact form is

$$(\sigma_t)_H = K_1 R^{11/12} (2\pi/\lambda)^{7/12} C_n$$
 (1)

Here σ_t is the theoretical standard deviation of the log signal intensity, K₁ is a dimensionless constant, and the subscript H denotes a horizontal path. This theory, which is based on the so-called Rytov approximation, fits observations well for low thermal-turbulence conditions and relatively short ranges.

Tatarski's theory also predicts the scintillation magnitude for the case of optical propagation along a slant path (subscript S),

$$(\sigma_t)_s = K_2 (2\pi/\lambda)^{7/12} \left[\int_0^R C_n^2 (r) r^{5/6} dr \right]^{1/2},$$
 (2)

where the coordinate origin (r = 0) is at the receiver. The term shown in brackets is referred to as the range integral and is a function of range, path geometry, the slant profile of thermal-turbulence intensity, and receiver-transmitter orientation. For the normal case of a decrease in C_n with increasing height, the theory predicts that the scintillation

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will be larger for a ground-to-air propagation path than vice versa. The results of our earlier slant-path studies (Johnson et al., 1970, and Dabberdt and Johnson, 1971) indicated that the applicability of Equation (2) may be restricted to relatively small values of the range integral.

Application of the theory to longer ranges and higher turbulence levels has not been intuitively appealing since for these conditions, the predicted scintillation magnitude (and hence the eye-damage probability) increases indefinitely without bound. However, no better theory has been available, and indeed, recent advances have come principally through experimentation.

The first breakthrough came from experiments in Russia by Gracheva and Gurvich (1965) and by Gracheva (1967), which showed a saturation, or leveling off, of the scintillation magnitude with increasing range beyond about 1 km. (The longest range at which measurements are reported in the Russian work is 1.75 km.) Subsequently, Tatarski (1966) and DeWolf (1968) developed variations of the propagation theory that conform to some degree to the Russian observations. A second breakthrough resulted from our earlier work (Johnson et al., 1970) at a field site in Woodland, California, that showed the presence of a supersaturation region where the scintillation magnitude for a helium-neon laser and a near-ground, horizontal path actually decreases with increasing range and thermal-turbulence intensity beyond the saturation level. An analytical expression was given that relates the measured scintillation magnitude $(\sigma_m)_H$ to the theoretical $(\sigma_t)_H$:

$$(\sigma_{m})_{H} = \frac{(\sigma_{t})_{H}}{1 + 0.16 (\sigma_{t})_{H}^{2}}$$
(3)

Figure 1 gives a comparison of the measured values of the scintillation intensity with the values predicted by Tatarski's theory.



FIGURE 1 COMPARISON OF MEASURED VALUES OF LOG INTENSITY STANDARD DEVIATION WITH VALUES PREDICTED BY TATARSKI'S THEORY, SHOWING THE SUPERSATURATION EFFECT, FOR THE WOODLAND EXPERIMENT (Johnson et al., 1970)

Another experimental program was conducted in September 1970, at an excellent field site in Mercury, Nevada, that was designed to investigate the dependence of optical scintillations on range, thermal-turbulence intensity, path geometry, and wavelength. Because of the location and time of the experiment, a significantly wider variation (~ 50%) of C_n values were measured over longer ranges (to 7.6 km) than in our earlier experiments. We found that the measured scintillation magnitude for a near-ground horizontal path: (1) saturated with increasing range and thermal-turbulence level (as represented by the scaling factor σ_{tH}), (2) reached this peak (σ_{mH}^{*}) at about $\sigma_{tH} = 2.5$ and decreased thereafter ("supersaturation"), and (3) showed evidence of leveling off beyond $\sigma_{tH} \approx 15$ at a value of approximately 0.5. An analytical expression that fits the 0.6325- μ data well is

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$$\sigma_{mH} (0.6328 \ \mu) = \frac{(\sigma_t)_H}{1 + 0.30 \ (\sigma_t)_H^{5/3}}$$
(4)

where $\sigma_{\rm mH}$ is the measured log-intensity standard deviation along a horizontal path. Furthermore, our multiwavelength measurements (0.4880 μ , 0.6328 μ , and 1.064 μ) showed that: (1) the ratios of $\sigma_{\rm mH}^{*}$ for the various wavelengths are well approximated by Tatarski's "minus seven-twelfths" dependence on wavelength; (2) the value of $\sigma_{\rm tH}$ at the measured peak ($\sigma_{\rm mH}^{*}$) varies inversely with wavelength; and, most significantly, (3) optical scintillations show little apparent dependence on wavelength in the farsupersaturation region. Analytical expressions for the 0.4880- μ and 1.064- μ data are given by

$$\sigma_{mH} (0.4880 \ \mu) = \frac{(\sigma_t)_H}{1 + 0.25 \ (\sigma_t)_H^{1.77}}$$
(5)

and

$$\sigma_{\rm mH} (1.064 \ \mu) \approx \frac{(\sigma_{\rm t})_{\rm H}}{1 + 0.48 \ (\sigma_{\rm t})_{\rm H}^{1.60}} \tag{6}$$

Application of Tatarski's slant-path theory is also restricted owing to the monotonic increase of the predicted scintillation magnitude with increasing turbulence levels and range. The results of the earlier program (Johnson et al., 1970) indicated the possibility of scintillation saturation along a slant path, although the limited range (< 4000 m) precluded possible supersaturation. During the 1970 field study, static slantpath scintillation measurements were made using a 465-m tower as a receiver platform for a ground-based helium-neon laser (0.6328 μ); vertical profiles of thermal turbulence intensity were also collected. These measurements were made during daytime--lapse conditions--and the measured scintillation magnitude (σ_{ms}) was observed to: (1) saturate with increasing range and thermal-turbulence level (as represented by σ_{ts}) and (2) show some indication of supersaturation beyond $\sigma_{ts} \approx 8$. The observed scintillation

maxima for the slant- and horizontal-propagation paths were virtually the same at about 1.25. We found that, for our experimental conditions, the eye-damage hazard was larger along the slant path for ranges greater than 4 km. This resulted from saturation along the slant path together with supersaturation on the horizontal path at these ranges. 「「「「「「」」」

B. Summary of Results

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An extensive field program was conducted during July 1971 at the Mercury site to study the nature of the scintillation of a helium-neon laser beam for ground-to-air and air-to-ground propagation paths during both daytime (lapse) and nighttime (inversion) periods. The scintillation measurements were made simultaneously along the two coincident paths, together with concurrent measurements of the differential-temperature structure (used to determi..e the refractive index structure function, C_n) at four heights from the surface to 460 m (the height of the elevated laser and receiver). Supplemental mean wind and temperature profiles were also obtained.

One significant aspect of the program was the data it provided on the time-height variations of the refractive index structure function. As expected, C_n is a minimum during the near-sunrise and -sunset adiabatic periods, while nighttime (inversion) values are typically about one-half those observed during the midday (lapse) periods. The general feature of the vertical C_n profile is the quasi-exponential decay with height. However, during the sunrise and sunset stability-transition periods, a secondary C_n maximum occurs well above the surface. This feature is particularly significant when evaluating the slant-path scintillation in terms of the theoretical value given by Equation (2). A simple model that describes the features of the time-height dependence of C_n is:

$$C_{n}(z,t) = \sum_{i} \left\{ \overline{C}_{n,i} + \Delta_{i} C_{n} \cos \left(w_{i}t - z/Z_{i} + \zeta \right) \right\} \quad . \tag{7}$$

The overbar denotes the time average of the i harmonic, ΔC is the harmonic amplitude, ω is the frequency, Z is the damping depth, and ζ is the phase lag.

A particularly significant finding of the program is the apparent stability dependence of the scintillation pattern. As with the earlier horizontal path studies, σ_t [in this case, Equation (2)] is used as a range-turbulence-wavelength scaling parameter. While the observed scintillation patterns for both the ground-to-air and air-to-ground paths are similar for the two stability categories (see Figures 2 and 3), corresponding absolute values of σ_t are twice as large for the lapse cases than for the inversion cases. This suggests that there is a scaling effect not only of range, geometry, wavelength, and turbulence intensity, but also of the stability types, i.e., lapse or inversion. We therefore propose, in way of conjecture, that the scintillation magnitude is dependent on the frequency (or scale) as well as the magnitude of the thermal fluctuations.

During lapse conditions, there is a decrease in the atmospheric potential temperature with height and a tendency for convective activity resulting from the unstable density stratification; for inversion conditions the reverse is true and the atmosphere is regarded as stable. Typically, the spectrum of near-surface thermal fluctuations during inversion conditions (typical of clear nights) is characterized by relatively high frequencies (and low wavelengths) due to the height variation of temperature and the action of mechanical turbulence. During lapse conditions (characteristic of sunny days), the spectrum of thermal fluctuations is often augmented by the effects of buoyancy (free convection). The impact of this convective activity is reflected in the occurrence of a second peak in the spectrum at lower frequencies (higher wavelengths). In sunmary, nighttime conditions are characterized by relatively small though frequent turbulent



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FIGURE 3

COMPARISON OF MEASURED VALUES OF LOG INTENSITY STANDARD DEVIATION WITH VALUES PREDICTED BY TATARSKI'S THEORY, SHOWING THE DEPENDENCE ON ATMOSPHERIC STABILITY

elements, whereas daytime conditions with free convection may be dominated by the larger, infrequent convective cells. As a consequence, it may be that the "effective range" (or number of refractive occurrences) is significantly less for these daytime conditions although the value of C_n may not differ from the nighttime case. The idea of an effective range is introduced to specify the relationship between the scale of turbulence and the scintillation: For equal values of C_n and a given propagation path, daytime scintillation under free convection is observed to occur as if the range were effectively reduced. The occurrence of scintillation saturation is indicated at large σ_t for all path and stability categories, but there is no evidence of a supersaturation effect within the range of σ_t values observed. Again there appears to be an influence of the stability category--in this case on the magnitude of the scintillation at saturation, σ_m^* . For the inversion cases, σ_m^* is about 1.7, while for the lapse cases it is about 1.4. This difference, though only about 20% or 1.3 dB, is quite important in the evaluation of the eye-damage probability because of non-linear effects.

These findings have been incorporated into a revised procedure for the evaluation of the probability of laser eye-damage. Additionally, a short and simplified procedure has been developed to estimate the worstcase probability of eye damage.

III EXPERIMENTAL PROGRAM

A. General

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The general objectives of the program were to extend and supplement our previous laser eye-safety research (Johnson, Evans, and Uthe, 1970, and Dabberdt and Johnson, 1971) and to develop a simplified laser eyesafety guide covering a broad range of use of laser systems in terms of path geometry, atmospheric conditions, and laser characteristics. Specifically, the objectives of the experimental program were to:

- Verify the existence of scintillation saturation and supersaturation for ground-to-air propagation, and simultaneously determine whether saturation and supersaturation occur for the air-to-ground path.
- (2) Examine the path dependence of the magnitude of the scintillation maximum.
- (3) Develop relationships between slant-path scintillation and atmospheric structure.

Toward these ends, an experimental program was conducted during the period 8 to 23 July 1971 at the Nevada Test Site (NTS). Simultaneous measurements were made sequentially of the intensity fluctuations in the beams of two 15-mW helium-neon lasers, along ground-to-air and air-toground propagation paths at six ranges. A chronological summary of our activities is given in Table 1. Two receivers with 5-mm diam. apertures were used, one near the top of the 465-m BREN Tower and the other in a mobile instrumentation laboratory. The horizontal range between the tower and the six sites varied between 0.625 and 10.0 km; both daytime and nighttime measurements were made. Coincident thermal-turbulence measurements were made at four heights ranging from 1.7 to 460 m;

Table 1

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CHRONOLOGICAL SUMMARY, 1971 BREN TOWER EXPERIMENT, NEVADA TEST SITE (NTS)

Date	Activity
6 July	Equipment departs SRI
7 July	Equipment and field party arrive Las Vegas
8 July	Equipment and field party arrive NTS, clear security; unpack equipment, locate field sites, calibrate and begin installation of equipment with aid of EG&O personnel; Air Resources Laboratory personnel activate wind and temperature system on BREN Tower
9 July	Continue equipment check-out, calibration, and installation
10 July	Complete equipment installation and 11 daytime data runs
11 July	Rest day
12 July	Complete 26 daytime data runs
13 July	Begin nighttime data collection sequence; 13 Fruns completed
14 July	Complete nighttime data collection sequence; 19 runs completed
15 July	Com plete 28 daytime data runs
16 July	Complete 15 daytime data runs
17-18 July	Rest days
19 July	Begin nighttime data collection sequence; 18 runs completed

Table 1 (Cont.)

Date	
20 July	Complete nighttime data collection sequence; 17 runs completed
21 July	Complete 9 daytime data runs
22 July	Complete 26 daytime data runs; shut down
23 July	Begin equipment take-down and packaging
24 July	Complete equipment packaging, clear NTS security and depart
26 July	Equipment arrives SRI

supplemental wind and temperature profiles were also made using available tower instrumentation.

B. Site Description

The BREN Tower facility at the NTS is located about 80 miles northwest of Las Vegas at Lat 36° 46' 50.4" N, Long 116° 14' 33.4" W, at an elevation of 1110 m msl. The tower is an equitriangular structure approximately 4 m on a side, with an open steel framework. The terrain slope within a 2.5-km radius of the tower is approximately 1:40, with the fall line ENE to SSW, except for a ridge 5 km distant in the SE quadrant (see Figure 4). All runs were made over paths to the west of the tower to ensure maximum homogeneity of the surface, thereby permitting us to be reasonably confident that the meteorological conditions measured at a fixed point over suitable averaging time would be representative of the entire propagation path. Figure 5 is a topographic cross section between the BREN Tower and Site 6 (range 10 km); the slope (1:62) is quite uniform over the entire path. The surface is basically a sandy, pebbly gravel of



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FIGURE 4 MAP OF THE FIELD SITE AT THE NEVADA TEST SITE

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volcanic rock fragments, primarily tuff with some basalt and andesite. This uppermost stratum (caliche) extends to a depth on the order of 30 m. The instrumentation runway on which the shorter-range measurements (0.63 km) were made is devoid of vegetation; the surrounding terrain has a typically sparse growth of sagebrush.

C. Instrumentation

1. Laser Measurements

The tower and truck laser-receiver systems were virtually identical (Figures 6 and 7). Two Spectra-Physics^{*} Model 124 helium/ neon lasers (wavelength 0.6328 μ) with an output power of approximately 15 mW were used for this experiment; the surface laser was positioned 1.7 m above the ground, while the elevated laser was at the 460-m level on the tower. Transmitter-receiver alignment was controlled with micropositioners on both the laser mount and the receiver mount; a corner cube retroreflector mounted on the receiver aided in positioning the laser. Beam-expanding and collimating optics (S-P Model 336) were used to obtain a transmitted beam diameter of approximately 20 mm (measured between the e^{-2} intensity levels). A spatial filter (S-P Model 332) with an aperture of 15 μ (S-P Model A6) was used to ensure a smooth, mean (Gaussian) intensity profile across the beam.

Two virtually identical receivers were used to measure the laser intensity fluctuations. One receiver was positioned near the truck to monitor the signal from the tower-mounted laser, while the second receiver was at the 460-m level on the tower and monitored the signal from the truck laser. Each receiver employed a 5-mm diam. aperture to simulate the average

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size of the pupil of the human eye, a $10-\mathring{A}$ interference filter centered at 0.6328 μ to reduce background (ambient) radiation, and a 3-mrad fullangle field of view. An RCA^{*} Model 7265 photomultiplier tube (PMT) with an S-20 photocathode surface was used in each receiver.

The output signal from each PMT was fed into a logarithmic amplifier (PM^{\dagger} Model 1002) and the output voltage was then recorded in FM mode on an analog instrumentation tape recorder ($H-P^{\dagger}$ Model 3960A). The mean PMT current was monitored by a meter using an R-C circuit with a time constant of approximately 7 seconds. Data from the truck-based PMT were recorded in the truck; power for the mobile instrumentation was supplied by a bank of storage batteries. These were capable of 8 to 12 hours continous operation and were recharged during off-periods. Data from the tower-based PMT were recorded in a bunker (see Figure 8) at the base of the tower.

2. Meteorological Measurements

The primary meteorological instrumentation consisted of four fast-response differential thermometers (Figure 6) for the measurement of the temperature structure function. A vane was used to maintain the orientation of two horizontally separated temperature sensors perpendicular

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 940 Industrial Avenue
 Palo Alto, California 94303
- # Hewlett-Packard Company 1101 Embarcadero Road Palo Alto, California 94303

to the wind direction; two 0.0005-in. diam. chromel-constantan thermocouples were used, physically separated by 60 cm but electrically connected in series. The voltage generated by the temperature difference between the thermocouples (64 μ V/°C, as determined from repeated calibration tests) was then amplified by a high-gain differential amplifier (designed and constructed at the Institute) and recorded in FM mode on the analog magnetic tape recorders (H-P Model 3960A). The time constant of the differential thermometer was determined experimentally to be 0.015 s when ventilated at 2 m/s. This response was sufficiently fast so that the error in the computed fluctuation variance caused by neglecting the higher frequencies should be small. 4

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The four differential thermometers were used to provide a vertical profile of the temperature structure function for the slant-path scintillation measurements. The lower-most sensor was positioned near the truck atop a tripod at the approximate height of the surface laser (1.7 m); the other three sensors were mounted on booms that extended 3 m outward from the tower at heights of 91.5, 213, and 460 m. The near-surface differential thermometer was used at the location of the near-surface laser to provide thermal-turbulence measurements at the point where turbulence effects on the intensity fluctuations are most pronounced--near the source. For the elevated laser, the 460-m differential thermometer provided the resolution required. Thermal-turbulence measurements at the two intermediate levels were used to help define the vertical structure of the temperature structure function.

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Supplementary mean-temperature profiles were obtained as hardcopy output from an electromechanical printer at 10-min. intervals from existing National Weather Service (NWS) sensors mounted at ten levels on the tower: 3.0, 16.4, 25.9, 47.3, 90.0, 133, 175, 213, 303, and 460 m. Mean wind speed and direction were taken visually from strip chart records over the course of each run; NWS wind sensors at eight levels were used:

3.0, 16.4, 25.9, 90.0, 175, 218, 303, and 460 m. Additional measurements of wind speed and direction were obtained using a propeller-vane maintained at a height of 1.7 m at a location approximately 100 m SW of the tower (see Figure 9). These data were recorded on an incremental, dual-channel chart recorder.

D. Experimental Procedure

The basic configuration of the path geometry and range dependence experiment is illustrated in Figure 10. Lasers and receivers were located at the top of the BREN Tower and sequentially at various horizontal ranges: 0.63, 1.4, 2.5, 5.0, 7.5, and 10.0 km. The signal inputs from the tower receiver and three differential thermometers were brought into a recording bunker located near the base of the tower. A second recording system in the truck was used for the ground-based laser scintillation and temperature fluctuation measurements.

The experimental procedure entailed the simultaneous measurement of laser scintillations over reciprocal slant-propagation paths sequentially at the six different ranges; temperature fluctuation data, together with the wind and temperature profiles, were recorded simultaneously with the laser data. In practice, the technique entailed the transport of the mobile instrumentation system to the desired range. A 6-min. run was made at a site, including calibration levels and a check of the background (ambient light) noise. The system was then transported by truck to the next site, and the procedure was repeated; transit and setup time varied typically from 15 to 35 min., depending on the range change and the laserreceiver alignment time.

Before each run, the PMT supply voltage was adjusted to give an approximate mean output current of 10 μ A. The log amplifiers were adjusted to give zero output voltage from an input of 10 μ A, so that the means of the recorded (logged) signals would be near zero.



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FIGURE 8 RECORDING INSTRUMENTATION FOR TOWER RECEIVER AND DIFFERENTIAL THERMOMETERS: (1) FM INSTRUMENTATION TAPE RECORDER, (2) PROBABILITY DENSITY ANALYZER, AND (3) X-Y PLOTTER



FIGURE 9 VIEW TO THE WEST OF BREN TOWER ILLUSTRATING THE TOPOGRAPHY AND SHOWING THE LOW-LEVEL WIND SENSOR

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The high-gain differential amplifier for the near-surface differential thermometer was set so that a 50- μ V input signal (~ 0.78^oC differential) produced a 1-V output. The other three amplifiers produced a 1-V dc output for a 25- μ V input signal (~ 0.39^oC differential) owing to the smaller temperature fluctuations at the higher levels.

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A total of 182 data runs were collected at six ranges for all hours of the day. The runs are tabulated in Table 2.

E. Preliminary On-Site Data Analysis

As mentioned earlier, the laser scintillation and temperature fluctuation data were recorded in analog fashion on magnetic tape. In addition, the signals from the tower instrumentation were monitored on line with a probability density analyzer (PDA, see Figure 8) to examine the quality of the data in real time. The PDA automatically "builds up" a probability density histogram (PDH) as data are being collected. When a preselected number of samples has been collected, the PDH is automatically displayed and can then be recorded on an on-line x-y plotter. (This procedure has since been improved, and the PDH is now automatically transferred to a desk computer for statistical analysis--see Chapter IV). In this manner we were able to monitor laser-receiver alignment, background noise level, thermal turbulence, and so forth. Then, for example, if the mean laser signal level varied during a run, we were able to remedy the problem and repeat the run.

Table 2

DATA SUMMARY--RECIPROCAL SLANT PATH EXPERIMENT, NEVADA TEST SITE, 1971

Site ranges: 1 = 0.63 km, 2 = 1.4 km, 3 = 2.5 km, 4 = 5.0 km, 5 = 7.5 km, 6 = 10.0 km

RUN		TIME	SITE	RUN		TIME	SITE
NO.	DATE	(PDT)	NO.	NO.	DATE	(PDT)	NO.
A	7/10	1011	1	16	7/12	1737	4
в	• -	1025	1	17		1756	5
С		1034	1	18		1812	6
D		1111	2	19		1833	4
E		1132	. 3	20		1854	4
F		1205	4	21		1915	4
G		1213	4	22		1933	4
н		1238	6	23	7/13	1910	1
I		1255	6	24		1944	4
J		1325	5	25		1955	4
к		1333	5	26		2012	4
L	7/12	1012	4	27		2030	4
М		1028	4	28		2057	4
N		1059	6	29		2132	6
0		1142	6	30		2152	5
1		1155	6	31		2211	4
2		1238	1	32		2233	3
3		1.247	1	33		2243	3
4		1312	1	34		2301	2
5		1340	2	35		2331	1
6		1406	3	36	7/14	0026	6
7		1438	4	37		0033	6
8		1446	4	38		0050	6
9		1509	5	39		0109	5
10		1518	5	40		0131	4
11		1538	6	41		0149	3
12		1547	6	42		0205	2
13	•	1626	1	43		0227	1
14		1653	2	44		0302	6
3.0		1710	2	A 8		0207	

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Table 2 (Cont.)

DATA SUMMARY--RECIPROCAL SLANT PATH EXPERIMENT, NEVADA TEST SITE, 1971

		4 = 0	.0 Km, 0 -	- 1,0 Amj	0 - 10		
RUN		TIME	SITE	RUN		TIME	SITE
NO.	DATE	(PDT)	NO.	NO.	DATE	(PDT)	NU,
46	7/14	0345	4	76	7/15	1638	6
47		0403	3	77		1648	6
.48		0422	2	78		1657	6
49		0453	6	79		1720	4
50		0500	6	80		1727	4
51		0510	·. 6	81		1751	2
52		0530	4	82		1800	2
53		0546	4	83	7/16	0944	6
54		0556	4	84		1001	5
55	7/15	0643	6	85		1009	5
56		0709	6	86		1027	4
57		0726	5	87		1043	3
58		0737	5	88		1101	2
59		0757	4	89		1139	1
60		0812	4	90		1304	5
61		0829	3	91		1322	4
62		0847	2	92		1330	4
63		0917	1	93		1355	3
64		0924	1	94		1415	2
65		1008	6	95		1440	1
66		1028	5	96		1448	1
67		1047	4	97		1510	2
68			4	98	7/19		4
69		1115	3	99			4
70		1132	2	100			4
71		1153	1	101		1940	4
72		1509	2	102		1954	4
73	•	1530	3	103		2011	4
74		1602	4	104		2031	4
75		1620	5	105		2044	4

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Table 2 (Concluded)

DATA SUMMARY--RECIPROCAL SLANT PATH EXPERIMENT, NEVADA TEST SITE, 1971

Site	a range	s: 1 = 0 4 = 1),63 km, 5.0 km, 5	2 = 1.4 km = 7.5 km,	, 3 m 2 6 m 10	1.5 km,).0 km	۱.
RUN		TIME	SITE	RUN		TIME	SITE
NO.	DA'FE	(1,DL)	NO.	NO.	DATE	(PDT)	NO.
106	7/19	2106	4	136	7/21	1156	4
107		2124	4	137		1204	4
108		2155	6	138		1226	5
109		2204	6	138A		1234	5
110		2227	5	139		1255	6
				140		1478	1
111		2247	4				
112		2257	4	141	7/22	0900	2
113		2308	4	142		0910	2
114		2331	3	143		0930	3
115		2353	2	144		0957	4
				145		1014	5
116		0019	1				
117		0028	1	146		1036	6
118		0133	6	3.47		1101	3
119		0156	5	148		1119	4
120		0204	5	149		1134	5
				150		1141	5
121		0222	4				•
122		0241	3	151		1159	6
123		0250	3	151A		1208	6
124		0312	2	152		1247	3
125		0319	2	153		1256	3
100		0244	4	154		1314	4
120		0344	1	1044		1321	4
127		0445	6	100		1337	5
120		0407	6	150		1064	0
129		0540	0	100		1401	6
130		0040	4	157		1400	6
191		0548	Л	150		1400	3
132	7/20	0040	3	160		1443	3
133	7/20	1029	1	TOO		7.1.10	5
134	17 61	1102	- 2	181		1 500	4
135	•	1132	- 3	162		1517	5
100		* * * *	-	163		1534	8
				164		1543	6

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In practice, the laser is aligned with the receiver before the start of the run. The run then begins with the recording of calibration levels, after which the laser output is shielded for approximately 15 s while the noise in the receiver system is recorded. The PDA is then stopped, and its output is displayed on the x-y recorder while the data continue to be recorded on tape. Next, the PDA collects the density of the scintillation data, and this is plotted over the calibration plot. An example of a PDH collected on line is given in Figure 11. The figure illustrates the calibration and "noise" checks made at the beginning of the run, in addition to the signal received along a groundto-air propagation path. 医黑上的时候的 医子宫的 化化化性化化化性 化化化学



FIGURE 11 PROBABILITY DENSITY HISTOGRAM OF LASER SCINTILLATIONS WITH NOISE AND CALIBRATION LEVELS, AS COLLECTED IN THE FIELD WITH THE PROBABILITY DENSITY ANALYZER

IV DATA REDUCTION AND ANALYSIS

A. Data Processing

As discussed in Chapter III, the laser scintillation and temperature fluctuation data were recorded in analog fashion on FM magnetic tape. The probability density analyzer (PDA) discussed earlier was used to process the data to obtain frequency distributions; the variance of the signal is then easily obtained for une in the application of the theories of Tatarski and Kolmogoroff (1941).

In operation, the PDA takes a large number of samples of the analog waveform and records the number of samples that occur in each of 1024 voltage bins. Typically, about one million sumples are obtained. The data are presented as a relative frequency-of-occurrence histogram that constitutes an estimate or "measured value" of the probability density function of the scintillation or thermal waveform with spectral content from do to 12 GHz. (Actually the spectral content of the system is limited by the frequency passband of the tape recorder that is about O to 1250 Hz at the tape speed used.) Specifically, a sampling oscilloscope in the PDA takes nearly instantaneous samples of the signal and generates a boxcar waveform whose height is proportional to the sampled voltage. In the pulse-height analyzer section, an analog-to-digital converter categorizes the section of the waveform corresponding to each sample as being within one of the 1024 contiguous voltage intervals. The number of times a sample occurs in each bin during a given test is recorded in memory. After a selected number of samples has been obtained, the data in the memory are displayed on a CRT and can be analyzed to obtain the statistics of the probability function.

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For this purpose, we have constructed a hardware interface to transfer the data to a Wang 720/703 Programmable Calculator/Plotter." When a density of sufficient length has been collected, it is transferred through the interface to the calculator. Software programs have been developed to analyze the density to obtain the mean, standard deviation, skewness, and kurtosis of the distribution. These output data can then be displayed with an on-line typewriter-plotter.

Figure 12 is an example of a typical display. The probability density histogram generated by the PDA is indicated by the crosses in the figure. To decrease the time required to print the curves, only every fifth point is plotted; however, this spacing can be controlled by the operator according to the resolution required. The distribution has been normalized about a zero mean, and the second, third, and fourth moments are listed beneath the plot. The Gaussian curve corresponding to the variance of the measured distribution is also plotted routinely; it is indicated by the heavy dots in the figure. The difference between the two curves is shown by the distribution of stars at the bottom of the plot.

A powerful capability of the data reduction program is illustrated in Figure 13. At the longer ranges the negative, normalized intensity fluctuations often drop into the background noise level of the PMT (photomultiplier tube) detector. Fortunately, however, most of the scintillations are detected, although the distribution is severely skewed in the positive sense. One of the results of our earlier programs (Johnson et al., 1970) was the recognition that the scintillation can be accurately represented by a log-normal distribution. Therefore, we have developed an optional software subprogram that automatically locates the

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weighted median of the distribution and computes the standard deviation from the positive half of the data. The results of this routine are illustrated in Figure 13 for an evening run at a 10-km range along an air-to-surface path. The signal for this run begins to drop off systematically below approximately -3.5 dB. The weighted median is computed for the -3.5- to +3.5-dB range and normalized, or set to zero; the standard deviation is computed for the half of the distribution where the relative log intensity is positive. The fitted curve is seen to represent the "good" data accurately.

During the course of the data processing, we also sought to examine the short term variations of the variance of the scintillation. This is especially important as the scintillation is a result of turbulence conditions over the entire path, while the temperature fluctuations are measured at discrete locations. Figures 14 and 15 illustrate the nature of the scintillation distribution measured along a 2.5-km surface-to-air path over three consecutive 1-min. periods during inversion (midnight) and lapse (late morning) conditions. The scintillation for the nighttime runs (Figure 14) is quite consistent, ranging from 1.7 to 1.9 dB. The characteristic meteorological feature was a surface-based radiation inversion of 2.5° C between the surface and 90 m; winds were light (1.5 m/s) although steady, both in speed and direction, from the SE. An interesting feature is illustrated by the daytime sequence (Figure 15): The standard deviation of the scintillation intensity is quite steady about 1.9 dB, but a shift in the mean level of the scintillation intensity occurs during the second minute [Figure 15(b)]. The distribution appears to be a composite of two populations whose mean levels differ by about 5 dB. The lower atmosphere was unstable, with a temperature decrease of 3.8°C between 3 and 16 m; winds were light (2 m/s) and variable from the south. Moderately strong convective activity was present under these conditions and it can be expected that the horizontal temperature structure of the atmosphere was





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Table 3

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A LOUAL MATCHMARKS

	T	σ	(d B) *			σ	(°C)			
RUN	SITE	SURFACE	TOWER	T (°C)			1	<u> </u>		
NO.	NO.	RECEIVER	RECEIVER	2 = 3 m	2=2m	z = 92m	z = 213m	z = 460 m		
A	1	1.65	1.22	27.5	0.648	0.087	0.046	0.029		
В	1	1.34	0.80	28.7	0.690	0.093	0.053	0.028		
С	1	1.41	0.97	28.7	0.722	0.088	0.057	0.037		
D	2	2.25	1.77	29.4	0.620	0.051	0.034	0.040		
E	3	2,88	3.69	29.9	0.777	0.056	0.024	0.034		
G	4	4.01	5.30	31.2	0.786	0.129	0.061	0.044		
L	4	4.32	4.04	33.4	0.561	0.067	0.047	0.024		
м	4	4.72	5.68	33.4	0.596	0.064	0.064	0.030		
2	1	1.51	1.15	35.9	0.682	0.060	0.059	0.039		
3	1	2.25	1.88	35.9	0.697	0.077	0.072	0.057		
5	2	3.02	2.79	36.4	0.608	0.078	0.053	0.039		
6	3	2.12	3.24	35.2	0.389	0.062	0.039	0.024		
8	4	2.68	4.13	36.4	0.320	0.032	0.028	0.031		
13	1	1.52	1.51	36.5	0.465	0,050	0.025	0.019		
14	2	1.46	1.74	37.2	0.353	0.036	0.025	0.028		
15	3	1.93	2.56	36.6	0.384	0.049	0.025	0.018		
16	4	3.22	4.01	36.2	0.246	0.041	0.036	0.031		
17	5	3.38	5.26	36.0	0.234	0.038	0.031	0.027		
19	4	2.06	2.85	35.3	0,129	0.026	0.022	0.014		
20	4	1.69	2.26	35.0	0.082	0.032	0.024	0.014		
21	4	1.16	2.00	34.1	0.039	0.023	0.017	0.014		
22	4	0.84	0.99	33.6	0.046	0.018	0.016	0.012		
23	1	0.25	0.45	35.4	0.117	0.027	0.017	0.017		
25	4	0.91	0.87	32.8	0.093	0.009	0.015	0.014		
26	4	1.08	1,06	32.4	0,118	0.010	0.015	0.015		
27	4	1.05	1.36	31.7	0.162	0.015	0.019	0.016		
28	4	1.46	1.62	30.4	0.211	0.019	0.023	0.017		
29	6	2.61	2.66	29.6	0.239	0.015	0.019	0,014		
30	5	2.92	2.94	29,1	0.209	0.025	0.018	0.014		
31	4	3.79	3.07	29.0	0.315	0.016	0.017	0.014		

RESULTS FROM NTS PATH GEOMETRY AND RANGE DEPENDENCE EXPERIMENT

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Table 3 (Cont.)

			σ	(d B)*		T	σ	(°C)	
	RUN	SITE	SURFACE	TOWER	T (°C)		Τ	1	1
	NO.	NO.	RECEIVER	RECEIVER	z=3m	z = 2 m	z = 92m	z = 213m	z = 460 m
	32	3	1.47	1.57	28.9	0.152	0.009	0.020	0.014
	33	3	1.98	2.07	29.0	0.116	0.010	0.019	0.014
	34	2	0.63	0.61	28.6	0.174	0.010	0.022	0.014
	35	1	0.71	0.48	28.0	0.242	0.016	0.018	0.014
	38	6	6.00	5.88	26.5	0.091	0.069	0.016	0.020
	39	5	6.36	6.53	26.5	0.119	0.029	0.061	0.017
	40	4	3.69	4.17	25.3	0.099	0.025	0.001	0.017
	41	3	2.38	3.06	24.3	0.122	0.033	0.004	0.022
	42	2	1.48	1.18	25.3	ú.190	0.028	0.034	0.025
	43	1	0.98	0.63	26.5	0.172	0.028	0.049	0.021
		_	•		2010		0.028	0.048	0,024
	44	6	6.24	5.64	25.6	0.165	0.043	0.058	0.023
	45	5	5.71	5.39	25.0	0.180	0.033	0.046	0.025
	46	4	4.60	5.00	25.3	0.164	0.051	0.042	0.024
	47	3	2.68	2.47	25.5	0.140	0.027	0.042	0.018
	48	2	0.94	1.05	24.1	0.131	0.025	0.028	0.015
	49	6	5 56	8.09	22.4	0 000	0.020	0.000	0.017
	50	a	6 44	6.05	44.4 01.7	0.200	0.022	0.038	0.015
	51	e	5 90	5.90	21.7	0.238	0.020	0.034	0.014
	52	4	3.85	3.02	22.0	0.222	0.034	0.022	0.014
	53	4	4 60	3,03 / 0/	41.4 00 0	0.200	0.043	0.035	0.013
		3	7.00	7.04	64.4	0.179	0.001	0.030	0.0.0
	54	4	4.74	5.30	21.9	0.170	0.048	0.037	0.017
	55	6	4.78	6.41	24.1	0.165	0,028	0.027	0.018
	57	5	1.69	2.11	30.3	0.161	0.016	0.017	0.021
1	58	5	2.40	2.37	30.9	0.166	0.020	0.022	0.016
	59	4	1.40	2.72	31.4	0.273	0.021	0.021	0.013
	60	4	2.01	2.42	31.4	0.325	0.030	0.033	0.012
	61	3	1.37	1.45	32.3	0.236	0.038	0.039	0.013
	62	2	2.06	1.94	33.3	0.386	0.049	0.051	0.039
	63	1	· 1.04	0.92	34.0	0.478	0.064	0.045	0.029
	64	1	0.88	1.00	34.0	0.513	0.052	0.030	0.024

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RESULTS FROM NTS PATH GEOMETRY AND RANGE DEPENDENCE EXPERIMENT

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Table 3 (Cont.)

			(d B) *			σ	(°C)	
RUN NO.	SITE NO.	SURFACE RECEIVER	TOWER RECEIVER	⊤ (°C) z = 3 m	z = 2m	z = 92m	z = 213m	z = 460 m
65	6	6.07	6.90	34.4	0.579	0.064	0.038	0.069
67	4	2.27	2.31	34.2	0.225	0.028	0.025	0.040
69.	3	2.01	1.78	36.4	0.340	0.083	0,071	0.026
70	2	2.37	2.98	38.3	0.588	0.063	0.024	0.037
71	1	0.69	1.09	38.3	0.655	0.051	0,028	0.043
72	2	1.01	0.88	38.3	0.593	0.053	0.036	0.033
73	3	2.06	2.26	37.1	0.531	0.024	0,018	0.019
74	4	2.89	3.13	38.3	0.273	0.050	0.040	
75	5	3.16	3.65	35.6	0.213	0.011	0.017	0.055
78	6	4.08	4.01	36.2	0.268	0.027	0.032	0.015
79	4	2,53	2,10	37.9	0.419	0.060	0.031	0.027
80	4	2.92	2.17	37.2	0.396	0.049	0.031	0.021
82	2	1.63	1,12	37.1	0.435	0.038	0.037	0.026
85	5	4.50	5,17	34.2	0.481	0.048	0.044	0.035
86	4	4,89	4,88	33.3	0.726	0.075	0.053	0.033
87	3	2,77	3,24	33.4	0.570	0.039	0.079	0.022
88	2	1.99	1.69	34.4	0,609	0.055	0.084	0.016
89	1	0.97	1.12	34.5	0.742	0.035	0.090	0.071
93	3	3.57	4.24	38.1	0.489	0,102	0.094	0.082
94	2	1.35	1.18	37.5	0.518	0,064	0,075	0.020
96	1	1.40	1.25	38.0	0.809	0.061	0.085	0.045
97	2	2.31	1.87	37.8	0.701	0.054	0.063	
101	4	0.58	0.74	33.0	0.045	0.010		0.014
102	4	0.42	0.48	32.3	0.044	0.010		0.015
103	4	0,48	0.55	31.3	0.057	0.011		0.015
104	4	0,39	0,50	30.3	0.087	0.010		0,015
105	4	0.76	0.64	29.8	0.082	0.011		0.015
106	4	1.83	1.04	28.7	0.155	0.024		0.013
107	4	1.14	1.16	28.3	0.120	0.019	[0.014
108	6	2.40	2.69	28.3	0.139	0.015		0,014

RESULTS FROM NTS PATH GEOMETRY AND RANGE DEPENDENCE EXPERIMENT

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Table 3 (Cont.)

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		σ	(d D) *			σ	(°C)	
RUN	SITE	SURFACE	TOWER	T (°C)				····
NO.	NO.	RECEIVER	RECEIVER	z=3m	z = 2m	z = 92m	z = 213m	z = 460 m
109	6	3.61	3.91	28.2	0.128	0.016	~-	0.014
110	5	2.57	3.04	27.7	0.104	0.015		0.015
111	4	1.48	1.77	27.1	0.116	0.013		0.018
112	4	2.67	2.67	27.3	0.081	0.017		0.017
113	4	2.01	2.05	28.0	0.092	0.043		0.016
114	3	1.07	1.08	27.5	0.132	0.029		0.019
115	2	1.57	0.93	27.5	0.090	0.029		0.014
117	1	0.95	0.50	26.9	0.193	0,052		0.031
118	6	5.38	5,20	26.5	0.082	0.039		0.024
120	5	4.61	4.77	25.8	0.121	0.018		0.022
121	4	3.76	2.89	25.6	0,104	0.020		0.020
122	3	1.48	1.31	26.1	0.128	0.012		
123	3	2.62	1.94	26.0	0.206	0.027		0.027
124	2	1.24	0.88	25.9	0.150	0.027		0.028
125	2	1.12	0.67	25.5	0.095	0.032		0.026
	_				_		1	
126	1	1.08	1.04	24.9	0.070	0.039		J.043
128	6	5,50	5.46	24.8	0.108	0.012		0.028
129	5	5.11	5.46	24.4	0,121	0.037		0.030
131	4	3.47	3.81	25.4	0.092	0,023		0.029
132	3	1.08	1.15	24.7	0.112	0.040		0.016
133	1	1.14	0.92	31.9	0.562	9.062	0.057	 ·
134	2	1.49	1.77	32.5	0.756	0.046	0.063	0.031
137	4	4.08	3.96	35.6	0.606	0.075	0.090	0.062
140	1	0.77	1.18	36.8	0.671	0.069	0.038	0.022
141	2	0.87	1.01	29.5	0.346	0.054	0.033	0.126
	}							
143	3	1.87	1.50	31.4	0.587	0.061	0,113	0.166
144	4	4.34	4.65	32.3	0.627	0.095	0.040	0.033
145	5	6.07	5.87	33.4	0.701	0.076	0.050	0.056
146	6	5.91	6.79	32.2	0.474	0.035	0.070	0.020
147	3	3.29	3.20	33.1	0.722	0.049	0,083	0.033

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2. *

RESULTS FROM NTS PATH GEOMETRY AND RANGE DEPENDENCE EXPERIMENT

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		σ	(d 0) *			σ	(*C)			
NO.	NO.	SURFACE	TOWER RECEIVER	T (●C) 2 * 3 m	2 * 2m	m36+5	2 = 213m	n 00#+5		
148	4	4.55	4.92	34,4	0.796	0.082	0.084	0.078		
149	5	5,58	6.56	31,8	0.794	0.052		0.047		
150	5	5.24	5,67	33,6	0.599	0.107	0.071	0.073		
152	3	4.08	4.25	35,6	0,609	0.068		0.060		
153	3	3,54	4.22	37.3	0.613	0,092		0,060		
155	5	5,19	6.37	36.7	0,879	0.071	0.045	0.030		
157	6	5.59	8,53	36.4	0.669	0.030	0.030	0.065		
159	3	2,60	3.72	37.1	0.752	0.079	0.062	0.059		
160	3	2,96	3.57	37,1	0.882	0.059	0.049	0.043		
161	4	6,26	6.55	37.1	0,788	0.078	0,059	0.034		
162	5	6.10	6.15	36,8	0.684	0,059	0.051	0.035		
163	6	5.48	6.72	37.9	0,689	0.114	0.109	0.065		
164	6	5.05	7.59	38.1	0.732	0.038	0.024	0.030		
104	Ø	0.00	1.0 8	38.1	0.734		0,038	0,038 0,034		

RESULTS FROM NTS PATH GEOMETRY AND Range Dependence experiment

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* Divide values by 4.34 to convert from dB to conventional natural logarithms.

-- Data missing or invalid.

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quite inhomogeneous. These lateral thermal gradients could cause the laser beam to wander, thereby producing the bimodal distribution shown in the figure. Regments of data containing these bimodal distributions have been deleted in the processing routine by the operator.

Similarly, cases of poor receiver-transmitter alignment, laser malfunction, mechanical vibration, and so forth have been detected and omitted from the analyses. Furthermore, we have chosen to discard those runs where only a single laser may have been operating satisfactorily or where the near-surface differential thermometer was inoperative. Of the total of 183 runs made in the field, 133 were suitable for subsequent analysis as distated by the above criteria. The standard deviations of the laser and differential temperature data for these runs are tabulated in Table 3.

B. Results

1. General

The analysis procedure described in the preceding section provides values of the standard deviation (σ) of the log-intensity signals from the two laser recoivers and of the differential temperature fluotuations (Δ T) from the four differential thermometers.

The measurements of $\sigma(\Delta T)$ are used to derive values of C_n , the refractive index structure constant. Specifically, the temperature structure function, D_m , is defined as

$$D_{T} = [T(r_{1}) - T(r_{2})]^{2} = 0^{2} (\Delta T)$$
 (8)

In the inertial subrange of the spectrum of atmospheric turbulence, the turbulence is isotropic and the Kolmogorov (1941) "two-thirds" law can be applied to describe the refractive index structure function, $D_{\rm c}$:

$$D_{ij}(r) = [n(r_1) - n(r_2)]^2 = C_n^2 r^{2/3}$$
, (9)

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where r is the separation distance and C_n is the refractive index structure constant. When the Kolmogorov law is applied to the temperature fluctuations, the analog of Equation (9) is seen to be

$$D_{T} = C_{T}^{a} r^{a} r^{3}$$
, (10)

where C_T is the temperature structure constant. On combining Equation (10) with (8),

$$C_{T} = \sigma(\Delta T) r^{-1/3} , \qquad (11)$$

It can easily be shown (e.g., Tatarski, 1971) that the structure constants for the refractive index and temperature are essentially proportional and, when neglecting the minimal effects of water vapor, are related by

$$C_n = (79 \times 10^{-6}) (p/T^2) C_T$$
, (12)

where p is atmospheric pressure in millibars, and T is the absolute air temperature in degrees Kelvin. Combining Equations (11) and (12),

$$C_n = (79 \times 10^{-6}) (p/T^2) r^{-1/3} \sigma(\Delta T)$$
 (13)

Surface pressure observations were obtained from the nearby National Weather Service station at Yucca, Nevada (elevation 1200 m msl). Because of the large variation in height over which the differential temperature measurements were made, it was necessary to compute pressure values at the various levels. In this regard, the pressure-height relationship in a standard atmosphere (Berry et al., 1945) was used, where

$$\mathbf{p} = \mathbf{p}_{0} \left(1 - \frac{\overline{\mathbf{v}}_{\mathbf{R}}}{\mathbf{v}_{0}} \right)^{\mathbf{R}/\mathbf{K}^{*}\overline{\mathbf{v}}}, \qquad (14)$$

and a is the elevation above the reference level where temperature and pressure are T_0 and p_0 , respectively; g is the auceleration of gravity; $\overline{\gamma}$ is an average temperature lapse rate (assumed equal to 6.5° K km⁻¹); and K[#] is the gas constant. Under the assumed conditions, the exponent has the value of 5.26.

For a slant path (subscript a) of length R with the coordinate origin at the receiver, Tatarski (1961) has developed a theoretical expression for the standard deviation (a_t) of the log of the intensity fluctuations of a plane monochromatic beam in a turbulent atmosphere, where

$$J_{t=1,49} (2\pi/\lambda)^{7/12} \left[\int_{0}^{\pi} C_{n}^{2}(\vec{r}) r^{5/6} dr \right]^{1/2} .$$
 (15)

For a spherical wave, the equation for σ has the same form but the constant has the value 0.97.

To evaluate the integral, C_n must be specified as a function of distance along the slant path. There is insufficient knowledge about the vertical structure of C_n and indeed the measurements made during this program represent a substantial contribution in this area. In integrating Equation (15), we have assumed that C_n is independent of distance in the horizontal plane. Vertical variations of C_n have been treated in two ways: (1) assuming a simple exponential decay, and (2) on the basis of a linear variation between measurement levels.

The model assumption for C_n is that used in our earlier studies (Johnson et al., 1970, and Dabberdt and Johnson, 1971),

$$C_n = C_{no} \exp(-kz) , \qquad (16)$$

where k is a selectable parameter with units of m^{-1} and C_{no} is the nearground, measured value. When the proposed C_n profile is substituted into Equation (15), and geometrical considerations involving the slantpath elevation angle (0) are taken into account, we obtain the following:

$$v_{ts} = 1.43 (2\pi/\lambda)^{7/12} C_{no} A^{1/2}$$
 (17)

The value of the constant is changed slightly irom Tatarski's plane-wave value in keeping with our earlier format as determined by the results of horizontal propagation experiments (Johnson et al., 1970). The range integral (A) in Equation (17) is dependent on the direction of propagation and is given by

Case I (surface laser-elevated receiver):

$$A = A_{1} = \int_{0}^{\infty} e^{-B(R-r)} r^{5/6} dr , \qquad (18)$$

Case II (elevated laser-surface receiver):

$$A = A_{2} = \int_{-\infty}^{R} e^{-Br} r^{5/6} dr , \qquad (19)$$

where $B = 2k \sin \theta$. Equations (18) and (19) are then solved by numerical integration.

In the second method, Equation (15) is solved analytically through the use of a linear interpolation of C_n between measurement levels, where

$$C_n (z_1 \rightarrow z_2) = C_n (z_1) \{ 1 + a [z - z_1] \}$$
, (20)

The bracketed term in Equation (15) is then integrated using Equation (20), where .

Case ! (surface laser-elevated receiver):

$$R^{*} = R_{1}^{*} = \sum_{i=1}^{3} c_{n,4-i}^{2} \int_{r_{i}}^{r_{i+1}} \left[1 + a_{4-i} (r_{i+1} - r) \sin \theta \right]^{2} r^{5/6} dr, \quad (21)$$

Case II (elevated laser-surface receiver):

$$R^{*} = R_{2}^{*} = \sum_{i=1}^{3} c_{ni}^{2} \int_{r_{i}}^{i+1} \left[1 - a_{i}z_{i} + (a_{i}\sin\theta)r\right]^{2} r^{5/6} dr.$$
(22)

The subscript notation i denotes the layer over which the integration is performed where $r_i = z_i \csc \theta$, and a_i is the constant in Equation (20) for the layer with lower bound z_i . The use of Equations (18), (19), (21), and (22) is discussed in subsequent sections of this report.

2. <u>Height Dependence of the Refractive Index</u> Structure Function

Equation (13) is used to compute values of the refractive index structure function, C_n , using the mean and fluctuation temperature measurements, the computed profile of atmospheric pressure [Equation (14)], and a 60-cm separation distance. The C_n data were stratified according to the atmospheric stability in the lowest 92 m:

Inversion conditions

$$T(2 m) - T(92m) < 0.9$$
°C ,

Lapse conditions

$$\Gamma(2 m) - T(92 m) > 0.9^{\circ}C$$
.

The individual C_n profiles were then used to evaluate the parameter k from Equation (16), where

$$k = -\frac{1}{z} \log \left(\frac{C}{n} \right)$$

Three values of k were obtained for each profile and these have been stratified by the stability. The mean and standard deviation of the ratio C_n/C_n and the average k value for each category are summarized in Table 4. Only those runs were used where simultaneous ΔT measurements were obtained at all four heights; these include 30 inversion and 68 lapse cases.

Table 4

HEIGHT AND STABILITY DEPENDENCE OF C /C AND k n no

Laver	Inver	sion	Lapse		
(m)	$(\overline{C_n/C_n})$	k [m ⁻¹]	$(\overline{C_n/C_n})$	k [m-1]	
0-92 0-213 0-460	0.179 ± 0.14 0.194 ± 0.13 0.106 ± 0.04	0.0187 0.0077 0.0049	0.129 ± 0.08 0.109 ± 0.07 0.086 ± 0.07	0.0223 0.0104 0.0053	

The observed height dependence of C_n is illustrated in Figure 16, together with the theoretical structure given by Equation (16) using two typical values of k. It is highly significant that the theoretical, exponential decay of C_n with height does not provide a particularly good representation of the details of the average profile structure; individual profiles are even less well represented. The reasons for the apparent failure of this simple model to simulate observed conditions can be explained through a consideration of both micro- and mesometeorological processes. In the case of the latter, the effects of such meteorological phenomena as frontal activity, squall lines, and air mass structure must be considered when describing the temporal and spatial variations of C_n .

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Clearly, these cannot be simulated on the basis of purely local conditions. In the absence of these effects, micrometeorological influences will determine the C structure. Temporal variations will then occur with a predominantly diurnal periodicity. Shortly after sunrise, solar energy will be absorbed at the earth's surface and subsequently partitioned, in part, as a flux of sensible heat in both the soil and atmosphere. In comparison, direct heating of the air by solar absorption is minimal and can be ignored. Under these conditions, the input of heat to the atmosphere is controlled by the surface, and the transport of heat to higher levels occurs with a finite time lag. Moreover, the time lag is height dependent. At night, the situation is reversed because of radiational cooling at the surface and the subsequent transport of heat is from the atmosphere to the surface. Since the magnitude of C is proportional to the absolute value of the atmospheric sensible heat flux, one must consider both the nature of diurnal variations at the surface and the timeheight dependence of the atmospheric diffusion process.

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As a first-order approximation, the problem may be considered as an analogy to the classical case of thermal diffusion of heat in a homogeneous medium with a periodic source function. Therefore, the neursurface time variation of C_n is given by

$$C_{no}(t) = \sum_{i} \left\{ \overline{C}_{no,i} + \Delta_{i} C_{no} \cos (\omega_{i} + \zeta) \right\}, \qquad (23)$$

where the overbar denotes the time-averaged value, i is the number of the harmonic period with frequency ω , ζ is a constant phase lag, and t is time. Similarly, the nonsurface variation is expressed as

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$$C_{n}(z,t) = \sum_{i} \left\{ \overline{C}_{n,i} + \Delta_{i}C_{n} \cos \left(\omega_{i}t - z/Z_{i} + \zeta \right) \right\}$$
(24)

Z is the so-called "damping depth," where the amplitude of the wave is 1/e (about 0.37) times "We surface value. For illustration purposes," we may consider only the diurnal period and make the additional model assumptions:

$$\overline{C}_{n} = \overline{C}_{no} \exp(-z/Z)$$
, and (25)

$$\Delta C_{n} = \Delta C_{no} \exp(-z/Z). \qquad (26)$$

Combining Equations (23-26), the ratio C /C is

$$\frac{C_{n}}{C_{no}} = \exp((-z/Z)) \left\{ \frac{\overline{C}_{no} + \Delta C_{no} \cos(\omega t - z/Z + \zeta)}{\overline{C}_{no} + \Delta C_{no} \cos(\omega t + \zeta)} \right\}.$$
(27)

Although the NTS experimental program did not encompass any complete diurnal cycles, we may take advantage of the similar meteorological conditions that persisted over the first few experimental days to construct a "typical" diurnal variation using data from the following periods: 1000-1930, 12 July; 1900, 13 July - 0600, 14 July; and 0640-1000, 15 July. The composite diurnal cycle for C_{n0} is illustrated in Figure 17. The value of C_{n0} is about $2.5 \times 10^{-7} \text{ m}^{-1/3}$ while ΔC_{n0} is on the order of 2.0×10^{-7} . These values and a 100-m damping depth have been used to illustrate the simple, descriptive model [Equation (27)] in Figure 18. Vertical c_n/C_n profiles are shown for six times during the period; the phase lag ζ would be about 12 hours so that the profile at t = 0 would correspond to 120C LST.



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FIGURE 17 DIURNAL VARIATION OF THE NEAR-SURFACE REFRACTIVE INDEX STRUCTURE FUNCTION (C_{no}) AT THE NEVADA TEST SITE (1971)



FIGURE 18 THEORETICAL TIME-HEIGHT VARIATION OF THE RATIO C_n/C_{no} , WITH Z = 100 m AND $C_{no}/\Delta C_{no}$ = 1.25

3. Slant-Path Scintillation

The theoretical value of the standard deviation of the log of the intensity fluctuations was computed using Equation (15) with the two model assumptions [Equations (16) and (20)] for the height variation of the refractive index structure function:

and

$$\sigma_{\rm ts} = 1.43 \ (2\pi/\lambda)^{7/12} \left[\int_{0}^{R} c_{\rm n}^{2} (\vec{r}) r^{5/6} dr \right]^{1/2}$$

 $C_n = C_{no} \exp(-kz),$

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$$C_{n}(z_{1} \rightarrow z_{2}) = C_{n}(z_{1}) \left\{ 1 + a \left[z - z_{1} \right] \right\}$$

In making the computations with the linear interpolation method for C_n , values of the coefficient <u>a</u> were determined for each run between 2 and 92 m, 92 and 213 m, and 213 and 460 m, and Equation (15) was then integrated anaytically using Equations (21) and (22). Figures 19 and 20 depict the relationship between the theoretical and measured values of σ along air-to-ground and ground-to-air propagation paths, respectively. These data have been fitted by a nonlinear, least-squares computer program to an empirical equation of the form

$$\sigma_{\rm m} = \frac{\sigma_{\rm t}}{1 + \alpha \sigma_{\rm t} \beta} \qquad (28)$$

where the subscript m refers to the measured value, and α and β are constants. Equation (28) has been evaluated independent of the atmospheric stability and is plotted along with the data in the two figures. For the air-to-ground path, $\alpha = 0.47$ and $\beta = 1.10$, while for the ground-to-air case, $\alpha = 2.31$ and $\beta = 0.53$.



Figures 19 and 20 also illustrate the apparent dependence of the scintillation on the class of atmospheric stability. Those experimental runs that were conducted under stable lower atmospheric conditions are depicted by the triangular symbols in the figures; unstable conditions are shown by the crosses. In interpreting these data, the theoretical sigma values provide a convenient scaling factor of atmospheric (C_n) and geometric (r, θ) conditions. Clearly, the measured scintillation is consistently larger for stable conditions than for the unstable cases.

To examine these differences in greater detail, the scintillation data have been stratified according to both the path-type and stability category in Figures 21 through 24. The values of the constants α and β from the regression Equation (28) for each case are summarized in Table 5; the individual functions are plotted on the respective figures.

Table 5

VALUES OF α AND β FROM EQUATION (28) USING THE MODEL ASSUMPTION

			Atmosphe:	ric Stab:	llity			
Path Type	Inve	rsion	La	pse	A11	Cases		
	α	β	۵	β	۵	β		
Air-to-ground	0.16	1.64	0.72	0,82	0.47	1.10		
Ground-to-air	1.38	0,61	3.21	0.42	2.31	0.53		

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 $C_{n}(z_{1} \rightarrow z_{2}) = C_{n}(z_{1}) \left\{ 1 + a \left[z - z_{1} \right] \right\}$

Within the broad range of experimental conditions represented by these data, there are indications of scintillation saturation for both propagation paths. While saturation may be inferred, the data provide no evidence of scintillation supersaturation as had been noted earlier by Dabberdt and Johnson (1971) for near-ground horizontal paths.



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FIGURE 24 SCINTILLATION ALONG AN AIR-TO-GROUND PATH FOR INVERSION CASES; LINEAR INTERPOLATION MODEL FOR $C_n(z)$ -EQUATION 20

If saturation does indeed occur along the slant path, then one would expect to find evidence first along the ground-to-air path (because of the dominance of conditions near to the source). Presumably, saturation should also first be noted during unstable atmospheric conditions when the magnitude of the refractive index structure function is largest. These experimental conditions are the basis for the data prosented in Figure 31. As expected, there appears to be a systematic leveling off of the observed scintillation ($\sigma_m \approx 1.7$) at large distances and high C_n values (as reflected in the scale factor, σ_{χ}). However, there are too few data points in this range to fully confirm that saturation has indeed occurred, A surprising aspect of ground-to-air scintillation is illustrated in Figure 32. These data were obtained under inversion (mightime) conditions and consequently span a smaller range of σ_t values (as shown in Figure 17). In spite of the smaller values of σ_t , the magnitude of the scintillation is the same us that observed under the unstable atmospheric conditions. Comparing the two cases, it appears that the scintillation under stable conditions is comparable to the "unstable" scintillation where scale values (σ_t) are about two times larger. A significant consequence of this observation may be the dependence of the scintillation on the frequency or scale of the thermal fluctuations.

Figures 23 and 24 show a similar pattern for the variation of sointillation along the air-to-ground path for lapse and inversion donditions, respectively. Surprisingly, there is an even stronger indication of possible sointillation saturation for the unstable cases with this path configuration than was noted earlier for the ground-to-air, unstable cases. Again, the small number of cases preoludo a definitive analysis of the saturation phenomenon. The maximum g_m values are about 1.4, in contrast with the ground-to-air value of 1.7. The stability

dependence of air-to-ground scintillation is illustrated by the comparison of Figures 23 and 24. As with the ground-to-air cases, the maximum observed scintillation of about 1.4 for the air-to-ground configuration is independent of stability (i.e., lapse or inversion conditions). As noted before, the relative $\partial_{\underline{x}}$ dependence of $\sigma_{\underline{x}}$ is virtually identical for both stability types, but the comparable $\sigma_{\underline{x}}$ values are again about two times larger for the lapse cases. This suggests that there is a scaling effect not only of range, geometry, wavelength, and turbulence intensity, but also of the stability types, i.e., lapse or inversion. We therefore propose, in way of conjecture, that the scintillation magnitude is also dependent on the frequency (or scale) as well as the magnitude of the thermal fluctuations.

During lapse conditions, there is a decrease in the atmospheric potential temperature with height and a tendency for convective activity resulting from the unstable density stratification; for inversion conditions the reverse is true and the atmosphere is regarded as stable. Typically the spectrum of near-surface thermal fluctuations during inversion conditions (typical of clear nights) is characterized by relatively high frequencies (and low wavelengths) due to the height variation of temperature and the action of mechanical turbulence. During lapse conditions (characteristic of sunny days), the spectrum of thermal fluctuations is often augmented by the effects of buoyancy (free convection). The impact of this convective activity is reflected in the occurrence of a second peak in the spectrum at lower frequencies (higher wavelengths). In summary, nighttime conditions are characterized by relatively small though frequent turbulent elements, whereas daytime conditions with free convection may be dominated by the larger, infrequent convective cells. As a consequence, it may be that the "effective range" (or number of refractive occurrences along the path) is significantly less for these daytime conditions although the value of C_n may not differ from the nighttime case. The idea of an effective
range is introduced to specify the relationship between the scale of turbulence and the scintillation: For equal values of C_n and a given propagation path, daytime scintillation under free convection is observed to occur as if the range were effectively reduced.

As mentioned earlier, the measured sointillation (c_m) represents a line-integral value, while the theoretical values are computed on the basis of a few point measurements of the refractive index structure function. Two possible sources of uncertainty result: (1) the vertical profile of C_n obtained from the measurements may not provide sufficient spatial resolution under all atmospheric conditions. This is illustrated by the hypothetical, time-dependent vertical profiles of C_n illustrated in Figure 18; and (2) the concept of "frozen" turbulence may not always be fulfilled, i.e., the time-average of C_n at a point may not always provide an adequate measure of the space average of C_n at a given time. While these effects presumably add some noise to the system, they do not affect the overall or average picture as presented in Figures 21 through 24.

At present, there is insufficient information to parameterize the amplitude and phase functions in Equation (27) for the incorporation into the eye-safety evaluation procedure (Chapter V). Similarly, Equation (20) cannot be applied in this manner because it requires in situ measurements of the vertical structure of C_n . The use of Equation (16) therefore is retained in the evaluation procedure since it provides conservative (safe) results and represents a model's successful simulation of conditions and is easily parameterized. Figures 25 through 28 illustrate the $\sigma_m - \sigma_n$ relationship incorporating Equation (16) for the data stratified in an identical manner to the presentations in Figures 21 through 24, respectively. The relative features are the same for the two sets of data and only the absolute values of σ_t differ. The unstable, ground-to-air cases (Figure 25) are similar to the slant-path

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data collected previously by Dabberdt and Johnson (1971); the results from the two programs agree quite well. For the present study, evaluation of the regression Equation (28) for these cases yields values for the two constants of $\alpha = 2.07$ and $\beta = 0.45$, while the earlier (1971) results give $\alpha = 1.79$ and $\beta = 0.69$.

In summary, the use of the linear interpolation model for $C_{\mu}(z)$ -- Equation (20) -- is to be preferred for the evaluation of the field data as it provides the best representation of ambient conditions as determined from the in situ measurements. However, the exponential model for $C_n(z)$ -- Equation (16) -- is more suited for incorporation into the eye-hazard evaluation procedure as it is more readily parameterized. It is desirable, therefore, to compare the two application in Tatarski's theory, Equation (8). Figures 29 through 32 illustrate these σ_1 values for both path types and the two stability classes. For the two stability classes and the ground-to-air path, the "exponential" model consistently gives $\sigma_{\mathbf{t}}$ values about twice those obtained from the "linear" model, while along the air-to-ground path the two models provide essentially similar values of σ_{\downarrow} for both stability categories. As would be expected, the scatter is larger for the inversion cases than with the lapse cases and probably reflects the greater atmospheric homogeneity associated with the latter. The application of Equation (16) in the eye-hazard evaluation procedure has been revised on the basis of the path dependence of the exponential model assumption for $C_n(z)$.

The classical slant-path propagation theory of Tatarski [see Equation (15)] predicts scintillation values that are heavily dependent on the direction of propagation in the planetary boundary layer because of the height dependence of C_n . While first seeking to confirm the validity of this relationship, the ratio of measured scintillation along



FIGURE 29 GROUND-TO-AIR PATH--LAPSE CASES



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FIGURE 31 AIR-TO-GROUND PATH-LAPSE CASES



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the two reciprocal paths was compared with the theoretical ratio using Equation (15) and the C_n computations. A surprising result of this comparison is that there is virtually no systematic relationship that can be observed. Therefore, the observed scintillation ratio was examined in view of the corresponding value of the theoretical, groundto-air scintillation (σ_t). The use of σ_t is justified on the basis of its role as a convenient scaling parameter for range and C_n. The results of this comparison are illustrated in Figure 33 and have been stratified according to atmospheric stability. The best-fit linear regression equation for each case is also illustrated. It can be noted that there is a slight dependence of the ratio of the magnitude of σ_t , although the scatter is quite large and particularly so at the low σ_t values. Again, the stability dependence is evident in the difference in the magnitude of the slope of the regression line for the two stability classes. We may conclude that the simple relationship between scintillation and path type, as in the theory of Tatarski, is not evidenced by our observations and that additional research into the complexities is required.

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A. General

In three earlier reports on this project (Johnson et al., 1968, 1973, and Dabberdt and Johnson, 1971), a procedure was described for estimating the probability of eye damage from exposure to a laser beam. Similar work has been reported by Deitz (1968, 1969). The eye-hazard evaluation procedure presented in this section incorporates minor revisions that reflect the results of our latest experimental work. The equations and assumptions underlying each part of the eye-hazard evaluation procedure (as represented by Figures 34 through 41 and Tables 6 and 7 will be briefly explained in a subsequent section.

It should be emphasized that these eye-safety guidelines should be considered tentative and used with caution until the new experimental results that they reflect can be confirmed for a variety of laser-beam and propagation-path configurations.

B. Eye-Hazard Evaluation Procedure

The input parameters required for the eye-hazard evaluation procedure are as follows:

 φ , latitude (deg)

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- U, surface wind speed (knots)
- V, atmospheric visibility (miles)

N, cloud cover (tenths)

 θ , slant-path elevation angle (deg)

R, range (km)

P, laser peak power (W)

Q, laser pulse rate (pulses/s)

 λ , laser wavelength (μ)

 β , laser beam divergence (mrad)

d, minimum beam diameter (m)

T, exposure time (s)

Laser type (CW, long pulse, or Q-switched)

Type of slant path (ground-based or airborne laser)

Date and time.

Using the above information, one can estimate the probability of eye damage by the method outlined below:

- In the case of relatively low-power lasers, go to Step (2).
 For other lasers, skip to Step (3).
- (2) Divide the LASER POWER P (W) by the minimum beam area $\pi d^2/4$ (m²), using the MINIMUM BEAM DIAMETER, d (m), to compute the maximum power density available for eye damage (W/m²). If this value does not exceed the appropriate MAXIMUM SAFE POWER DENSITY LEVEL (I) given in Table 7, then the laser can be considered safe and the rest of the procedure disregarded.
- (3) Use TIME OF YEAR, HOUR OF DAY, and LATITUDE, Φ , in Figure 34 to find SOLAR ELEVATION ANGLE, α . Interpolate between graphs for dates between those given. For latitudes in the southern hemisphere, reverse the dates on graphs (a) and (c). For nighttime, proceed to Step (5).
- (4) Use a and CLOUD COVER, N (tenths), in Figure 35 to find INSOLATION CATEGORY, S (strong, moderate, or weak).

- (5) For daytime, use 8 and 8URFACE WIND, U (knots), in Table 8 to find NEAR-(ROUND REFRACTIVE INDEX STRUCTURE CONSTANT, $C_{\rm R}$ (10-6m^{-1/3}). For nighttime, use last two columns of table, given N.
- (d) For a near-ground horizontal propagation path, proceed to Step (6). For a slant path, use RANGE H (km), and SLANT-PATH ELEVATION ANGLE, α , in Figure 36 to find RANGE INTEGRAL, A (m-11/6).
- (7) For a slant path, use A, C, LASER WAVELENGTH, λ (μ), propagation direction, and the atmospheric stability in Figure 37 to find LOG-INTENSITY STANDARD DEVIATION, σ . Assume LAPSE CONDITIONS during the daytime and INVERSION CONDITIONS at night. [Proceed to Step (9)].
- (8) For a near-ground horizontal path, use R, C, and LASER WAVELENGTH, (u), in Figure 38 to find LOG-INTENSITY STANDARD DEVIATION, σ_{*}
- (9) Use ATMOSPHERIC VISIBILITY, V (miles), LASER BEAM DIVERGENCE, β (milliradians), and R in Figure 39 to find NORMALIZED MEAN POWER DENSITY, 1/P (m⁻²).
- (10) Multiply I/F by LASER POWER, P (W), to obtain MEAN POWER DENSITY, I (W m⁻²).
- (11) Use λ and LASER TYPE (Q-switched, long pulse, or CW) in Table 7 to obtain MAXIMUM SAFE POWER DENSITY, I (W m⁻²). For a CW laser, use the following characteristic pulse" times: (1) 2 to 10 ms for a slant path involving an aircraft, and for static paths and U > 10 knots, and (2) 10 to 500 ms for static paths and U < 10 knots.
- (12) Divide I by \overline{I} to obtain SAFE-TO-MEAN-POWER-DENSITY RATIO, I safe \overline{I} .
- (13) Use J and I $/\overline{I}$ in Figure 40 to obtain INSTANTANEOUS PROBABILITY OF EYE DAMAGE, γ .

(14) Une y and KVENT PREQUENCY, F (m⁻¹), in Figure 41 or, alternatively, in Equation (38), to obtain INTEGRATED PROBABILITY OF EYE DAMAGE, F, for given EXPOSURE TIME, T, For pulsed lasers, set F equal to the LAREN PULSE RATE, Q (pulses/s). For CW lasers, set F equal to the values given below:

Mtatic path

U # 10 knots: F = 800 U ≥ 10 knots: F = 1000

Aircraft path: F = 5000



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Table 6

RELATION	OF	NEAR -GROU	ND	(1	2 m)	REFRAC'	r i ve	INDEX	STRUCTURE
		CONSTANT	(0)	70	WEATHER	COND	ITIONS	5

	$C_n (10^{-6} m^{-1/3})$						
	Dayt C	ime Insola ategory (S	ation S)	Nighttime Conditions			
Surface Wind (knots)	Strong	Moderate	Weak	Thin Overcast or ≥ 5/10 Cloudiness	≤ 4/10 Cloudiness		
< 3	0,60	0,50	0.40	0.30	ð.4 0		
3-6	0.50	0.40	0.25	0,20	0.35		
6-10	0.40	0,25	0.15	0,10	0.20		
10-12	0.20	0.12	0.05	0.05	0,05		
> 12	0.12	0.05	0.05	0,05	0,05		



FIGURE 36 RANGE INTEGRAL (A) AS A FUNCTION OF RANGE (R) AND SLANT-PATH ELEVATION ANGLE (θ), FOR THE TWO TYPES OF SLANT PATHS



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MORMALIZED MEAN POWER DENSITY (1/P) AS A FUNCTION OF BEAM DIVERGENCE ANGLE (8) AND RANGE (R), FCR VARIOUS VALUES OF ATMOSPHERIC VISIBILITY (V)

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Table 7

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MAXIMUM SAFE POWER DENSITY LEVELS, I (w/m^2) , FOR CORNEAL EXPOSURES safe

Laser	Time	Q-Switched	Long Pulse	Continuo	us Wave
Vave length	of Day	(20 ns)	(1 ms)	2 - 10 ms	10-500 ms
Visible	Day	3.53 × 10 ⁶	5.65 × 10 ²	2.83 × 10 ²	1.41 × 10 ²
(0.4 - 0.7 u)	Night	6.50 × 10 ⁵	1.04 × 10 ²	0.52 x 10 ²	0.26 × 10 ²
Neodymi um	Day	1.77 × 10 ⁷	$2.83 imes 10^3$	14.1 × 10 ²	7.07 × 10 ²
(1.06 µ)	Night	3.24 × 10 ⁶	5.21×10^{2}	2.59 × 10 ²	1.30 × 10 ²

Source: U.S. Air Force (1971)

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C. Basis for Eye-Hagard Evaluation Procedure

1. Figure 34

The curves in this figure are based on the following (Smithsonian Meteorological Tables, 1963):

$$\alpha = \sin^{-1} \left\{ \sin^{\phi} \sin \phi + \cos^{\phi} \cos [0.363(h-12)] \right\} , \qquad (29)$$

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 α = solar elevation angle

- = latitude
- ζ = solar declination
- h = hour of day.

2. Figure 35

The relative insolution strength (S), on a scale from zero to one, is given by

$$S = \sin \alpha$$
 (30)

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for a cloudless, nonattenuating atmosphere. When the cloud cover (N) in tenths is considered and the albedo of the clouds is taken to be 0.5, Equation (30) becomes

$$S = sin [\alpha(1 - 0.5N/10)]$$
, (31)

which is the basis for Figure 35. The categories of S (strong, moderate, and weak insolution) were determined simply by dividing the range of S into three equal intervals: 0 to 0.33, 0.33 to 0.67, and 0.67 to 1.0.

3. Table 6

This table is based principally upon empirical data from our experiments and those of other investigators, such as Wright and Schutz (1967), Fried et al. (1967), Davis (1966), and Goldstein et al. (1965). Unfortunately, most of the values of C_n reported by these other workers have not been accompanied by a full account of the concurrent meteorological conditions. Hence the dependence of C_n on weather conditions as given in the table is based principally on our measurements. The values in the table must be considered only as approximate, since some extrapolation was required, and also since at least one important variable, ground condition, has been omitted for the sake of simplicity.

The basic structure of the table is patterned after that given by Pasquill and Meade (see Slade, 1968) for the estimation of atmospheric stability categories. Since C_n is related to the absolute value of the stability, appropriate values of C_n were substituted for those of stability category.

4. Figure 36

Equations (18) and (19) were used for the computations for the curves presented in this figure. The value of the constant k was taken to be 0.01 so the eye-hazard estimates would be on the conservative (safe) side, as determined from the BREN Tower experimental results.

5. Figure 37

This figure was based on Equation (17) for the slant-path configuration, but we have limited σ to a maximum value according to the direction of propagation and the atmospheric stability. The curves are thus derived from the Tatarski relationship but take into account the saturation effect indicated by experimental results (Chapter IV). Since the occurrence of scintillation supersaturation on the slant path has not yet been adequately confirmed, we have not made any allowance for this. As a result of this omission, any resulting errors would give eye-hazard predictions on the safe side.

6. Figure 38

This figure uses the results of Dabberdt and Johnson (1971)--Equations (10) and (16), Section III-F--and incorporates the supersaturation effect as observed during that horizontal propagation experiment. The coefficients of their Equation (16) used in the calculation are those reported by Johnson et al. (1970). These values were chosen because they give more conservative (higher) estimates of σ_{m}^{*} than the revised equation. The leveling off of the scintillation magnitude in the far-supersaturation region is also incorporated in the figure; again, a safe value (0.5) was chosen.

7. Figure 39

This figure is derived principally from considerations of the luser-beam geometry, represented by the equation

$$\frac{-}{I/P} = \frac{4G}{\pi B^2 R^2} , \qquad (32)$$

where I = mean power density (W/m²) (assumed to be uniform across the beam)

- P = laser output peak power (W)
- β = beam divergence (milliradians)
- R = range (km)
- G = atmospheric transmission.

The transmission is given by

$$G = e^{-aR} , \qquad (33)$$

where a is the attenuation coefficient (km^{-1}) . To a first approximation, the relation between the atmospheric visibility (V, miles) and the attenuation coefficient is given by

$$V = 2,43/a$$
 (34)

for visible and near-infrared wavelengths.

8. Table 7

The maximum safe power density levels $(I_{safe}, W/m^2)$ given in this table are those recommended by the U.S. Air Force in AFM 161-8, Change 1 (1971).

9. Figure 40

The curves in this figure were computed by means of the following equations:

$$Y = \frac{1}{\sqrt{2\pi}} \int_{M}^{\infty} \exp(-x^2/2) dx , \qquad (35)$$

where γ is the instantaneous probability of eye damage, x is a dummy variable, and

$$M = \sigma/2 + \sigma^{-1} \ln \left(i_{safe} / \overline{I} \right) , \qquad (36)$$

where σ is the log intensity standard deviation. The development of these equations, as detailed in the last report (Johnson et al., 1968), involves the assumption of a log-normal probability distribution of intensity fluctuations.

10. Figure 41

When one looks at a laser beam continuously for T seconds, the integrated probability of eye damage (Γ) over that period will be greater than the instantaneous probability of eye damage (Y). One simple way to assess this increased probability is to assume that the intensity peaks occurring at a single observational point represent separate events. If (1-Y) corresponds to the probability of no damage for a single event (i.e., the probability that any one intensity peak will not exceed I_{safe}), then the integrated probability of no damage (1- Γ) for a given number of occurrences (N) in the time period (T) is given simply by multiplying the individual probabilities:

$$1-\Gamma = (1-\gamma)^{N}$$
,
or $\Gamma = 1 - (1-\gamma)^{N}$

Since N = FT, where F is the frequency of events,

$$\Gamma = 1 - (1 - \gamma)^{FT}$$
 (37)

This equation forms the basis for Figure 41. For $\gamma \ll 1$, Equation (37) may be rewritten in approximate form as

$$\Gamma = \gamma FT \qquad . \tag{38}$$

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The event frequency F may be considered to be equivalent to the pulse rate for a pulsed laser, or to the scintillation frequency in the case of a CW laser. If we assume the turbulent elements separated by a mean correlation distance (ρ_0) to move with the wind, then to a first approximation we have

$$F = U_n / \rho_0$$

where U is the wind component perpendicular to the propagation path. Since the variation in ρ_0 with range that is predicted by theory disagrees with that measured, it seems best for our purposes to assume that F depends only on wind speed and beam sweep rate. On the basis of our measurements, the following values have been selected as being representative of the cases given:

Static paths

U \leq 10 knots: F = 500 U > 10 knots: F = 1000 Aircraft slant paths: F = 5000

These coefficients allow for the maximum scintillation frequencies observed during our earlier experiments.

11. Setting a Level of Acceptable Risk

After the probability of eye damage (Γ) is found, it becomes necessary to compare this value with a preestablished value (Γ_{safe}) representing the highest probability judged to be an acceptable risk. The magnitude of Γ_{safe} may change as the nature of the situation changes, but values in the range of 10⁻³ to 10⁻⁵ (one chance of eye damage in 1000 to 100,000 occurrences) seem reasonable. By way of comparison, the probability of an average American being killed in an automobile accident in the year 1968 was one in 3600, or 2.8×10^{-4} , while the probability of being injured in an automobile accident was one in 100, or 10⁻² (World Almanac, 1970).

D. Examples of Use of Eye-Hazard Evaluation Procedure

To illustrate the use of the procedure given above, four examples are presented in Table 8. The input parameters for these examples were selected to be as representative and realistic as possible and to cover a variety of conditions. Example 2 represents the conditions of an actual recent field experiment.

Table 8	,
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Parameter	<u>Examp</u>	le 1 Examp	le 2 Exam	ple 3 Examp	ole 4	
A. SPECI	FIED PARA	AMETERS				
Date	21 De	эс 1 Ма	ay 21.	June 21 J	lune	
Time	2200) 1200	0 150	00 150)0 (Li	ST)
φ	30 ⁰ N	1 40 ⁰ 1	۱ 20⁰	°S 20°	S	
N	2	0	6	6	(ten	ths)
U	5	8	12	12	(kn	ots)
v	20	8	20	20	(mi)	les)
Path Typ	e Slar	it Slar	nt Hori	lz. Hori	z.	
Laser Sit	e Airbor	me Groun	nd		-	
θ	60 ⁰	20 ⁰	0 ⁰	0 0		
R	0.4	1 5	1	6	(kı	n)
λ	0,488	30 0 ,69 4	13 1.0	06 1.0	6 (₁	()
Q		· 0.5	i 10	10	(puls	ses/s)
в	0.5	i 0.5	j 0.	5 0.	5 (mra	ad)
d	2		•		- (10	-3 m)
Р	1	2.5 x	10 ⁷ 10	o ⁷ 10	7 (W	1)
Т	1	0.1	0.	1 0.	1 (5	3)
Laser Typ	e CW	Q-sw	. Q-s	w. Q-s	w.	· /
		<u></u>	······			
B. DERIV.	ED PARAME	TERS				
Step No.						
3	α	o°	60 0	30 0	30 0	
4	S		Strong	Mod.	Mod.	
5	c _n	0.35	0.40	0.12	0.12	$(10^{-6} m^{-1}/3)$
6	A	1.5×10^3	1 x 10 ⁵			(m11/6)
7,8	g	0.3	0.65	0.65	1.20	
9	Ī/P	30	6×10^{-2}	6.7	9 x 10 ⁻²	(m ⁻²)
10	ī	30	1.5×10^{6}	6.7×10^{7}	9 x 105	$(W m^{-2})$
11	I _{safe}	0.52×10^2	3.53×10^6	1.77×10^7	1.77×10^{7}	$(w m^{-2})$
12	I _{safe} /I	1.73	2.36	0.26	20	
13	Ŷ	10^{-2}	5 x 10 ⁻¹		10-3	
14	ſF	5×10^3	0.50		10	(sec^{-1})
	1 Γ	> 10 ⁻¹	5 x 10 ⁻¹		10-3	(500)
15	Safe?*	No	Nc	No	Yes	

EXAMPLES OF LASER EYE-HAZARD EVALUATION

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* Based upon a selected value of $\Gamma_{safe} = 10^{-3}$.

Appendix

EVALUATION OF THE MAXIMUM RISK OF LASER EYE DAMAGE



Appendix

EVALUATION OF THE MAXIMUM RISK OF LASER EYE DAMAGE

A. General

The results in the main body of this report outline a detailed procedure for the estimation of the probability of eye damage from exposure to a laser beam. These guidelines are the result of developments and refinements that have been made during past several years (Johnson et al., 1968 and 1970; Deitz, 1968 and 1969; and Dabberdt and Johnson, 1971). The procedure used in these guidelines incorporates the simulation of local atmospheric conditions and other factors in some detail. While the procedure is quite rigorous and the predictions agree well with observations, the guide is not particularly well suited for ready application by the novice in remote field situations.

Recognizing this particular need, a simple guide has been developed to estimate the typical, "worse-case" level of eye hazard using as input only the most readily available information:

- Total laser output or energy/pulse
- Air Force Permissible Exposure Levels (PEL)
- Laser beam divergence
- Eye pupil diameter
- Laser wavelength
- Laser pulse repetition rate
- Clear atmospheric conditions
- Total personnel exposure time
- Given total probability of super-PEL exposure that is acceptable
- Approximate laser beam elevation angle.

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To ensure accurate estimates in a minimal amount of time, the procedure incorporates only a few simple graphs, tables, and arithmetic steps.

B. Procedure

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The probability of eye damage from exposure to a laser beam under worst-case conditions is estimated on the basis of the following information on environmental and operating conditions:

> Range, R (km) Laser peak power, P (W) Laser pulse rate, Q (s^{-1}) Laser wavelength, λ (μ) Laser beam divergence, β (mrad) Wind speed, U (kts) Exposure time, T (s) Ground-level elevation, z (km) Laser mode (CW, long pulse, Q-switched) Time of day (day or night) Type of path (horizontal or slant)

The method is illustrated schematically in Figure A-1 and detailed the the following step-by-step procedure:

- Step 1: Use GROUND-LEVEL ELEVATION, z (km); LASER BEAM DIVERGENCE, 8 (mrad); LASER WAVELENGTH, λ (μ); and RANGE, R (km); in Figure A-2 to determine the NORMALIZED MEAN POWER DENSITY, I/P (m⁻²).
- <u>Step 2</u>: Multiply I/P by LASER PEAK POWER, P (W), to obtain the MEAN POWER DENSITY, I (W m^{-2}).
- Step 3: Use LASER WAVELENGTH, λ (μ) and LASER MODE in Table A-1 to obtain the MAXIMUM SAFE POWER DENSITY, I_{safe} (W m⁻²).

For a CW laser, use the following characteristic "pulse" times:

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A-4

• 2-10 ms for a slant path involving an aircraft, and static paths with U > 10 knots

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- 10-500 ms for static paths and U \leq 10 knots.
- Step 4: Divide I_{safe} by I to obtain the SAFE-TO-MEAN-POWER DENSITY RATIO, I* (n.d.)
- <u>Step 5:</u> Use I* and the PATH TYPE (horizontal or slant) 3 to obtain the INSTANTANEOUS PROBABILITY of EYE DAMAGE, y.
- <u>Step 6</u>: Ascertain the value of the EVENT FREQUENCY, F (s⁻¹). For pulsed lasers, set F equal to the LASER PULSE RATE, Q. For CW lasers, set F equal to the values given below,
 - Static path
 - U < 10 knots: F = 500
 - U > 10, knots: F = 1000
 - Aircraft path: F = 5000
- <u>Step 7</u>: Determine the INTEGRATED PROBABILITY of EYE DAMAGE, Γ , from the INSTANTANEOUS PROBABILITY of EYE DAMAGE, γ ; the EVENT FREQUENCY, F; and the EXPOSURE TIME, T, using Figure A-4 for Short Exposure times (T \cong 0.1 s) and the following equation for relatively long exposure times (T \geq 1 s):

 $\Gamma = \gamma \mathbf{F} \mathbf{T}$



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FIGURE A-1 FLOW CHART FOR "WORST-CASE" USERS GUIDE TO EVALUATE LASER EYE SAFETY HAZARD

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FIGURE A-2 NORMALIZED MEAN POWER DENSITY (1/P,m⁻²) AS A FUNCTION OF LASER BEAM DIVERGENCE (β) AND RANGE (R) FOR VARIOUS WAVELENGTHS (λ) AND HEIGHTS (z) IN A CLEAR STANDARD ATMOSPHERE

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Table A-1

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MAXIMUM SAFE POWER DENSITY LEVELS, I (W/m^2) , FOR CORNEAL EXPOSURES safe

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Laser	Time	Q-Switched	Long Pulse	Continuo	us fave
Wave length	of Day	(20 16)	(1 ms)	2 - 10 ms	10-500 ms
Visible	Day	3.53 × 10 ⁶	5.65 × 10 ²	2.83 × 10 ²	1.41 × 10 ²
(0.4 - 0.7 L)	Night	6.50 × 10 ⁵	1.04 × 10 ²	0.52 x 10 ²	0.26 × 10 ²
Neodyni un	Day	1.77 × 10 ⁷	2.83 × 10 ³	14.1 × 10 ²	7.07 X 10 ²
(1.06 µ)	Night	3 .24 × 10 ⁶	5.21 × 10 ²	2.59 × 10 ²	1.30 × 10 ²

Source: U.S. Air Force (1971)

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FIGURE A-3 INSTANTANEOUS PROBABILITY OF EYE DAMAGE (γ) AS A FUNCTION OF THE SAFE-TO-MEAN POWER DENSITY RATIO (1°)

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C. Summary

For convenience, these steps are summarized in Table A-2. Figure A-2 is derived principally from considerations of the laser-beam geometry, represented by the equation,

$$\overline{I/P} = \frac{4G}{\pi B^2 R^2}$$

where

- $\ddot{I} = mean power density (W/m²)$ (assumed to be uniform across the beam)
- P = laser output peak power (W)
- beam divergence (milliradians)
- R = range (km)
- G = atmospheric transmission.

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SUMMARY OF EYE-HARARD EVALUATION PROCEDURE

Step No.	Task	Reference		
1	Determine I/P	Figure A-2		
2	Compute Ï	I = P (Ī/P)		
3	Determine I _{safe}	Table A-1		
4	Compute I*	$I^* = I_{aafe} / \overline{I}$		
8	Detormine y	Figure A-3		
6	Ascertain F	Step 6		
7	Evaluate (*	$\begin{cases} Figure A-4, or \\ \Gamma = \forall F T \end{cases}$		

The atmospheric transmission is taken from the work of Elterman (1963) for a clear standard atmosphere as a function of wavelength and height. The maximum safe power density levels given in Table A-2 are those referenced by the U.S. Air Force (1971). For the daytime cases, the eye-pupil diameter was taken as 3 mm, while a 7-mm diam, was used for nighttime cases.

The curve in Figure A-3 was computed by means of the following equations:

$$\gamma = \frac{1}{2\pi} \int_{M} \exp(-x^2/2) dx,$$

where γ is the instantaneous probability of eye damage, \varkappa is a dummy variable, and

 $M = \sigma/2 + \sigma^{-1} \ln (I_{safe}/\tilde{I}) ,$

A-11

where σ is the log-intensity standard deviation. For this guide, σ is taken equal to the saturation (maximum) value of the log-intensity standard deviation, which is 1.25 for a near-ground horizontal propagation path and 1.65 for a slant puth. These values have been determined from an extensive series of field experiments. The development of these equations, as detailed in a previous report (Johnson et al., 1970), entails the assumption of a log-normal probability distribution of intensity fluctuations.

When one looks at a laser beam continuously for T seconds, the integrated probability of eye damage (Γ) over that period will be greater than the instantaneous probability of eye damage (γ). One simple way to assess this increased probability is to assume that the intensity peaks occurring at a single observational point represent separate events. If (1- γ) corresponds to the probability of no damage for a single event (i.e., the probability that any one intensity peak will not exceed I_{sufe}), then the integrated probability of no damage (1- Γ) for a given number of occurrences (N) in the time period (T) is given simply by multiplying the individual probabilities:

or

$$\Gamma = 1 - (1 - \gamma)^{N}$$

or (since N = FT, where F is the frequency of events),

$$\Gamma = 1 - (1 - \gamma)^{FT}$$

This equation forms the basis for Figure A-4. For $\gamma << 1$, this equation may be rewritten in approximate form as

 $\Gamma = \gamma FT$.

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The event frequency, F, may be considered to be equivalent to the pulse rate for a pulsed laser, or to the scintillation frequency for a CW laser. If we assume the turbulent elements separated by a mean correlation distance (ρ_0) to move with the wind, then (to a first supproximation) we have

$$\mathbf{F} = \mathbf{U}_{\mathbf{n}} / \mathbf{\rho}_{\mathbf{o}}$$

where U_n is the wind component perpendicular to the propagation path. Since the variation in ρ_0 with range that is predicted by theory disagrees with that measured, it seems best for our purposes to assume that F depends only on wind speed and beam sweep rate. On the basis of our measurements, the following values have been selected as being representative of the cases given:

Static paths

$U \leq 10$ knots:	F	*	500
U > 10 knots:	F	Ħ	1000
Aircraft slant naths	F	-	5000.

These coefficients allow for the maximum scintillation frequencies observed during our experiments.

After the probability of eye damage (Γ) is found, it becomes necessary to compare this value with a preestablished value (Γ_{safe}) representing the highest probability judged to be an acceptable risk. The magnitude of Γ_{safe} may change as the nature of the situation changes, but values in the range of 10⁻³ to 10⁻⁵ (one chance of eye damage in 1000 to 100,000 occurrences) seem reasonable. By way of comparison, the probability of an average American being killed in an automobile accident in the year 1968 was one in 3600, or 2.8 x 10⁻⁴, while the probability of being injured in an automobile accident was one in 100, or 10⁻² (World Almanac, 1970).

To illustrate the use of the worst-case procedure given in Section B, four examples are presented in Table A-3.

A-13

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Table	A-3
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Paramet	er Ex	ample 1	Example 2	Example 3	Example 4	
A, SPECI	FIED PA	RAMETERS				
Date Time Lat U Path Ty Laser Si Elev. Ang R λ Q θ P T Laser Ty	pe te Ai le ope	1 Dec 2200 30 ⁰ N 5 Slant rborne 60 ⁰ 0.4 0.4880 0.5 1 1 CW	1 May 1200 40°N 8 Slant Ground 20° 5 0.6943 0.5 0.5 2.5 $\times 10^7$ 0.1 Q-sw.	21 June 1500 20°s 12 Horiz. 0° 1 1.06 10 0.5 107 0.1 Q-sw.	21 June 1500 20°S 12 Horiz. 0° 6 1.06 10 0.5 107 0.1 Q-sw.	(LST) (knots) (km) (µ) (pulses/s) (mrad) (W) (s)
B. DERIV <u>Step No</u> . 1 2 3 4 5 6 7	ED PARA I/P I safe I* γ F Γ Safe?*	$\begin{array}{c} \text{METERS} \\ 5 \times 10^{1} \\ 5 \times 10^{1} \\ 0.52 \times 1 \\ 1.0 \\ >10^{-1} \\ 5 \times 10^{3} \\ >5 \times 10 \\ >5 \times 10 \\ \end{array}$	10-1 2.5 x 02 3.53 x 1.4 >10 ⁻ 0.5 2 >10 ⁻² No	5×10^{0} $10^{6} 5 \times 10^{7}$ $10^{6} 1.77 \times 1$ 0.35 $1 > 10^{-1}$ 10 $1 > 10^{-1}$ No	10^{-1} 10^{6} 0^{7} 1.77 x 10 18 10^{-3} 10 10^{-3} Yes	(m ⁻²⁾ (W m ⁻²) 0 ⁷ (W m ⁻²) (s ⁻¹)

EXAMPLES OF WORST-CASE LASER EYE-HAZARD EVALUATION

* Based on a selected value of $\Gamma = 10^{-3}$. safe i

Johnson, W. B., W. E. Evans, and E. E. Uthe, "Atmospheric Effects Upon Laser Eye Safety," Final Report, Part I, Contract F41609-69-C-0001, SRI Project 7472, Stanford Research Institute, Menlo Park, California (April 1970).

- Kolmogorov, A. N., "Energy Dissipation with Locally Isotropic Turbulence," DAN SSAR, Vol. 32, No. 1, pp. (1941).
- Slade, D. H. ed., "Meteorology and Atomic Energy," USAEC Division of Technical Information, Oak Ridge, Tennessee (TID-24190, CFSTI, National Bureau of Standards, U.S. Department of Commerce, Springfield, Virginia, 1968).
- Smithsonian Meteorological Tables, Publication 4014 R. J. List, ed. (The Smithsonian Institution, Washington, D.C., 1963).
- Tatarski, V. I., Wave Propagation in a Turbulent Medium, translated by R. A. Silverman (McGraw-Hill Book Company, New York, New York, 1961).
- Tatarski, V. I., "On Strong Fluctuations of Light Wave Parameters in a Turbulent Medium," Soviet Physics JETP, Vol. 22, pp. 1083-1088, (1966).
- Tatarski, V. I., "The effects of the Turbulent Atmosphere on Wave Propagation," J. W. Strohbehn, Sc. Ed., published for the National Oceanic and Atmospheric Administration, U.S. Department of Commerce and the National Science Foundation (Israel Program for Scientific Translations, TT 68-50464, 1971).
- USAF AFM 161-8, Change 1, Laser Health Hazards Control, Department of Air Force, Headquarters USAF Washinging, D.C. (September 1971).
- Vassiliadis, A., R. C. Rosan, and H. C. Zweng, "Research on Ocular Laser Thresholds," Final Report, Contract F41609-68-C-0041, SRI Project 7191, Stanford Research Institute, Menlo Park, California (1969).
- World Almanac, p.73, (Newspaper Enterprises Association, Inc., 230 Park Ave., New York, New York 10017, 1970).
- Wright, N. J., and R. J. Schutz, "Measurements of the Refractive Index Structure Coefficient C_n," Memo. Report No. 1885, Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland (1967).

REFERENCES

- Berry, F. A., E, Bollay, and N. R. Beers, Eds., <u>Handbook of Meteorology</u> (McGraw-Hill Book Company, New York, New York 1945).
- Dabberdt, W. F., and W. B. Johnson, "Atmospheric Effects Upon Laser Eye Safety -- Part II," Final Report, Contract F41609-69-C-0001, SRI Project 7472, Stanford Research Institute, Menlo Park, California (May 1971).

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- Davis, J. I., "Consideration of Atmospheric Turbulence in Laser Systems Design," <u>Appl. Opt.</u>, Vol. 5, pp.139-147 (1966).
- Deitz, P. H., 1968: Twelve eye safety nomographs. Technical Note No. 1709, Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland.
- Deitz, P. H., "Probability Analysis of Ocular Damage due to Laser Radiation Through the Atmosphere," Appl. Optics, Vol. 8, pp.371-375, (1969).
- DeWolf, D. A., "Saturation of irradiance fluctuations due to a Turbulent Atmosphere," J. Opt. Soc. Am., Vol. 58, pp. 461-466 (1968).
- Elterman, L., "Atmospheric Attenuation Model," in <u>Handbook of Geophysics</u> <u>and Space Environments</u>, Chapter 7.1 USAF Cambridge Research Laboratories, Office of Aerospace Research, Hanscom Field, Massachusetts, (1963).
- Fried, D. L., G. E. Mevers, and M. P. Keister, Jr., "Measurements of Laser Beam Scintillation in the Atmosphere," J. Opt. Soc. Am., Vol. 57, pp. 787-797 (1967).
- Goldstein, I., P. A. Miles, and A. Chabot, "Heterodyne Measurements of Light Propagation Through Atmospheric Turbulence," <u>Proc. IEEE</u>, pp. 1172-1180, 1965.

Gracheva, M. E., <u>Izv. VUZ, Radiofizika</u>, Vol. 10, pp. 775 (1967).

Gracheva, M. E., and A. S. Gurvich, "Strong Fluctuations in the Intensity of Light Propagated Through the Atmosphere Close to the Earth," <u>Radiofizika</u>, Vol. 8, pp. 717-724 (1965).