DOT/FAA/AM-03/12

Office of Aerospace Medicine
Washington, DC 20591

The Effects of Laser Illumination on Operational and Visual Performance of Pilots Conducting Terminal Operations

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August 2003

Final Report

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

U.S. Department of Transportation

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/AM/03-12		

4. Title and Subtitle
Effects of Laser Illumination on Operational and Visual Performance of Pilots Conducting Terminal Operations.

5. Report Date
August 2003

6. Performing Organization Code

7. Author(s)
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8. Performing Organization Report No.

9. Performing Organization Name and Address
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10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency name and Address
Office of Aerospace Medicine
Federal Aviation Administration
800 Independence Ave., S.W.
Washington, DC 20591

13. Type of Report and Period Covered

14. Sponsoring Agency Code

15. Supplemental Notes
Work was accomplished under approved task AM-B-03-PRS-94.

16. Abstract
INTRODUCTION. Several hundred incidents involving the illumination of aircrew members by laser light have been reported in recent years. Consequently, FAA Order 7400.2 was revised to establish new guidelines for Flight Safe Exposure Limits (FSEL) in specific zones of navigable airspace. The purpose of this study was to evaluate the performance of test subjects exposed to laser radiation while performing approach and departure maneuvers in the Critical Flight Zone (CFZ). **METHODS.** Pilot performance was assessed in a Boeing 727-200, Level C, flight simulator using four levels of laser illumination (0, 0.5, 5, and 50 $\mu W/cm^2$) and three operational maneuvers (takeoff and departure, visual approach, and instrument landing system [ILS] approach). Subjective responses were solicited after each trial and during an exit interview. The pilots were asked to rate on a scale from 1 to 5 (1 = none, 2 = slight, 3 = moderate, 4 = great, and 5 = very great) the affect each laser exposure had on their ability to operate the aircraft and on their visual performance. Average subjective ratings were calculated for each exposure level and flight maneuver, and an analysis of variance (ANOVA) was performed. **RESULTS.** Thirty-four pilots served as test subjects for this study. Average subjective ratings for operational and visual performance were 1.57 and 1.74, 1.89 and 2.15, 2.43 and 2.76, for the 0.5, 5 (i.e., CFZ), and 50 $\mu W/cm^2$ laser exposure levels, respectively. ANOVA found a significant difference ($p < 0.05$) between the subjective ratings for each exposure level. No significant differences were found between the types of flight maneuvers or between the operational and visual performance ratings for a given maneuver or exposure level. **CONCLUSION.** The FSEL of 5 $\mu W/cm^2$ was validated for pilots illuminated by laser light while conducting terminal operations in the CFZ. Familiarization with the aircraft flown and instrument training appeared to improve the pilot's ability to deal with laser exposure. Laser illumination at a higher level of exposure resulted in an unacceptable number of visual and operational problems. Laser effects may be especially serious for inexperienced or visually susceptible pilots.

17. Key Words	18. Distribution Statement
Lasers, Eye, Perception, Performance, Pilots, Vision	Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	13	

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The Effects of Laser Illumination on Operational and Visual Performance of Pilots Conducting Terminal Operations

INTRODUCTION

The use of laser (Light Amplification by Stimulated Emission of Radiation) devices in private industry, medicine, defense, and research has grown rapidly in recent years. Lasers are often used outdoors to attract and entertain the public with elaborately orchestrated productions at special events, theme parks, and casinos. Other outdoor uses for lasers include astronomical research, deep-space communications, orbital satellite imaging, and defense systems designed to target, track, and destroy airborne military targets. In addition, lasers have become less expensive and more available to the general public. These include lasers used for sighting handguns and rifles, laser pointers used to highlight areas of interest while conducting presentations, as well as other more powerful, commercially available, industrial-type lasers. When used responsibly lasers can be very beneficial; however, the improper or careless use of these devices can result in serious hazards for those exposed to their radiation. Aviators conducting low-level flight operation at night can be particularly vulnerable to accidental or malicious laser illumination that can compromise aviation safety.

Approximately 90% of all information needed to safely fly an aircraft is received by the pilot through the sense of vision. A pilot needs good vision at far distances to "see-and-avoid" other aircraft while in-flight and objects on the runway or taxi lanes, at intermediate distances to see the instrument panel, and at near distances to see maps, charts, and flight manifests. Operation of an aircraft at night can present additional visual challenges for the pilot. To ensure optimal visual performance for viewing targets inside and outside the cockpit at night, a pilot's eyes should be adapted for mesopic vision, where elements of both photopic and scotopic vision can be utilized. Maintaining this mesopic state can sometimes be difficult. For instance, prolonged exposure to darkness can result in night myopia (i.e., the inability to see distant objects or fine detail due to the loss of cone receptor function). Furthermore, exposure to relatively bright light can result in an inability to see well at low-light levels, due to deactivation of the eyes' rod receptors (1). If the eyes are briefly exposed to a source of intensely bright light, such as from a laser, while in a mesopic state of adaptation, temporary visual impairment will almost certainly occur (2). During critical phases of flight when the pilot does not have adequate time to recover, the consequences of laser exposure could be tragic.

The Civil Aerospace Medical Institute Vision Research Team has compiled a database containing several hundred documented and anecdotal reports of laser illumination incidents involving civilian aircraft while in flight, some of which have resulted in startle or distraction, visual impairment, and disorientation of flight crewmembers. While there have been documented aviation accidents that have resulted from exposure to high-intensity light sources, such as aircraft landing lights and runway approach lights (3,4), no accidents have been attributed to the illumination of crewmembers by lasers. However, given the increasing number of reported laser incidents, continued careless or malicious activity of this nature may eventually result in an aviation accident.

The demands on a pilot's vision are task dependent and change according to the particular phase of flight. Of principal concern to aviators is the possibility of laser illumination during terminal operations, which include taxiing, approach, and landing as well as takeoff and departure maneuvers. During these activities, the pilot's visual workload is highest, and recovery time from exposure to a visually debilitating light source is minimal. Under these circumstances, aviation safety could be compromised due to distractions or any physiological impairment that disrupts cockpit procedures, flight crew coordination, and communication between the pilot and air traffic control personnel. To minimize distractions and reduce the potential for flight procedure errors, the Code of Federal Regulations (CFR) Part 121, §121.133, 121.141, 121.401(5); Part 125, §125.287(6), Part 135, §135.293 (7) requires a "sterile" cockpit (i.e., only operationally relevant communication) below 10,000 feet (8). Below 1,000 feet, the aircraft must be in a landing configuration and in position to complete a normal landing. To continue the descent, crewmembers must be able to visually identify the runway threshold and/or appropriate lighting configurations. If these lighting configurations are not visually identifiable, the pilot must execute a go-around (5,6,7,8).

In 1995, an increase in the number of laser illuminations that resulted in the disruption of cockpit operations prompted a study to revise Federal Aviation Administration (FAA) Order 7400.2 (Part 6. Miscellaneous Procedures: Outdoor Laser Operations). Intended to protect flight crew personnel and passengers from biological tissue damage resulting from accidental exposure to outdoor laser activity, FAA Order 7400.2 was originally based on the Food & Drug Administration's (FDA's) "Performance Standards for Light-Emitting Products" (9). This FDA standard utilizes the recommended Maximum Permissible Exposure (MPE) of 2.5 milliwatts per centimeter square (mW/cm^2) for continuous wave (CW) lasers (10). The MPE is used to calculate the Nominal Ocular Hazard Distance (NOHD). The NOHD is the distance along the axis of a laser beam beyond which an individual may be exposed without risk of ocular tissue damage. FAA Order 7400.2 was revised to improve aviation safety by limiting acceptable laser exposure levels to below that which could cause visual impairment of flight crewmembers while performing critical flight maneuvers.

While not likely to cause permanent ocular damage, low-level laser exposure can result in temporary visual impairment. The effects of such exposure can be especially hazardous at night when the eyes are dark-adapted. Exposure to a bright light source can cause temporary blindness for several seconds to several minutes, and it may take an additional 30 minutes or longer for dark adaptation to be fully restored.

The three most common physiological effects associated with exposure to bright lights are (11):

1. Glare – Obscuration of an object in a person's field of vision due to a bright light source located near the same line of sight.
2. Flashblindness – A visual interference effect that persists after the source of illumination has been removed.
3. Afterimage – A transient image left in the visual field after an exposure to a bright light.

The revised FAA Order 7400.2 established new guidelines for Flight Safe Exposure Limits (FSELs) in specific zones of navigable airspace associated with airport terminal operations, in addition to the pre-existing MPE that limited exposure in the Normal Flight Zone (NFZ). Based on consultations with laser and aviation experts, scientific research, and historical safety data, 100 microwatts per centimeter squared ($\mu W/cm^2$) was identified as the level of exposure at which significant flashblindness and afterimages could interfere with a pilot's visual performance. Similarly, 5 $\mu W/cm^2$ was determined to be the level at which significant glare problems may occur. When a laser is to be operated outdoors in the vicinity of an airport or air traffic corridor, the FAA may be required to conduct an aeronautical study to identify the zones of airspace around an airport or airway that must be protected by the application of appropriate FSELs.

The new zones and FSELs are:

- Laser Free Zones = 50 nanowatts per centimeter square (nW/cm^2),
- Critical Flight Zone = 5 $\mu W/cm^2$,
- Sensitive Flight Zone = 100 $\mu W/cm^2$, and
- Normal Flight Zone = 2.5 mW/cm^2.

Figure 1 shows a profile view of how the new flight zones and FSELs would be applied to a single-runway airport. Not depicted in this figure is the NFZ, which would apply to all navigable airspace beyond the Sensitive Flight Zone (SFZ). (Note: The SFZ is optional and may be applied based on the findings of the aeronautical study.) The Laser Free Zone (LFZ) includes airspace in the immediate proximity of the airport, up to and including 2,000 feet above ground level (AGL), and extending 2 nautical miles (NM) in all directions measured from the runway centerline. Additionally, the LFZ includes a 3 NM extension, 2,500 feet each side of the extended runway centerline. The Critical Flight Zone (CFZ) includes the space outside the LFZ to a distance 10 NM from the Airport Reference Point (ARP) to 10,000 feet AGL.

The FAA, in response to a National Transportation Safety Board (NTSB) safety recommendation concerning outdoor laser illumination of pilots, agreed to complete a study to determine maximum safe laser beam exposure levels (12). Should the study findings warrant, the FAA agreed to use the data to revise FAA Order 7400.2 guidelines that regulate the use of laser devices in the proximity of airport operations. The purpose of this study was to evaluate the effect of laser exposure on pilots' operational and visual performance while conducting approach and departure maneuvers in the CFZ.

METHODS

To assess the affect of laser light exposure on the operational and visual performance of aviators, the FAA's Boeing 727-200, Level C, full-motion flight simulator at the Mike Monroney Aeronautical Center, in Oklahoma City, OK, was utilized. Thirty-eight multi-engine rated, civilian and military pilots were recruited to serve as human test subjects for this study. Prospective subjects were interviewed regarding their ophthalmic medical history. Every participant was given a pre-flight ophthalmic exam to ensure normal vision and ocular health. Persons reporting a history of eye disease, hypersensitivity to light, or taking photosensitizing drugs were not accepted for participation in the study. The pre-flight exam included fundus photography and visual field testing of both eyes. Participants were required to have visual acuity correctable to at least 20/20, a normal Amsler grid, and no

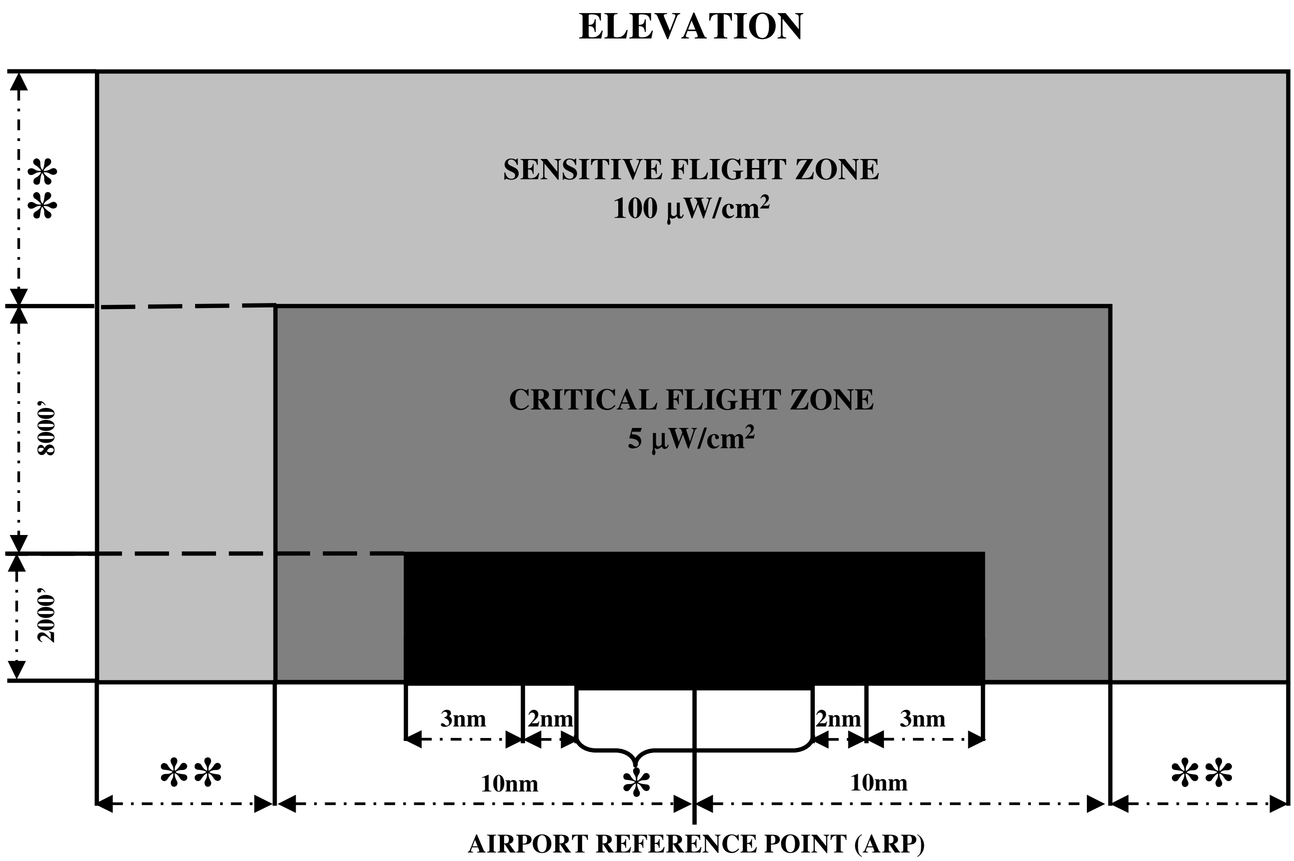


Figure 1: Profile view of a single-runway airport and the application of protected flight zones (Not drawn to scale). ** Runway length varies per airport. AGL is based on published airport elevation. ** To be determined by regional evaluation and/or local airport operations.*

ocular pathology. After completing the test flights, visual acuity, fundus photography, and visual field testing were repeated to verify that the subjects sustained no lasting adverse effects from the laser exposures.

As in previous human laser experiments conducted at Brooks Air Force Base in San Antonio, TX, the laser exposure level did not exceed 5% of the MPE for an individual exposure (13,14). The MPE for direct ocular viewing of a 532 nm laser beam imaged as a point source for 1 second is $1.8t^{0.75}$ mJ/cm², where t = seconds, or

$$\text{MPE} = 1.8(1)^{0.75} \text{ millijoules per centimeter squared (mJ/cm}^2\text{)} = 1.8 \text{ mJ/cm}^2.$$

The highest single planned exposure was 50 µJ/cm². A 50 µW/cm² exposure for 1 second is equal to 50 µJ/cm² or 2.8% of the MPE.

For multiple exposures, the calculation of MPE is sometimes more conservative if all exposures delivered over a 24-hr period are treated as a single continuous exposure. The MPE for an exposure duration between 18 x 10^{-6} and 10 seconds is also given by $1.8t^{0.75}$ mJ/cm². The planned cumulative exposure for each subject was 166.5 µJ/cm², over a total laser exposure time of 9 seconds. The MPE for a cumulative exposure of 9 seconds equals 9.4 mJ/cm². Therefore, the planned cumulative exposure of 166.5 µJ/cm² delivered to each subject was only 1.8% of the MPE.

Twelve test scenarios were developed based on the following independent variables:

Laser power levels
- 0 µW/cm²,
- 0.5 µW/cm² for 1 second,
- 5.0 µW/cm² for 1 second, and
- 50.0 µW/cm² for 1 second.

Operational maneuvers
- Takeoff and departure with steady-state turn,
- Visual approach, and
- Instrument landing system (ILS) approach.

The independent variables were randomly manipulated among the 12 test scenarios, and all laser exposures were 1 second in duration. The four levels of laser power and the three operational maneuvers resulted in a 4x3 factor, within-subject experimental design (see Table 1). The three zero-level-exposure trials were randomly introduced to provide the subjects with a sense of uncertainty as to whether the laser would come on during any given maneuver.

Table 1: The experimental conditions tested in the Boeing 727-200 simulator.

Power ($\mu W/cm^2$)	Laser Trigger	Pilot Action	Maneuver
0	15° ROLL	180° Left Turn	Takeoff/Departure
0.5	15° ROLL	180° Left Turn	Takeoff/Departure
5	15° ROLL	180° Left Turn	Takeoff/Departure
50	15° ROLL	180° Left Turn	Takeoff/Departure
0	025° HDG	180° Left Turn	Visual Approach
0.5	025° HDG	180° Left Turn	Visual Approach
5	025° HDG	180° Left Turn	Visual Approach
50	025° HDG	180° Left Turn	Visual Approach
0	335° HDG	30° Right Turn	ILS Approach
0.5	335° HDG	30° Right Turn	ILS Approach
5	005° HDG	30° Left Turn	ILS Approach
50	335° HDG	30° Right Turn	ILS Approach

During the experiment, each exposure level was presented three times, resulting in 12 trials (approximately 5 minutes/trial) for each pilot (see Table 1). The 12 trials included eight approaches and four departures. Total simulator flight time was about two hours. The levels of laser power were selected to effectively bracket the Critical Flight Zone's FSEL of 5 $\mu W/cm^2$. The order of the trials was randomized for each subject [1]. All trials were videotaped to observe the pilots' reaction to each exposure. Except for the zero-level-exposure trials, subjective responses were solicited after each trial and during an exit interview.

A collimated beam of green light with a peak spectral irradiance at 532 nm wavelength was generated by a continuous-wave (CW) doubled Nd:YAG laser. A fiber optic cable was used to deliver the beam to the simulator's visual display array. A 30° cone of diffuse laser light was emitted from the fiber optic cable and delivered to the subject's head position. A radiometer was used to measure the irradiance at the subject's eye. Seat height was adjusted for each test subject. Laser exposures were approximately equivalent for the expected variability in eye positions between subjects. Exposures occurred while the aircraft was on approach and during a steady-state turn following departure. Subjects were instructed to continue normal procedures and fly as efficiently as possible during the laser exposure. A trained laser operator was present throughout the experiment to ensure that the laser operated safely.

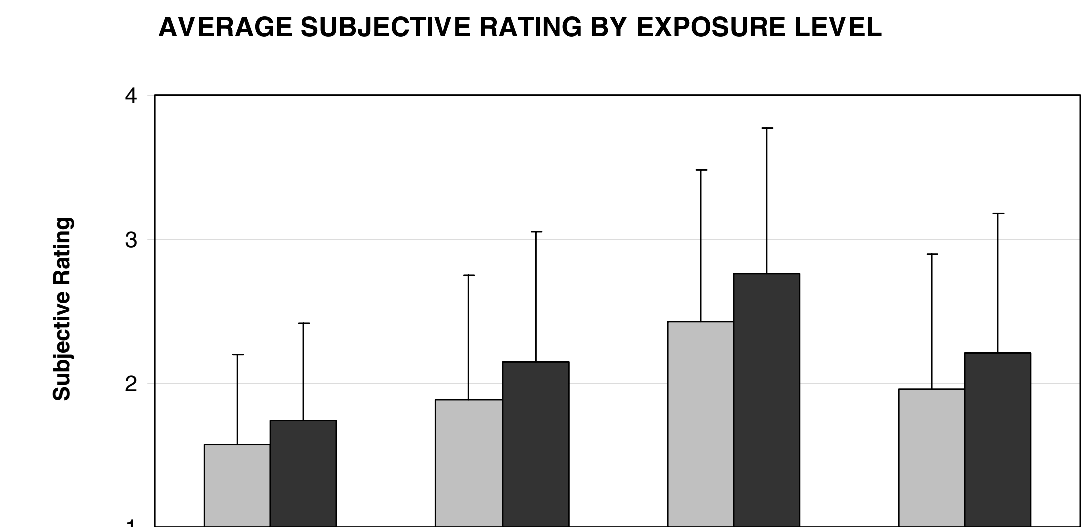
A simulation test director was present in the cockpit to initiate and monitor each test scenario. In addition, a cockpit operator flew as co-pilot and was responsible for recording the subject's responses to a series of questions after each test flight. The pilots were asked to rate on a scale from 1 to 5 (1 = none, 2 = slight, 3 = moderate, 4 = great, and 5 = very great) the effect each laser exposure had on their ability to operate the aircraft and on their visual performance. Average subjective ratings were calculated for each exposure level and flight maneuver, and an analysis of variance (ANOVA) was performed. Subjects were also asked to provide any comments relevant to potential exposure-induced performance or visual difficulties.

RESULTS

Of the 38 subjects recruited, 34 subjects completed all test scenarios. Four recruits were excused from this study due to pre-existing conditions (i.e., diabetes, refractive surgery) or eliminated due to problems with the laser control program that resulted in corrupted data. The average age of the pilots who completed the entire study was 40.3 years (standard deviation = 13.45; range: 22 to 70 years of age).

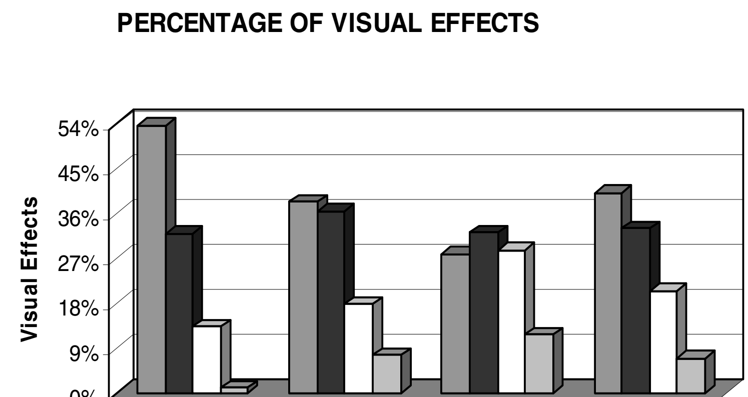
Figure 2 presents the average of all subjective responses to the in-flight questionnaires administered to each test subject. Subjects rated the laser's affect on visual performance higher than its affect on operational performance for all levels of exposure. For the CFZ exposure level (5.0 $\mu W/cm^2$), the average subjective ratings were 1.89 and 2.15 for operational and visual performance, respectively. ANOVA found no significant difference ($p > 0.05$) between the operational and visual performance ratings for any of the three exposure levels or in the overall (total) performance ratings. However, the operational and visual performance ratings increased significantly ($p < 0.05$) as the laser exposure level was increased. The error bars show the standard deviations of the ratings in this figure.

[1] NOTE: Four additional approach maneuvers were conducted to evaluate the test subjects' reactions to low-altitude laser illumination within the Laser Free Zone. Test subjects were exposed to the four laser exposure levels, which included a zero-level-exposure, just prior to landing (touchdown) at 100 feet above the runway. The results from this ancillary investigation will be reported in a separate paper. Only laser exposures within the CFZ were used in this analysis.



	0.5	5.0	50	TOTAL
Operational	1.57	1.89	2.43	1.96
Visual	1.74	2.15	2.76	2.21

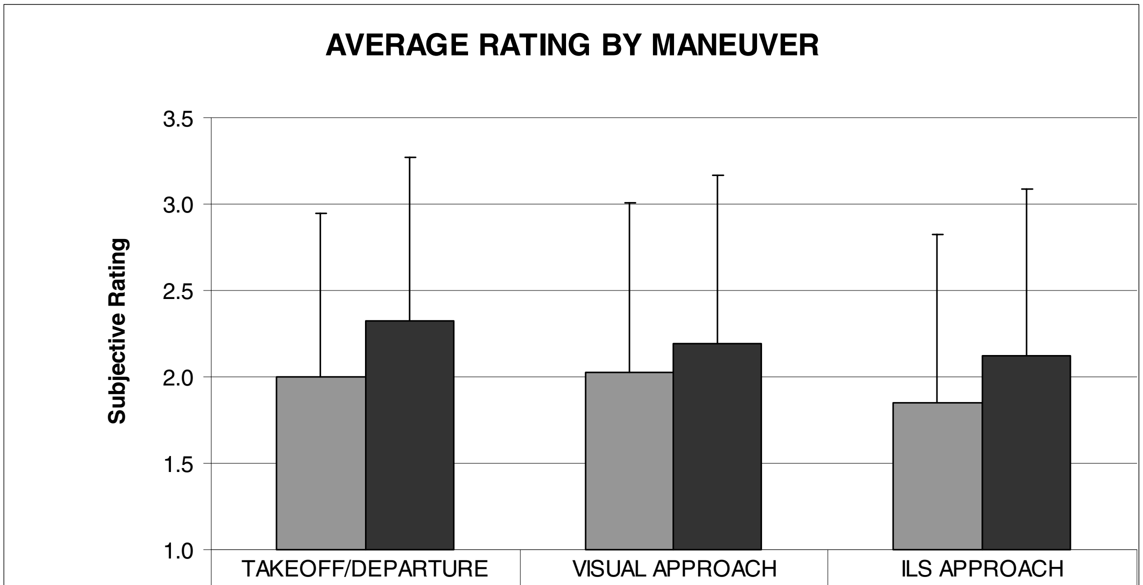
Figure 2. Average subjective rating of pilots' operational and visual performance by exposure level (µW/cm²).



	0.5	5.0	50	TOTAL
NONE	53.8%	38.3%	27.7%	40.0%
GLARE	32.1%	36.4%	32.1%	32.9%
FLASHBLINDNESS	13.2%	17.8%	28.6%	20.3%
AFTERIMAGE	0.9%	7.5%	11.6%	6.8%

Figure 3. Percentage of visual effects experienced by test subjects for each exposure level (µW/cm²).

Figure 3 summarizes the visual effect responses solicited from all subjects during and immediately after each exposure. The percentages shown in Figure 3 are relative to the total number of responses for each exposure level. In some instances, subjects reported that they had experienced a combination of two or all three visual effects for a particular exposure. Note that as the level of laser exposure increased, the percentage of responses for the more severe adverse visual effects (flashblindness and afterimages) increased. The single most common response (40.0%) indicated that no adverse visual effect was experienced. However, of the adverse effects reported, the most frequent response was glare (32.9%), followed by flashblindness (20.3%), and afterimage (6.8%).



	TAKEOFF/DEPARTURE	VISUAL APPROACH	ILS APPROACH
Operational	2.00	2.03	1.85
Visual	2.32	2.19	2.12

Figure 4. Average subjective ratings for all test subjects and exposures by maneuver.

Figure 4 illustrates the average subjective performance ratings by maneuver. Differences in the average ratings were small and ANOVA found no significant differences ($p > 0.05$) when the performance ratings were compared between the three different flight maneuvers. For both visual and operational performance, test subjects indicated their performance was affected least during ILS approach. Visual performance was affected more during the takeoff and departure maneuvers (2.32) than during visual approach (2.19), while operational performance was affected slightly more during visual approach (2.03) than the takeoff and departure maneuvers (2.00).

After each scenario, the test subjects were asked to comment on what affect the laser exposure had on their visual and operational capabilities. The following summarizes the subjects' most frequently reported comments for the corresponding flight maneuver and level of laser exposure.

At the 0.5 μW/cm^2 level of exposure, four subjects reported being momentarily distracted and/or losing sight of the instrument panel during the departure maneuver. Five subjects reported being distracted by the 0.5 μW/cm^2 exposure during the visual and ILS approaches.

At the 5.0 μW/cm^2 level of exposure (i.e., CFZ limit), six subjects reported various effects that included brief hesitation, leveling off too early, dipping the nose slightly, and/or difficulties in properly banking the aircraft during the departure maneuver. Three subjects reported being distracted, one subject felt his reactions were slightly delayed, and one subject became briefly disoriented (lost "cross check" of instruments) during the visual approach. Three subjects reported effects during the ILS approach including distraction and/or momentarily losing sight of the instrument panel.

At the 50.0 μW/cm^2 level of exposure, five subjects reported moderate effects on their ability to operate the aircraft when illuminated during the takeoff and departure maneuver. The reported effects included any or all of the following: startle, distraction, delayed reaction time, rolling out of the bank (turn), and dipping the nose of the aircraft. In addition, four subjects reported briefly losing sight of the instruments during departure. Four subjects reported that the exposure caused distraction and/or loss of reference or concentration during the visual approach. One pilot gave control of the aircraft to the co-pilot when exposed while attempting the visual approach. Five subjects reported difficulties during the ILS approach that included losing altitude and airspeed as a result of being startled and distracted.

DISCUSSION

When exposed, the human body can be vulnerable to the radiation emitted by certain lasers. Depending on the power output, wavelength, and duration of exposure, laser radiation can damage the eyes and skin. The eyes are much more vulnerable to injury than the skin. The cornea (the clear outer surface of the eye), unlike the skin, does not have an external layer of dead cells to protect it. In the far-ultraviolet (UV) and far-infrared (IR) regions of the electromagnetic spectrum, the cornea can absorb laser radiation and be damaged. Figure 5 illustrates the absorption characteristics of the eye for different wavelengths of radiation. At certain wavelengths in the near-UV region and in the near-IR region, the crystalline lens of the eye can be vulnerable to injury. Of greater concern, however, is exposure to laser radiation in the retinal hazard region, ranging from approximately 400 nm to 1400 nm and including the entire visible portion (400 – 780 nm) of the electromagnetic spectrum. Within this spectral region, the eye focuses the collimated energy emitted by a laser into a single point on the retina, intensifying the effects of the laser light.

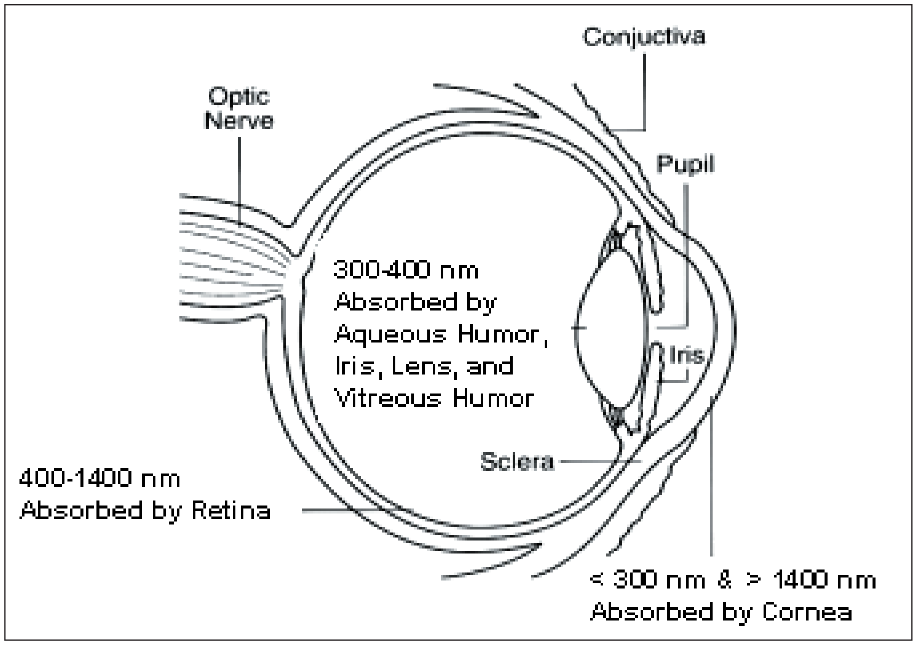


Figure 5. Light absorption characteristics of the human eye.

The eye is particularly vulnerable when it is focused at a distant object and a direct or reflected laser beam enters the pupil. The combined optical gain of the cornea and crystalline lens will amplify the laser energy by a factor of more than 100,000 times when it reaches the retina. For example, a 1-mW/cm^2 laser beam entering the pupil could result in a 100-watt/cm^2 exposure to the retina. Use of binoculars or other magnifying optical devices may further increase retinal irradiance (energy per unit area) more than a million-fold. The skin is far less vulnerable to injury from laser exposure than the retina since there is no naturally occurring optical gain.

A lesion that results from laser radiation striking the retina can spread due to the release of various noxious agents by the injured neurons (15). The damaged area may continue to expand for several hours or days after the initial injury before it begins to subside. The resulting effect on visual performance may be much greater than the physical size of the retinal lesion may suggest. Unfortunately, there is no proven treatment for injuries to the retina from laser exposure (16). Therefore, the use of wavelength-specific protective eyewear to prevent eye injuries is strongly recommended whenever there is probable risk of exposure to laser light (17).

A variety of laser safety standards, including federal and state regulations, are available for guidance. The most frequently applied guidelines are found in the ANSI Z136 series of laser safety standards. These standards are the foundation of laser safety programs in industry, medicine, research, and government. The ANSI Z136 series are referenced by the Occupational Safety and Health Administration (OSHA) and state agencies as the basis of evaluating laser-related occupational safety issues. ANSI Z136.1 (American National Standard for Safe Use of Lasers), the parent document in the Z136 series, provides information on how to classify lasers, perform laser safety calculations and measurements, apply laser hazard control measures, and contains recommendations for Laser Safety Officers and Laser Safety Committees. It is designed to provide the laser user with the information needed to properly develop a comprehensive laser safety program. In 2000, ANSI published the American National Standard for the Safe Use of Lasers Outdoors, Z136.6 (11). Similar to the revised FAA Order 7400.2, this standard recommends the implementation of flight hazard zones.

For manufacturers of laser products, the standard of principal importance is the regulations established by the FDA's Center for Devices and Radiological Health (CDRH), which regulates product performance. All laser products sold in the United States since August 1976 must be certified by the manufacturer as meeting certain product performance (safety) standards, and each laser must bear a label indicating compliance with the standard and denoting the laser hazard classification.

Safe exposure limits for nearly all types of laser radiation have been established (10). Safety professionals generally refer to these limits as the MPE for a laser. The experience gained through laboratory research and industry practice has permitted the development of a system of laser hazard classifications. The manufacturers are required to certify that a laser product fits into one of four general classes and must label it accordingly. This allows the use of standardized safety measures to reduce or eliminate accidents, depending on the class of the laser or laser system being used. The four primary classifications of lasers are (10):

- Class 1 – The laser is considered safe based upon current medical knowledge. It includes all lasers or laser systems that cannot emit levels of optical radiation above the exposure limits for the eye under any exposure conditions inherent in the design of the laser product. There may be a more hazardous laser embedded in the enclosure of a Class 1 product, but no harmful radiation can escape the enclosure (e.g., laser printers, compact disk and digital video disk players, supermarket scanners).
- Class 2 – The laser or laser system must emit a visible laser beam. Due to its brightness, a Class 2 laser light is considered too dazzling to stare at for extended periods. Momentary viewing is not considered hazardous since the upper radiant power limit on this type of device is less than the MPE for exposure of 0.25 second or less. Intentional extended viewing is considered hazardous (e.g., laser levels, laser pointers, laser-sighted handguns and rifles).
- Class 3 – The laser or laser system can emit any wavelength, but it cannot produce a diffuse reflection hazard unless viewed for extended periods at close range. It is not considered a fire hazard or serious skin hazard. Any CW laser that is not Class 1 or Class 2 is a Class 3 device, if its output power is 0.5 W or less. Since the output beam of such a laser is hazardous for intrabeam viewing, control measures center on eliminating this possibility (e.g., meteorology, dentistry, guidance/navigation, and range-finding lasers).
- Class 4 – The laser or laser system that exceeds the output limits of a Class 3 device. These lasers may be either a fire or skin hazard or a diffuse reflection hazard. Stringent control measures are required for a Class 4 laser or laser system (e.g., military, astronomy and deep space communications research, industrial, medical, and outdoor entertainment lasers).

FAA Order 7400.2 provides protection for aviators and passengers in designated zones of navigable airspace from both biological tissue damage and temporary visual impairment due to exposure from visible laser beams. The particular class of laser is not an issue as long as exposure levels are maintained at or below that assigned to the zone of airspace in question. In this study, a Class 4, 532-nm doubled Nd:YAG laser was used. The laser's output power was limited to prescribed levels by filters, and the beam was diffused (i.e., divergence $\geq 30^{o}$) by passage through a fiber optic cable. The laser radiation delivered to the test subjects was essentially Class 1 in nature, well below the MPE, and presented no possibility of ocular damage for a single, one-second exposure or for the cumulative exposures of all flight tests. Exposure levels and the diffuse delivery method were designed to emulate the effects of the divergence of the laser and the atmospheric attenuation over a considerable distance. The simulation was designed to mimic those described by pilots who had actually experienced in-flight laser exposure incidents.

Observations of test subjects during simulator flights exhibited the following common traits:

- Pilots varied the intensity of cockpit lighting while flying. In general, older pilots used more light in the cockpit, which helped them to see their instruments and charts. Younger pilots used proportionally less light in the cockpit, which accentuated the relative brightness of the laser light.
- Most of the pilots flew on instruments, while briefly going "heads up" to observe the outside scene. During laser illumination, a majority of pilots commented that they transitioned to their instruments and continued to fly. Several pilots reported that being instrument rated was a major advantage when illuminated. It was suggested that the performance of non-instrument rated pilots illuminated by similar laser exposures warrants further study.
- Once they realized that the duration of the laser exposures were brief, several pilots commented that they were less concerned about the laser's influence on their performance. Consequently, they became increasingly comfortable flying, even while visually impaired, during and immediately after exposure. This suggests that how a pilot performs when illuminated by laser exposures of differing time intervals warrants further study. Acquainting pilots with low-level laser exposure could minimize its effects and reduce the chance of an extreme reaction.
- Although the test subjects were allowed to perform pre-test flights to become accustomed to the simulator, the majority of subjects were not certified in the Boeing 727-200 aircraft. Because of their unfamiliarity with this particular aircraft, some pilots may have been more easily startled and disoriented by the laser illuminations than those who had more experience in this aircraft.
- A few pilots experienced cumulative effects from the laser exposures resulting in an increased inability to totally suppress the effects of subsequent laser exposures. Limited access to the test subjects and the flight simulator made longer re-adaptation periods after laser

exposures impractical during this study. However, the cumulative effects of repeated exposures may be of greater concern for older airmen or those for whom dark adaptation requires more time than normal.

- Although assured of the safety of the laser intensities used in the experiment, the reactions of some test subjects were quite animated when illuminated, while others were essentially non-responsive to the same exposure levels. The psychological effects of laser illumination are difficult to measure, and it is unknown how a pilot would respond to an actual laser exposure of undetermined potential for ocular injury.

The average subjective ratings for the CFZ FSEL (5 $\mu W/cm^2$) indicated operational ability (1.89) and visual performance (2.15) were affected only slightly. When illuminated, subjects complained of adverse visual effects (flashblindness and afterimages) 25.3% of the time. However, post-flight comments indicate that these effects were brief and no serious operational errors were noted during these trials. These findings indicate that pilots were able to compensate and/or had ample time to recover when exposed to a 5 $\mu W/cm^2$ laser beam in the CFZ and safely continue with normal approach and departure activities.

On average, test subjects indicated that visual performance was affected more than operational performance (2.21 and 1.96, respectively); however, this difference was not found to be statistically significant. Of particular interest was the fact that test subjects indicated the departure maneuver was the most difficult of all scenarios (i.e., visual performance rating = 2.32). This may be due to the absence of other exterior lights in the subjects' visual field when the laser flashed during the departure maneuver. A darkened field of view would have increased the test subject's pupil size and intensified the visual effect of the laser exposure. In contrast, during the approach maneuvers, the pilot could usually see the runway approach lights in the distance. This would have constricted the pupils slightly, allowing less light to enter the eyes during the laser flash. In addition, the runway lights would also provide a visual point of reference to help the pilot maintain proper orientation during final approach.

The average subjective ratings for the 50 $\mu W/cm^2$ laser exposure level indicated operational ability (2.43) and visual performance (2.76) were influenced by a "slight" to "moderate" degree. Given that flashblindness and afterimage were reported 40.2% of the time and that one subject had to turn over control of the simulator, laser exposures of this magnitude would appear to be unacceptable in the CFZ.

In summary, the recommended FSEL for laser light exposure in the CFZ, established in the revised FAA Order 7400.2, was validated by the simulator flight tests. On average, test subjects reported a "slight" affect on their operational and visual performance during all flight maneuvers at the 5.0 $\mu W/cm^2$ exposure level. In addition, the altitude of the aircraft above the ground and distance from the landing area in the CFZ provided adequate time for visual recovery from the effects of a 5.0 $\mu W/cm^2$ laser exposure. Post-flight comments indicated that familiarization with the effects of laser exposure, instrument training, and recent flight experience in the aircraft type may be important factors in enhancing a pilot's ability to successfully cope with laser illumination at eye-safe levels of exposure. ANOVA found the differences in (operational and visual) performance ratings to be statistically significant ($p < 0.05$) between the three laser exposure levels. However, there was no significance between the differences associated with the three flight maneuvers or the differences between the operational and visual ratings themselves for any given trial. Further analysis of the data is being performed to evaluate operational problems resulting from exposure to laser light within the LFZ.

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