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The Effects of Laser Illumination on Operational and Visual Performance of Pilots During Final Approach

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16. Abstract

INTRODUCTION: Several hundred incidents involving the illumination of aircrew members by laser light have been reported in recent years, including several that could have had serious consequences. The purpose of this report is to evaluate the performance of pilots exposed to visible laser radiation during final approach maneuvers at 100 feet above the runway in the Laser-Free Zone (LFZ). **METHODS:** Thirty-four pilots served as test subjects for this study. Pilot performance was assessed in a Boeing 727-200 Level C flight simulator using four eye-safe levels of visible laser light (0, 0.5, 5, and 50 $\mu W/cm^2$) during four final approach maneuvers (three 30° left and one 30° right turn to final 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. The average subjective ratings were calculated for each exposure level and flight maneuver, and an analysis of variance (ANOVA) was performed. **RESULTS:** Average subjective ratings for operational and visual performance were 2.93 (Range = 2.35 – 3.29; SD = 1.37) and 3.16 (Range = 2.56 – 3.62; SD = 1.30), respectively. ANOVA found statistically significant differences ($p < 0.05$) between the 0.5 $\mu W/cm^2$ operational and visual performance ratings and those for the 5 and 50 $\mu W/cm^2$ exposures. Approximately 75% of the survey responses indicated that subjects experienced adverse visual effects resulting in some degree of operational difficulty when illuminated by low-level laser radiation. **CONCLUSION:** This study confirmed that the illumination of flight crewmembers with laser radiation $\geq 0.5\ \mu W/cm^2$ is unacceptable in the LFZ. Provided the exposure limit established for the LFZ (i.e., 50 nW/cm^2) is not exceeded, a sufficient margin of safety appears to exist for protecting pilots from accidental laser exposure during final approach.

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The Effects of Laser Illumination on Operational and Visual Performance of Pilots During Final Approach

BACKGROUND

In the United States and other developed countries, laser (Light Amplification by Stimulated Emission of Radiation) devices have become less expensive and more commonplace. When used responsibly, lasers have many beneficial applications; however, improper or careless use of these devices can result in serious hazards for those exposed to their radiation. Applications for lasers include entertainment equipment (CD and DVD players), supermarket scanners, fiber-optic communication networks, handgun and rifle sights, laser pointers for highlighting areas of interest during presentations, medical devices, and industrial tools. In addition, lasers are frequently used outdoors where their tightly collimated beams of light are projected into the sky to attract the public or provide entertainment in the form of elaborately orchestrated laser lightshows at special events, theme parks, and casinos. Other uses for lasers in navigable airspace include astronomical and atmospheric research, deep-space communications, orbital satellite imaging, and defense systems designed to track, target, and destroy military targets (1,2).

Pilots use their eyes to obtain the vast majority of all the information needed to safely fly an aircraft. A pilot must see well over a range of distances to avoid other aircraft in-flight and objects on runways and taxi lanes, scan instrument displays, and read maps, charts, and flight manifests. Operation of an aircraft at night presents additional visual challenges for the pilot. To ensure optimal visual performance at night when viewing objects inside and outside the cockpit, a pilot's eyes should be adapted for mesopic vision. 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 focus from over accommodation of the eye). 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 (3). 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 (4). Visual effects can last for several seconds to several minutes, and dark adaptation may take 30 minutes or longer to be fully restored. The three most common physiological effects associated with exposure to bright lights are (5):

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 demands on a pilot's vision are task dependent and frequently change according to the particular phase of flight and current visual conditions. Of principal concern to aviators is the possibility of being illuminated by a laser during terminal operations, which include approach, landing, takeoff, and departure maneuvers. Aviators conducting low-level flight operations at night are particularly vulnerable to accidental or malicious laser illumination. During these activities, the pilot's visual workload is highest, and the time to recover from exposure to a visually debilitating light source is minimal. Should distractions or physiological impairment disrupt cockpit procedures, flight crew coordination, or communication between the pilot and air traffic control personnel during critical phases of flight, the consequences could be catastrophic.

To minimize distractions and reduce the potential for flight procedure errors during approach to landing, the Code of Federal Regulations (CFR) Part 121, §542 (6); Part 125, §311 (7), Part 135, §100 (8) require a "sterile" cockpit (i.e., only operationally relevant communication) below 10,000 feet (9). Below 1,000 feet, the aircraft must be in a landing configuration and in position to complete a normal landing. In order 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 (6,7,8,9).

In recent years, the Civil Aerospace Medical Institute's Vision Research Team has compiled a database containing several hundred reports involving laser illumination of military and civilian aircraft, including law enforcement and medical evacuation helicopters. Some of these incidents have resulted in reports of pilots being startled, distracted, temporarily blinded, and disoriented. While there have been documented reports of aviation accidents associated with glare and flashblindness induced by natural sunlight (10) and exposure to high-intensity artificial light sources, such as aircraft landing lights and runway approach lights (11,12), no accidents have been attributed to the illumination of crewmembers by lasers. However, given the considerable number of reported laser incidents that have resulted in visual and operational problems, the potential for an aviation accident definitely exists. Two laser illumination incidents that seriously compromised aviation safety are summarized below:

• At approximately 6:30 pm PST on October 30, 1995, the first officer on Southwest Airlines flight 1367 sustained a debilitating eye injury after being irradiated by a laser beam on departure from McCarran International Airport, Las Vegas, NV. The airplane was enroute from Las Vegas to San Antonio, TX, climbing through 7,000 feet MSL, on a standard instrument departure route when the incident occurred. The pilot-in-command (first-officer) reported that the laser beam sweep through the cockpit, resulting in temporary blindness and pain in his right eye, in addition to after-image effects that impaired the vision in his left eye. The pilot could not focus or interpret any instrument indications and was disoriented for several minutes requiring the captain to assume control of the aircraft (13). Note: As a result of this incident, the Federal Aviation Administration (FAA) placed a moratorium on outdoor laser activities in the Las Vegas area.

• On November 29, 1996, a suspected laser beam illuminated a Skywest Airlines pilot during approach on flight 5410 into Los Angeles Airport (LAX). The Embraer EMB-120 was over a college campus on visual approach to LAX from Bakersfield, CA, when the incident occurred. The aircraft was on a right base leg, level at 6,000 feet MSL, when the captain was exposed to a bright light in his right eye while looking for downwind traffic through the right window. As the flight continued, the captain found it increasingly difficult to see because of the burning and tearing he was experiencing in that eye. On final approach, he relinquished control to the co-pilot who completed the landing. Examination revealed the pilot suffered multiple flash burns to his right cornea (14). Note: As a result of this incident, the National Transportation Safety Board (NTSB) recommended the FAA change the existing guidelines to protect pilots from temporary visual incapacitation and to conduct research to validate laser exposure limits.

Initially 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" (15). This FDA standard utilizes the recommended Maximum Permissible Exposure (MPE) of 2.5 milliwatts per centimeter squared (mW/cm^2) for continuous wave (CW) lasers (16). 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. The NTSB recommendation and the increasing number of reported laser illumination incidents prompted a study to improve aviation safety by limiting acceptable laser exposure levels below that which could cause visual impairment of flight crewmembers while performing critical flight maneuvers.

As a result of the NTSB recommendations and research activities supported by the FAA and the Society of Automotive Engineers (SAE) G-10T (Laser Safety Hazards Subcommittee), FAA Order 7400.2 (Part 6. Miscellaneous Procedures: Outdoor Laser Operations) was revised to include new guidelines for Flight Safe Exposure Limits (FSELs) in specific zones of navigable airspace associated with airport terminal operations. This revision was made to augment the existing MPE that limited exposure in the Normal Flight Zone below that which could cause ocular tissue damage. Based on consultations with laser and aviation experts, scientific research, and historical safety data, 100 microwatts per centimeter squared (µW/cm^2) was identified as the level of exposure at which significant flashblindness and after-images could interfere with a pilot's visual performance. Similarly, 5 µW/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 conduct an aeronautical study to identify the zones of airspace around an airport or airway that must be protected by the application of the appropriate FSEL. These zones and FSELs include:

• Laser Free Zones = 50 nanowatts per centimeter squared (nW/cm^2),
• Critical Flight Zone = 5 µW/cm^2,
• Sensitive Flight Zone = 100 µW/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 Normal Flight Zone (NFZ), which would apply to all navigable airspace beyond the Sensitive Flight Zone (SFZ). (Note: The SFZ

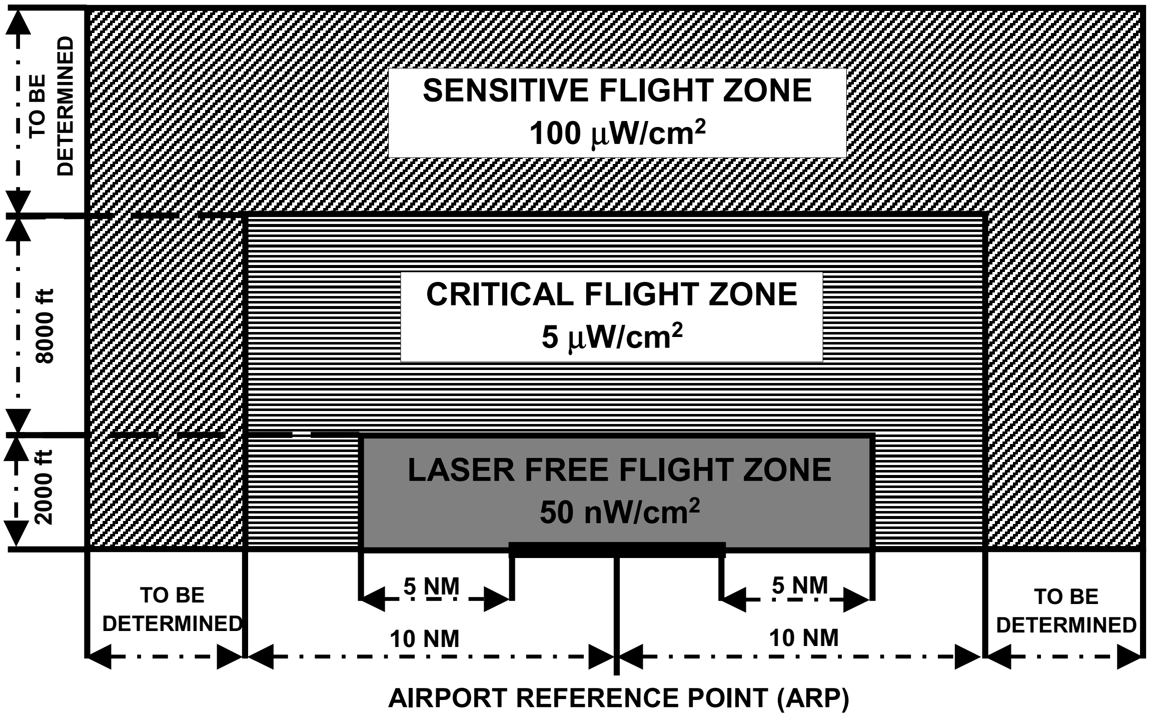


Figure 1: Profile view of a single-runway airport and the application of protected flight zones. (Not drawn to scale.)

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), 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.

Since the September 11, 2001, terrorist attacks on the United States, the FAA and other government agencies have become more aware of possible terrorist acts involving civil aviation aircraft. Advances in technology have increased the portability, output power, and accessibility of laser devices, together with the potential for an individual or group of terrorists to interfere with flight crewmembers conducting low-altitude maneuvers. A laser attack could be quickly deployed and withdrawn, leaving no obvious collateral damage or projectile residue, and would be difficult to detect and defend against. The possible visual impairment, startle, distraction, and the loss of spatial orientation created by such an attack could make landing an aircraft difficult at best. A sufficiently powerful laser could cause permanent ocular damage, blinding crewmembers and make a successful landing virtually impossible. While regulations cannot minimize the likelihood of a malicious act, research can provide insight into the seriousness of the threat and a basis for the development of defensive methodologies.

The FAA performed a study in response to an NTSB recommendation (17) to investigate the maximum safe level of laser light exposure for pilots conducting terminal operations. The original study focused attention on the CFZ where the majority of accidental laser exposures had occurred (18). This study found that the FSEL (5 $\mu W/cm^2$) established for the CFZ was adequate for protecting pilots from serious temporary visual impairment. However, this research paper reports on ancillary trials performed during the original study to investigate laser exposures in the Laser-Free Zone. This report evaluates the effect that laser exposures have on a pilot's operational and visual performance while conducting short-final maneuvers at 100 feet AGL.

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 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. This study received Institutional Review Board (IRB) clearance before its initiation. All subjects in the study gave their voluntary informed consent and were free to withdraw at any point during the study.

As in previous human laser experiments, such as those conducted at Brooks Air Force Base in San Antonio, TX, the laser exposure level did not exceed the MPE for any single exposure (19,20). 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/cm^2, where t = seconds, or

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

The highest single planned exposure was 50 µJ/cm^2. A 50 µW/cm^2 exposure for 1 second is equal to 50 µJ/cm^2, 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 18×10^{-6} and 10 seconds is also given by $1.8t^{0.75}$ mJ/cm^2. The planned cumulative exposure in the LFZ† for each subject was 55.5 µJ/cm^2 over a total laser exposure time of 3 seconds. The MPE for a cumulative exposure of 3 seconds equals 4.1 mJ/cm^2. Therefore, the planned cumulative exposure of 55.5 µJ/cm^2 delivered to each subject was only 1.4% of the MPE.

Four test scenarios were developed, based on the following independent variables:

Laser power levels:
- 0 µW/cm^2,
- 0.5 µW/cm^2 for 1 second,
- 5.0 µW/cm^2 for 1 second, and
- 50.0 µW/cm^2 for 1 second.

Operational maneuver:
- Short-final approach – 30° Left turn,
- Short-final approach – 30° Right turn.

During the experiment each exposure level was presented once, and total simulator time was about 40 minutes. The independent variables were randomly manipulated among the four test scenarios, and all laser exposures were 1 second in duration. The four approach scenarios included three 30° left turns and one 30° right turn. The single zero-level-exposure trial provided the subjects with a sense of uncertainty as to whether the laser would come on during any given maneuver. Except for the zero-level-exposure trials, subjective responses were solicited after each trial (see Appendix A) 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 following a steady-state turn at 100 feet AGL while the aircraft was on short-final approach. Subjects were instructed to continue normal procedures and fly as efficiently as possible during the laser exposure. A certified Laser Safety Officer operator was present throughout the experiment to ensure that the laser operated safely.

† NOTE: In a similar manner, eight additional approach maneuvers and four takeoff/departure maneuvers were conducted to evaluate the test subjects' reactions to laser illumination within the CFZ. Test subjects were exposed to the three identified laser exposure levels and a zero-level-exposure on three separate occasions, while on visual and ILS approach and during takeoff/departure maneuvers. Total cumulative exposure for both studies was 222 µJ/cm^2 for 12 seconds, or 2.2% of the MPE. The results from the CFZ investigation were reported in a separate paper (18). Only laser exposures within the Laser Free Zone were used in this analysis.

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. Subjects were also asked to provide any comments relevant to potential exposure-induced performance or visual difficulties.

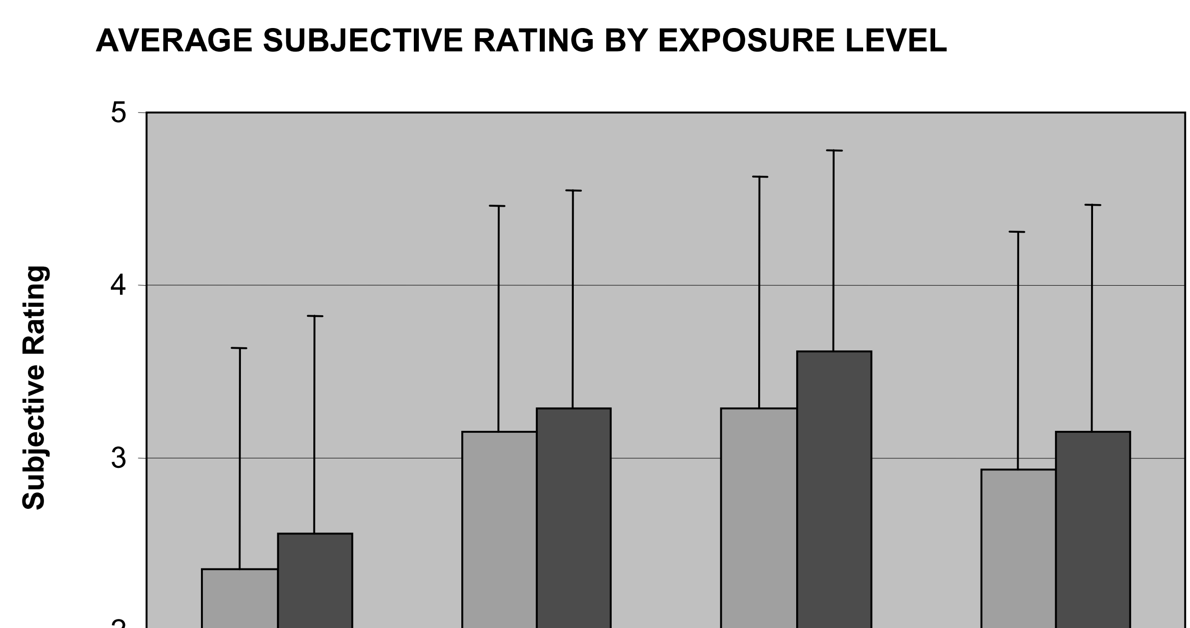
RESULTS

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., miotic pupils, recent 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). One subject was female; 19 subjects used refractive correction (16 spectacle and 3 contact lens) during the trials.

Figure 2 presents the average of all subjective responses to the in-flight questionnaires (see Appendix A) administered to each test subject after laser exposure at 100 feet AGL. Subjects rated the laser's affect on visual performance higher than its affect on operational performance for all levels of exposure. The average total subjective ratings were 2.93 and 3.16 for operational and visual performance, respectively. ANOVA found both the average operational and visual performance ratings increased significantly ($p < 0.05$) between the 0.5 and 5.0 $\mu W/cm^2$ laser exposure levels, while no significance was found between the 5.0 and 50 $\mu W/cm^2$ laser exposure levels. The error bars show the standard deviations of the ratings.

Table 1 shows the total frequency of visual effects reported by subjects immediately after each exposure. In some instances, subjects reported that they experienced a combination of two or all three adverse visual effects for a particular exposure. Reports of multiple visual effects increased as the laser exposure level increased (i.e., 5, 6, and 10 multiple reports, for the 0.5, 5.0, and 50 $\mu W/cm^2$ exposure levels, respectively), as did reports of the more severe visual effects (flashblindness and afterimages).

Figure 3 summarizes the percentage of visual effect responses solicited from all subjects immediately after each exposure. The most common adverse effects reported were glare (30.9%) and flashblindness (30.9%), followed by afterimage (13.0%). In 25.2% of all the responses, test subjects indicated they experienced no adverse visual effects when exposed to any of the three levels of laser irradiance.

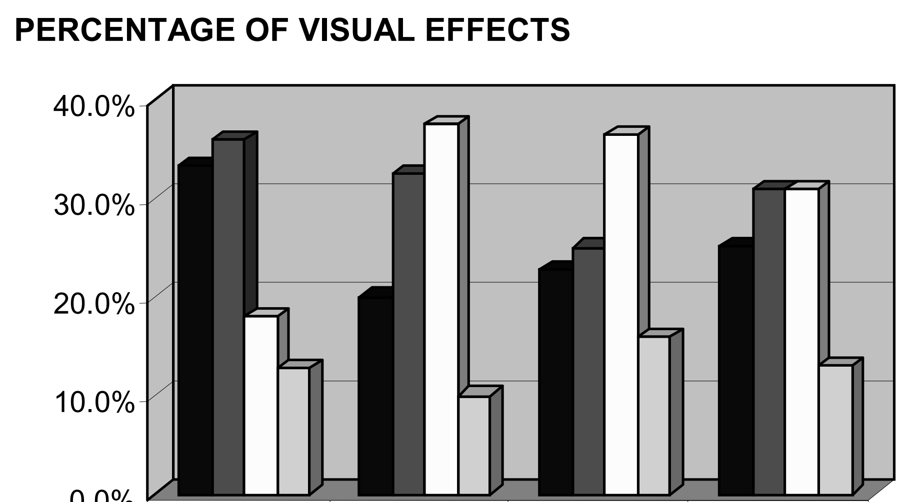


	0.5 uW/cm^2	5.0 uW/cm^2	50 uW/cm^2	TOTAL
Operational	2.35	3.15	3.29	2.93
Visual	2.56	3.29	3.62	3.16

Figure 2: Average subjective rating of pilots' operational and visual performance by exposure level.

Table 1: Frequency of visual effects reported by test subjects for each exposure level.

FREQUENCY OF VISUAL EFFECTS BY EXPOSURE LEVEL				
Effects	**0.5 μW/cm²**	**5.0 μW/cm²**	**50 μW/cm²**	**TOTAL**
None	13	8	10	**31**
Glare	14	13	11	**38**
Flashblindness	7	15	16	**38**
Afterimage	5	4	7	**16**
Total	**39**	**40**	**44**	**123**



	0.5 uW/cm^2	5.0 uW/cm^2	50 uW/cm^2	TOTAL
NONE	33.3%	20.0%	22.7%	25.2%
GLARE	35.9%	32.5%	25.0%	30.9%
FLASHBLINDNESS	17.9%	37.5%	36.4%	30.9%
AFTERIMAGE	12.8%	10.0%	15.9%	13.0%

Figure 3: Percentage of adverse visual effects experienced by test subjects for each exposure level.

After each scenario, the test subjects were asked to comment on what affect the laser exposure had on their visual and operational capabilities. The figure (see Figure 4) and text below summarize the subjects' most frequently reported comments for the corresponding level of laser exposure.

At the 0.5 μW/cm² level of exposure, 38% of the subjects (n=13) described either being momentarily disturbed, briefly distracted, flashblinded, or loss of depth perception, visual contact with the runway surface and/or visual clues outside the cockpit. One subject felt the need to execute a missed approach or "go around" maneuver (i.e., aborted landing = 1, or 3%).

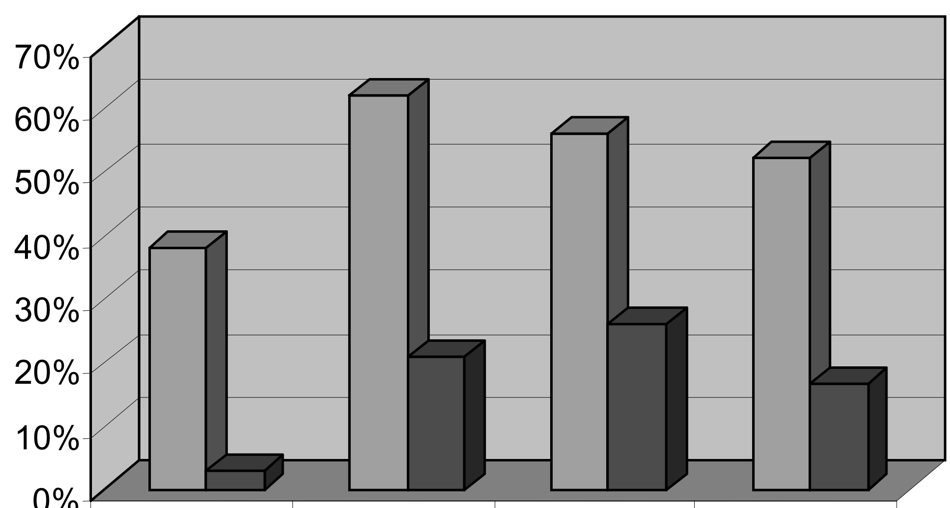
At the 5.0 μW/cm² level of exposure, 62% of the subjects (n=21) reported various effects that included momentary flashblindness, losing view of the runway surface, loss of depth perception, and/or brief distraction. Of these, four subjects (12%) executed "go around" maneuvers, while one subject (3%) relinquished control of the aircraft to the co-pilot, and two subjects (6%) commented that they would have aborted the landing if it were a "real-world" incident (i.e., actual and potential aborted landings = 7, or 21%).

At the 50.0 μW/cm² level of exposure, 56% of the subjects (n=19) provided comments regarding the difficulties they experienced, including having to seek shelter from the harsh light (ducking under the glare shield), momentary flashblindness resulting in the total loss of view outside the cockpit, and having to transition to instrument flight rules. Of these, four subjects (12%) executed "go around" maneuvers, while five subjects (15%) reported that they would have performed a missed approach if it were a "real-world" incident or if the duration of the laser exposure had been longer (i.e., actual and potential aborted landings = 9, or 26%).

DISCUSSION

Approximately 75% of the responses solicited from subjects indicated they had experienced adverse visual effects resulting in some degree of operational difficulty when illuminated by eye-safe levels of laser radiation during final approach maneuvers. Even at the lowest level of laser exposure (0.5 μW/cm²), two-thirds of the responses indicated that subjects experienced glare (36%), flashblindness (18%), and afterimages (13%), at least while the laser stimulus was present. These responses and a missed approach associated with the lowest level of laser exposure in this study confirm that laser illumination of flight crewmembers in the LFZ at or above 0.5 μW/cm² should be avoided. In addition, when illuminated by the two higher laser exposure levels (5 and 50 μW/cm²),

PERCENTAGE OF OPERATIONAL EFFECTS



	0.5 uW/cm²	5.0 uW/cm²	50 uW/cm²	TOTAL
VARIOUS EFFECTS	38%	62%	56%	52%
ABORTED LANDING	3%	21%	26%	17%

Figure 4: Percentage of adverse operational effects experienced by test subjects for each exposure level.

subjects missed eight approaches, relinquished command to the co-pilot once, and indicated they had significantly ($p < 0.05$) greater operational and visual performance problems compared to the lowest exposure level. The FSEL assigned to the LFZ (50 nW/cm^2) is one order of magnitude below the lowest laser exposure level used in these trials (0.5 μW/cm^2). While it appears reasonable to assume the FSEL established for the LFZ provides an adequate margin of safety, that exposure level was not evaluated in this study.

The device used to produce the stimulus in this study was a commercially available, CW 1-W doubled Nd: YAG laser, employing multiple filters and a fiber optic delivery system that effectively reduced the emitted laser radiation to the eye-safe levels. However, even relatively low-powered laser devices, such as laser pointers and targeting lasers (used for handgun and rifle sights), could be used to deliver irradiance levels that exceed the FSELs assigned to the LFZ, CFZ, or even the SFZ. These lasers are normally classified Class 3a by the FDA's Center for Devices and Radiological Health (CDRH). Table 2 provides a summary of the primary laser classifications, output power limits, and labeling requirements manufacturers of laser products must follow in the United States. Strict adherence to these regulations is difficult to enforce, and some imported devices may exceed the prescribed output limits or lack proper labeling.

Several incidents of lasers illuminating aircraft prompted an outright ban of Class 3a (i.e., output power >1 to ≤ 5 mW) laser pointers in the United Kingdom. One incident occurred on October 29, 1997, involving the illumination of an Airworld Airbus on final approach to Manchester Airport at 600 feet AGL by an individual using a laser pointer. The pilot was momentarily distracted but managed to safely land the aircraft carrying 180 passengers. The pilot reported that if the aircraft had been closer to the airport and the laser beam had been shone directly into his eyes, the situation could have been very dangerous. Furthermore, during this same period, a review conducted at Heriot-Watt University in Edinburgh, Scotland, of 17 laser pointers labeled as Class 2 (i.e., output power ≤ 1 mW) found that 14 of the devices were actually emitting laser energy at the more dangerous Class 3a limit, having an output power ≤ 5 mW (21).

Primarily due to the extended distances between the radiation source and those irradiated, the main threat to flight crewmembers from accidental or careless exposure to low-powered visible lasers is temporary visual impairment, as opposed to eye injury. The minimum distance at which a pilot can be exposed to laser radiation without experiencing a particular debilitating visual effect is called the Minimum Flight Safe Exposure Distance (FSED). For visible CW lasers of various output power, the FSED can be estimated (see Equation A) by assigning a common beam divergence and exit port diameter (e.g., Φ = 1 mrad and α = 0.2 cm, respectively), and assuming a dark-adapted pupil diameter (0.7 cm) for the exposed individual.

Equation A: $$\mathrm{FSED} = \frac{1}{\Phi}\sqrt{1.27\frac{P_o}{\mathrm{FSEL}} - \alpha^2}$$

Table 2: The FDA's Center for Devices and Radiological Health classification and labeling requirements for commercial laser products.

CLASS	MAX POWER (mW)	LOGOTYPE	WARNING LABEL
1	≤ 0.39	None Required	None Required
2a	> 0.39 to ≤ 1	None Required (Exposures < 1,000 sec)	
2	≤ 1	**CAUTION**	Laser Radiation – Do Not Stare into Beam
3a	≤ 5	**CAUTION** (Irradiance < 2.5 mW/cm^2)	Laser Radiation – Do Not Stare into Beam or View Directly with Optical Instruments
		DANGER (Irradiance ≥ 2.5 mW/cm^2)	Laser Radiation – Avoid Direct Eye Exposure
3b	≤ 500	**DANGER**	Laser Radiation – Avoid Direct Exposure to Beam
4	> 500	**DANGER**	Laser Radiation – Avoid Eye or Skin Exposure to Direct or Scattered Radiation

Table 3 provides estimates of FSEDs for lasers with output powers of P_o = 5 mW, 0.5 W and 1 W, at the LFZ limit (i.e., 50 nW/cm^2) with the estimates adjusted for atmospheric attenuation in clear air (i.e., attenuation coefficient: $\mu = 5 \times 10^{-7}$ cm^{-1}). At long distances, even a clear atmosphere will reduce the FSED significantly. A simple equation to include atmospheric attenuation cannot be found, but the following equation provides a conservative estimate.

Equation B: $$r_\mu = 0.5 r_c (1 + e^{-\mu r_c})$$

Where,

r_μ is the distance including atmospheric attenuation and r_c is the distance calculated from Equation A.

A laser pointer operating at the upper limit of the Class 3a range (5 mW) would expose a pilot to radiation levels above the FSEL established for the LFZ (50 nW/cm^2) at distances up to 2.03 miles, or 1.77 nautical miles (see Table 3). For the more resourceful and malicious individual intent on disturbing normal cockpit activity, that distance could be extended to approximately 17 miles with a 1-W laser. These estimates illustrate the disruptive range of influence that relatively low-powered lasers can cause. Targeting flight crewmembers through an aircraft windscreen at distances greater than a few hundred yards would be difficult without a suitable means for aiming the laser, such as a telescopic sight. Studies have been performed to examine the practicality of carrying out such attacks on military aircraft (19,20).

Table 3 summarizes the range of distances at which the misuse of relatively low-powered lasers (≤ 1 W) could present a potential threat to aviation safety in the LFZ based on the 50 nW/cm^2 FSEL. Similarly, Table 4 provides estimated distances within which a more powerful laser could disrupt flight crew activities in protected flight zones. Attenuation is often ignored in such calculations to afford an additional margin of safety. However, it is included here to provide a more realistic estimate of the potential range a 10-W laser would have in clear air. As these estimates indicate, a 10-W laser could present an ocular tissue hazard for almost one-half mile and visually disrupt flight operations in the LFZ, CFZ, and SFZ over considerable distances (i.e., 49.5, 7.18, and 2.03 miles, respectively), assuming an adequate aiming mechanism was employed.

Ad-hoc analysis using ANOVA was performed to compare the performance ratings obtained for the LFZ in this study with those of the CFZ collected in the previous study where the same test subjects performed visual and ILS approach maneuvers (18). Statistically significant ($p < 0.05$) differences were found between the operational and visual performance ratings reported at all three laser exposure levels. Since the exposure levels were the same, and the (approach) maneuvers were similar in both studies, this finding suggests that test subjects found the visual effects of laser exposure significantly more troublesome at 100 feet above the runway than they did in the CFZ, where altitude and recovery time were more abundant.

Table 3: Estimated minimum FSEDs for three visible CW lasers at the Laser-Free Zone, where FSEL = 50 nW/cm^2. (Note: Estimates are adjusted for atmospheric attenuation in clear air: $\mu = 5 \times 10^{-7}$ cm^{-1}.)

Output Power Watts	FSED Feet	FSED Miles	FSED Nautical Miles
0.005	10,738	2.03	1.77
0.5	68,300	12.94	11.24
1.0	89,327	16.92	14.70

Table 4: Protected flight zone estimated minimum FSEDs for a visible 10-Watt CW laser. (Note: Estimates adjusted for atmospheric attenuation in clear air: $\mu = 5 \times 10^{-7}$ cm^{-1}.)

Flight Zone & Exposure Limits	FSED Feet	FSED Miles	FSED Nautical Miles
LFZ: 50 nW/cm^2	261,530	48.5	43.0
CFZ: 5 uW/cm^2	37,938	7.18	6.24
SFZ: 100 uW/cm^2	10,738	2.03	1.77
NFZ: 2.5 mW/cm^2	2,297	0.44	0.38

In summary, aircraft have been illuminated by laser radiation as the result of unintentional carelessness and by the malicious acts of individuals. These incidents compromise aviation safety due to the distraction and temporary visual impairment they often cause for flight crewmembers. Laser exposure has proven most disruptive when it occurs at low altitude during critical phases of flight. This study investigated the performance difficulties test subjects experienced when exposed to three eye-safe levels of laser radiation on final approach (100 feet AGL) in the LFZ. At the lowest exposure level (0.5 $\mu W/cm^2$), 67% of the responses indicated that test subjects experienced adverse visual effects from laser exposure, while the average subjective ratings were between "slight" and "moderate" for both operational and visual performance. The two higher exposure levels resulted in significantly greater performance difficulties and a total of nine aborted landings. These results and the single missed approach associated with the lowest exposure level indicate that illumination of flight crewmembers by laser radiation at or above 0.5 $\mu W/cm^2$ is unacceptable in the LFZ. The exposure limit established for the LFZ (i.e., 50 nW/cm^2) precludes even 3a laser pointers in this zone. Provided the LFZ exposure limit is not exceeded, a sufficient margin of safety appears to exist for protecting pilots from accidental laser exposure during final approach; however, further research may be indicated to confirm this assumption.

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APPENDIX A

In-Flight Questionnaire

Date: ____________   Subject # ___________

These questions are to be asked after each scenario (trial) by either the first officer or simulator operator. Please answer the following questions on a scale of 1 to 5 where 1 = 'none', 2 = 'slight', 3 = 'moderate', 4 = 'great', and 5 = 'very great'. Circle the appropriate number.

Trial 1: Altitude Readings: Actual __________________   Pilot Response _________________

To what extent did the laser exposure affect your…	None	Slight	Moderate	Great	Very Great
1. ability to operate the aircraft?	1	2	3	4	5

Comments:

2. visual performance?	1	2	3	4	5

Comments:

3. What were the visual effects, if any, from the laser exposure?	None	Glare	Flashblindness	Afterimage

Other:

Trial 2: Altitude Readings: Actual _________________   Pilot Response _________________

To what extent did the laser exposure affect your…	None	Slight	Moderate	Great	Very Great
1. ability to operate the aircraft?	1	2	3	4	5

Comments:

2. visual performance?	1	2	3	4	5

Comments:

3. What were the visual effects, if any, from the laser exposure?	None	Glare	Flashblindness	Afterimage

Other:

Trial 3: Altitude Readings: Actual _________________   Pilot Response _________________

To what extent did the laser exposure affect your…	None	Slight	Moderate	Great	Very Great
1. ability to operate the aircraft?	1	2	3	4	5

Comments:

2. visual performance?	1	2	3	4	5

Comments:

3. What were the visual effects, if any, from the laser exposure?	None	Glare	Flashblindness	Afterimage

Other:

Trial 4: Altitude Readings: Actual _________________   Pilot Response _________________

To what extent did the laser exposure affect your…	None	Slight	Moderate	Great	Very Great
1. ability to operate the aircraft?	1	2	3	4	5

Comments:

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2. visual performance?	1	2	3	4	5

Comments:

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3. What were the visual effects, if any, from the laser exposure?	None	Glare	Flashblindness	Afterimage

Other:
