SAE INTERNATIONAL

AEROSPACE INFORMATION REPORT

AIR5995™	REV. A

Issued 2004-01
Reaffirmed 2011-12
Stabilized 2021-03

Superseding AIR5995

Evaluation of Human Factor Considerations for Outdoor Laser Operations in the Navigable Airspace

RATIONALE

The G-10 Operational Laser committee has agreed to stabilize this document as the content has been determined to be basic and stable information not dynamic in nature.

STABILIZED NOTICE

This document has been declared "Stabilized" by the SAE G10-OL Operational Laser Committee and will no longer be subjected to periodic reviews for currency. Users are responsible for verifying references and continued suitability of technical requirements. Newer technology may exist.

FOREWORD

The G-10T Laser Hazards Subcommittee of the SAE G-10 Human Factors Behavioral Engineering Committee has convened meetings over thirty times during the past four years to identify issues, technologies, operational capabilities, and potential flight hazards presented by outdoor laser shows and other laser illuminations which extend into the navigable airspace. Activities related to these endeavors have been supported by subcommittee members from seventeen different organizations, including both governmental agencies and commercial or private firms. Information resulting from these activities and other activities identified in this document was requested by the U.S. Federal Aviation Administration (FAA) to assist in the development of FAA Order 7400.2D, "Recommended Interim Guidelines," and the more recent development of FAA Advisory Circular 70-3, "Laser Operations in the National Airspace System."

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1. SCOPE

This report identifies the reasons for, and results associated with, the conduct of a flight simulation research project evaluating the effect of low powered laser beam illumination of pilot crewmembers operating in the navigable airspace. This evaluation was primarily concerned with the possible degradation of pilot performance when illuminated by a laser while operating in an airport terminal area where pilot workloads are normally at their maximum.

1.1 Purpose

The purpose of the reported simulation evaluation was to validate guidelines established by the FAA for allowable laser exposures in navigable airspace.

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3. BACKGROUND

During terminal flight operations, distractions in the cockpit are specifically minimized to enhance the orderly conduct of flight procedures. For example, below 10,000 feet, the Federal Aviation Regulations (FARs) require a sterile (quiet) cockpit that minimizes distractions and reduces the potential for flight procedure errors. However, sound is not the only factor that can cause distractions. Pilot vision factors can produce a variety of distractions that varies with pilot visual workload.

Pilot visual workload is task dependent relating to the particular phase of flight being undertaken. Below 1000 feet, the aircraft must be in a landing configuration and in position to complete a normal landing. In a landing approach the crewmembers must be able to visually identify the runway threshold or other lighting configurations. If these lighting configurations are not visually identifiable the pilot must execute a go-around.

In recent years there has been an increase of incidence of laser illuminations of flight crew personnel while conducting flight operations. These incidents have most generally occurred near airports located in close proximity to resort destinations and large entertainment events. Some of the incidents have resulted in temporary vision impairment and aversion reactions by flight crewmembers. As an example, during November of 1993, a Southwest Airlines B-737 departing Las Vegas, Nevada, USA, experienced a laser beam illumination at 500 feet AGL. The laser beam source was reported to have originated from one of the hotels located near the airport. The beam had entered the cockpit through the copilot's window. The copilot reported the loss of vision in his right eye for about 15 minutes. The following day, an ophthalmologist examined the copilot and found evidence of conjunctiva hemorrhage in the right eye. The captain of the referenced flight stated that if the laser had passed through the front windshield, illuminating both pilots, it was his opinion that they would have lost control of the aircraft.

During the eighteen-month period following this particular incident a series of fifty-one laser beam illuminations of aircraft were reported at or near the Las Vegas Airport. Air carrier operators operating large transport airplanes and local operators operating helicopter aircraft were the primary originators of these reports. In addition, emergency and law enforcement operators have also reported uncontrolled laser illuminations near the Los Vegas Airport.

The U.S. medical and aviation regulatory agencies have agreed that existing regulations and guidelines were not adequate for the current usage of laser beam technologies in navigable airspace. Clearly, there could be temporary functional impairments of flight crews at levels of illumination much lower than those normally associated with physical injury. An aviation safety issue was truly indicated.

The fifty-one documented laser incidents resulted in a moratorium on the use of outdoor lasers in Las Vegas, Nevada, USA, in late 1993 and during 1994. A number of these incidents resulted in temporary visual impairment of pilots operating commercial aircraft in the Los Vegas Airport terminal area. To date, no conclusive medical documentation exists of any permanent eye injuries to illuminated crewmembers.

There are two areas where outdoor laser operations potentially pose a safety concern to flight crewmembers. The first is a condition where maximum permissible exposure (MPE) is exceeded and physical injury to the illuminated eye can occur. The second area of concern is a situation where MPE is not exceeded but there is still a potential for functional impairment. This concern includes physiological effects such as flash blindness, after-image, glare and dazzle. These effects can be most hazardous when laser illuminations interfere with the vision of the crewmembers and result in a temporary vision loss (TVL) during certain critical phases of flight such as takeoff maneuvers, landing maneuvers, and especially standard instrument departures that require climbing steady state turns. TVL is associated with (1) flash blindness, (2) after-image, and (3) glare that may cause incapacitation or reduced physical performance.

During an illumination event certain physiological ocular symptoms may cause a momentary loss of vision due to light sensitivity, tearing or glare. This could result in crewmember disorientation. Glare can cause a reduction or total loss of vision, but the effect is temporary, lasting only as long as the light is present in the observer's field of view. Temporary visual impairment, normally associated with distraction, disruption and minor afterimages, while generally not leading to incapacitation, can be hazardous if it occurs at critical phases of flight, or at low altitudes.

4. FACTORS AFFECTING PILOT WORKLOAD

4.1 Flight Disorientation

Flight disorientation of pilots is characterized by one of two categories: geographical disorientation and spatial disorientation. Temporary loss of vision during steady state turns, for example, requires the crewmember to rely upon questionable vestibular responses which crewmembers have been previously trained to suppress during instrument flight. This unreliable vestibular sensory sensation can cause spatial disorientation (SD) and loss of situation awareness (LSA). Flight crewmembers receive 90% to 95% of their information visually to develop information patterns for alpha-numeric associations and trend vector analysis options. Loss of visual reference can create startle, distraction, disruption, disorientation, and in extreme cases, temporary incapacitation.

Since flight crewmembers are trained to interpret, integrate and process information in a dynamic environment without horizontal reference to the outside world, any interruption in visual performance during critical phases of flight creates a potential for incidents associated with loss of control of the aircraft.

4.2 Instrument Flight Training

Factors that have a significant impact on human performance that is based on information integration are included in instrument flight training programs. Flight crewmembers receive almost all of their flight control and guidance information visually to develop patterns, associations, and linear trend analysis options. This information requirement becomes more intense during nighttime operations where the retina's photoreceptor rods are responsible for detection of movements, shapes and night vision. Even without additional impairment from a laser's visual interference, statistics show the accident rate at night is almost three times the rate for daytime flight operations. Further increases in accident rates, particularly by night-time laser illuminations, would not be an acceptable development.

In certain phases of flight, flight crewmembers operate in a dynamic environment that requires constant and rapid intentional updates in order to maintain situational awareness. During flight in instrument meteorological conditions (IMC) crewmembers must rely, exclusively, on their flight instruments. These are classified as either (1) control instruments or (2) performance instruments for proper spatial orientation. Control instruments include such things as the attitude deviation indicator (ADI) and engine power instruments (percent of RPM, fuel flow). Performance instruments include: angle of attack (AOA), airspeed/mach, altimeter, rate of climb, horizontal situation indicator (HSI), compasses, head-up displays (HUDs), and multifunction displays (MFDs). Flight crewmembers must recreate the outside world with flight instruments to form dynamic linear and angular patterns. Images from the outside world are initially upside down and backwards when reaching the retina. Visual inputs balance the body through the brain's comparison of visual images transmitted from the retina to the brain's pre-existing mental model. This mental model is continuously updated with reference to the outside world for comparison and processing.

In flight, when flight instruments are the only source of information, flight crewmembers must direct their visual attention to interpret and process information from these instruments. This requires a visual scan technique that uses frequent scans of the instruments to obtain bits of information from the control and performance instruments. The highly proficient flight crewmember assembles the associated bits into related chunks of information that represent dynamic spatial patterns. These scan patterns are continuously updated by the control and performance instruments through a closed loop feedback. This procedure is commonly referred to as dynamic scan pattern chunking.

4.3 Human Balance Systems

Understanding the general principles upon which the human balance system operates is critical for flight crewmembers that operate IMC, or have temporary vision impairment (TVI) due to laser illuminations. Loss of outside visual reference with the horizon causes the balance system to send conflicting information resulting in disorientation and, potentially, vertigo (sensory cross coupling).

4.3.1 Visual System: The most important sensory system providing spatial orientation during flight is the pilot's visual system. When vision is impaired, or temporarily lost, spatial orientation is downgraded to a lower level of accuracy of motion and position cues during flight . These less accurate sensory stimuli are associated with the vestibular and somatosensory systems. The visual system is classified into two segments that minimize spatial disorientation tendencies. The first is visual dominance (through the eyes) where the flight crewmember receives all information used to maintain proper flight control and performance. Vestibular suppression is the ability to ignore unwanted sensations that conflict with visual performance. Through constant instrument training and practice the flight crewmembers develop confidence that the instrument displays are accurately recreating the outside world with reference to the horizon.

4.3.2 Ambient Vision: The ambient vision system is primarily concerned with the question of "where," thus providing spatial orientation. Because ambient vision is monitored at the subconscious level, its information is processed automatically at very high rates and without conscious effort. The focal visual system is primarily concerned with the question of "what," providing fine detail for recognition. For spatial orientation, focal vision provides visual cues for judgment about distance and depth, and retrieves information from the flight instruments. While focal vision operates with great precision and accuracy, it is processed in the conscious mind relatively slowly, requiring active thought.

4.3.3 Vestibular System: With the loss of visual orientation cues, the vestibular and somatosensory systems can provide orientational illusions. Somatogyral illusions result from the semicircular canal's inability to sense accurately a steady state turn (angular velocity). To stimulate the semicircular canal sensory organ requires a one degree per second per second acceleration. When angular acceleration ceases, such as when a constant rate turn is established, the semicircular canals are unable to detect angular velocity. If visual reference is lost (outside/inside) flight crewmembers will not recognize that the aircraft is turning.

4.3.4 Somatosensory System: This is a system that relies on the body's structure to provide important equilibrium information with respect to pressure and movement. The system is better known as "Seat of the Pants" or "Closed Loop Feedback System" and is based upon sensations that a flight crewmember senses when utilizing control and performance instrumentation of the aircraft. This type of body sensing of aircraft's attitude in space is very unreliable without visual reference to validate the stimuli. Other forms of physical stimuli are the sounds that flight crewmembers learn to recognize due to changes in the aircraft's performance. These auditory sounds are those resulting from airflow over the windscreen during acceleration and deceleration of the aircraft, and the change of the pitch as engine power settings change.

4.4 Situational Awareness

Situational awareness is generally defined as one's awareness of the state, or condition, of the elements that exist within the operational environment in which one is located, and understanding the effects of dynamic changes occurring within that environment. Situational awareness is required of flight crewmembers in the following areas:

- Operational Environment
- Navigation Requirements
- Weather
- Communications
- Aircraft Capability
- Spatial Orientation
- Aircrew Capability

Anything that leads to a loss of situational awareness in any of these areas can create a potential hazard. One of the most critical areas, and one most likely to be affected by laser illumination, is spatial orientation.

Spatial orientation is depicted as one of the several critical task elements comprising visual workload. Three types of spatial disorientation have been classified. Type I (unrecognized) is a situation in which the crewmember does not consciously recognize any of the sensations of spatial disorientation (SD). Type II (recognized) provides cues that alerts the flight crewmember and provides conscious sensing of the disorientation, commonly referenced as vertigo. Type III (incapacitating) is a situation in which the flight crewmember experiences incapacitation to determine proper reference to the outside world and must transfer control of the aircraft.

4.5 Vision Impairment From Excessive Illumination

4.5.1 Glare and Dazzle: Glare and dazzle are two terms often used interchangeably that refer to temporary disruptions in visual acquisition without biological damage. Glare can be caused by virtually any light source and is particularly disruptive under scotopic viewing conditions, especially when an eye is fully night-adapted. However, any glare source in the cockpit is undesirable. Glare is regarded as a source fixed effect, meaning that as the position of gaze shifts away from the light source, glare effects are diminished. The length of time during which glare is in effect is not only a function of how long the target is viewed, but also the overall dark adaptation state and pupil size in the target eye. Glare can be further broken down into discomfort glare and disability glare. Discomfort glare refers to glare of illumination so high that it forces the viewer to turn away. Discomfort glare tends to be exacerbated when the overall ambient illumination is low. Disability glare refers to the inability to see a target of regard because of the light source. In addition, veiling glare represents the ability of a glare source to impede visualization of structures around the glare source beyond the actual size of the glare source itself and is a more functional representation of the true level of disability glare.

Disability from glare from an external light source can be attenuated if there are any intervening ocular inter-faces, such as windscreens, canopies, or even corneas, and other optical appliances that scatter incident light. The more scatter that occurs, the greater the disability glare. Some interface materials can also reradiate light at different wavelengths, thus making an invisible laser a visible nuisance, if reradiated from a windscreen or canopy at a visible wavelength.

It can be shown that the visual effects from glare increases with age, which undoubtedly represents a function of age-related changes in the optical media in an older eye, particularly the lens. In general, a laser light source is a very bright light that can be an extremely effective disability glare source. Laser induced glare can be initiated by both continuous wave and pulsed laser sources, although it tends to be more of a concern with a continuous wave laser source It also appears that within the visual spectrum, all visible wavelengths have approximately the same scattering characteristics with one color not necessarily any better than another at inducing glare, all other aspects being equal.

4.5.2 Flash Blindness: Flash blindness is an effect that persists during a period of time while the eye attempts to recover from an exposure to a bright light source. The ability of any given light source to induce flash blindness is directly related to the brightness of the source and the level of dark adaptation in the target eye at the time of the exposure. It can be shown that the brighter the environmental luminance levels to which an eye is adapted at the time of the exposure, the brighter the flash of light needs to be to induce flash blindness. The corollary to this is that the brighter the light source in any given situation, the longer the flash blindness effect that ensues. This directly relates to the ability of the eye to recover from bleaching of the photosensitive pigments caused by a new bright extrinsic light source. During the period of recovery, the luminance conditions of the target(s) being viewed as a primary task will also determine how long it takes to recover from the flash blindness functionally. If the task at hand is generally a bright one, recovery times will be shorter, but if the task at hand is poorly lit or a dim visual task, then the times to recover will be more prolonged by virtue of the slowness of rejuvenation of rod photochemistry as compared to that of cones. Flash blindness can last from several seconds to several minutes and has been shown to be more prevalent in older individuals largely based on the speed and efficiency of recovery mechanisms and richness of vascular supply available in the target ocular tissue. Continuous and pulsed laser sources seem equally adept at inducing flash blindness.

4.5.3 After-images: After-images refer to perceptions, so-called after effects, that persist following illumination with a bright light source and are described as light, dark or colored spots following exposure. Such after-images are essentially a type of flash blindness, although after-image effects may last for more prolonged periods of time well beyond the time available for recovery of the ability to perform visual tasks required while in the cockpit. After-image effects may include color distortion that represents selective cone pigment depletion similar to those induced with flash blindness. However, after-images may persist for much longer periods than flash blindness and can persist from minutes to hours and as long as perhaps several days. They can also have different effects depending on the characteristic of the background under observation. Like flash blindness, afterimages also tend to last longer in older individuals. Their intensity, density, and duration are in direct proportion to the level of the instigating light sources.

5. VALIDATION OF PROPOSED ILLUMINATION STANDARDS IN TERMINAL AIRSPACE

5.1 The Tasks

The incidents involving laser illuminations of aircraft cockpits cited above have emphasized the need for research on the effects of laser beams within the flight operational airspace. It has been clear that existing medical standards did not adequately address the visual impairment that could occur with illumination values at less than the maximum permissible exposure (MPE) levels. U.S. civil aviation authorities (FAA) requested that the SAE Human Factors Behavioral Engineering Committee, G-10, review existing standards and, if warranted, convene a group of subject matter experts to prepare new standards for functional impairment for pilots operating in the national airspace. Review of known incidents and input from the subject matter experts resulted in formation of a committee of international experts to prepare new standards for operational airspace.

This committee proposed that the problem be dealt with on three levels. First, there was a need for an operational validation of the new levels of exposure proposed by the committee for terminal areas where operational requirements are extremely critical. During flight maneuvering within the terminal area, visual impairment of any kind has the potential to degrade flight performance, cockpit procedures, crew coordination, and pilot/ATC communications. This activity would have the highest priority and present the greatest challenge. The second activity was to develop a national (U.S.) reporting system that could identify and track laser illuminations of aircraft operating within the navigable airspace. The third activity involved the development of an educational program for pilots, the general public, and laser operators. This program should provide information regarding critical safety factors associated with the use laser illumination within operational airspace.

Since the proposed values were far below those considered dangerous by medical authorities, the Committee recommended that the operational validation of the new levels be evaluated in an advanced flight simulator using live subjects.

These low level exposures, while not causing physical damage, can significantly disrupt visual performance. The photostress effect of low level laser light exposure can reduce visual sensitivity. The reduction of visual sensitivity is especially hazardous at night when the eye is adapted to very low light levels. Exposure of the dark-adapted eye to intense light can render the eye incapable of sensing the visual scene. Therefore, the simulation task was to evaluate flight performance based upon any disruption of the pilot’s visual performance following low level laser light exposures.

5.2 Standards Evaluated

With assistance from the SAE G-10 Laser Safety Hazards Subcommittee, the FAA has recently modified FAA Order 7400.2, Part 6, Chapter 30, “Procedures for Handling Airspace Matters, Outdoor Laser Operations,” that governs outdoor laser demonstrations. Visual impairment characteristics associated with exposure to bright light were used to develop the new guidelines in 7400.2. These characteristics included: after-image, flash blindness and glare.

The original FAA Order 7400.2 was written in terms of the Food & Drug Administration's (FDA's) "Performance Standards for Light-Emitting Products," 21 Code of Federal Regulations (CFR) 1040. The FDA standard is based on the recommended Maximum Permissible Exposure (MPE) of 2.6 milliwatts per centimeter square (mW/cm2) from continuous wave lasers. The MPE limits are stated in the American National Standard for Safe Use of Lasers (ANSI Z-136.1-1993). The MPE is used to calculate the Nominal Ocular Hazard Distance (NOHD), within which ocular tissue damage may occur. The NOHD varies depending on the laser's output power, pulse duration, and beam divergence.

Revised FAA Order 7400.2E, in addition to the NOHD, includes new guidelines for Flight Safe Exposure Limits (FSELs) for specific zones of navigable airspace associated with airport terminal operations. Based on scientific research data and historical safety records of existing laser installations, the 100 microwatts per centimeter square ($\mu W/cm^2$) was designated as the level of exposure at or above which significant flash blindness and after-images could occur. Similarly, 5 $\mu W/cm^2$ was determined to be the level at or above which significant glare may occur. The FAA conducts aeronautical studies to identify the zones of airspace that must be protected around an airport or airway by applying the appropriate FSEL (see Figures 1, 2, and 3). The zones and FSELs include: Normal Flight Zone = 2.6 mW/cm^2, Sensitive Fight Zone = 100 $\mu W/cm^2$, Critical Flight Zone = 5 $\mu W/cm^2$, and Laser/High Intensity Light Free Zones = 50 nanowatts per centimeter square (nW/cm^2). (Note: The sensitive zone is an option that may or may not be designated by the aeronautical study.) The FSELs are used to calculate Flight Safe Exposure Distances (FSEDs) that are also dependent on the laser's output power and beam divergence.

5.3 Test Objective

The proposed research experiment was designed to validate the FAA guideline for the critical flight zone of 5 $\mu W/cm^2$ contained in the new laser illumination standards to be published in 7400.2E. The objective of this research was to evaluate laser illumination as a hazard to pilot performance under simulated operational conditions. The flight simulator test measured the response of pilots to eye-safe levels of laser illumination. The results of this research will help to validate guidelines established by the Federal Aviation Administration (FAA) for allowable laser exposures in navigable airspace.

5.4 Experimental Design

In order to assess the effects of laser light on an aviator's visual performance, it should be studied within the context of a full cockpit environment. Pilot performance in a full motion simulator, while performing routine approaches and departures, with and without intervening laser exposures, was assessed. Use of the simulator allowed the effects of distraction (stimulus that draws attention without degrading visual performance) and disruption (stimulus that degrades visual and flight performance) to be assessed.

The laser exposures in this experiment were similar to those of Armstrong Laboratory Advisory Committee on Human Experimentation (ACHE) previously approved protocols. These include: "Ground Test of Laser Canopy Glare Effects on Pilot Visual Performance" (AL ACHE # 95-04), "Canopy Laser Glare Measurement and Intraocular Glare Model Validation" (AL ACHE #95-20), and "The Effects of Lasers on Visual Search Performance" (AL ACHE #95-93). This experiment complemented those investigations and examined the potential distraction and disruption effects of laser light in operational scenarios.

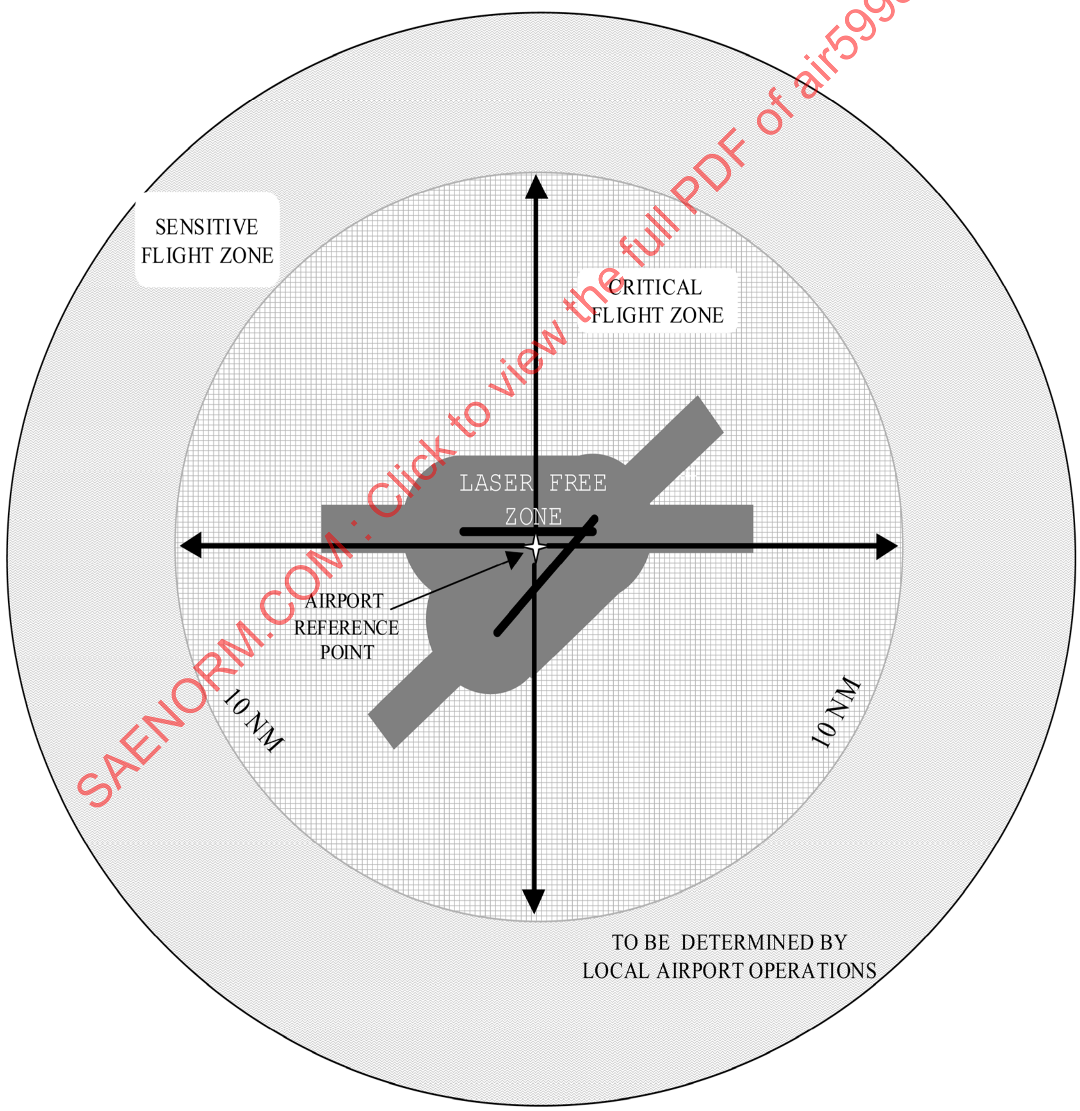

FIGURE 1 - AIRSPACE FLIGHT ZONES

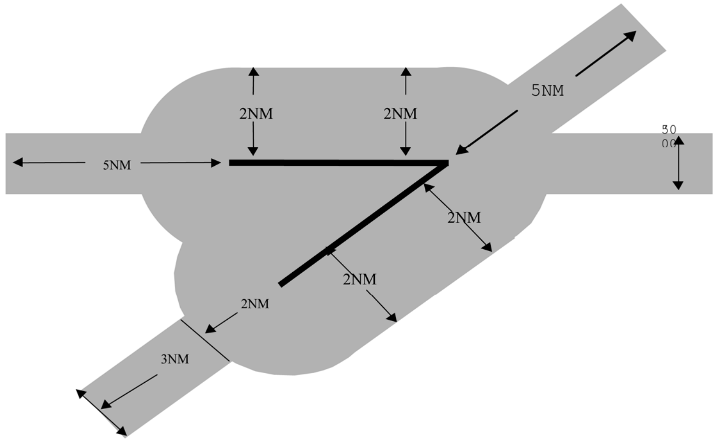

FIGURE 2 - MULTIPLE RUNWAY LASER FREE/HIGH INTENSITY LIGHT FREE ZONE

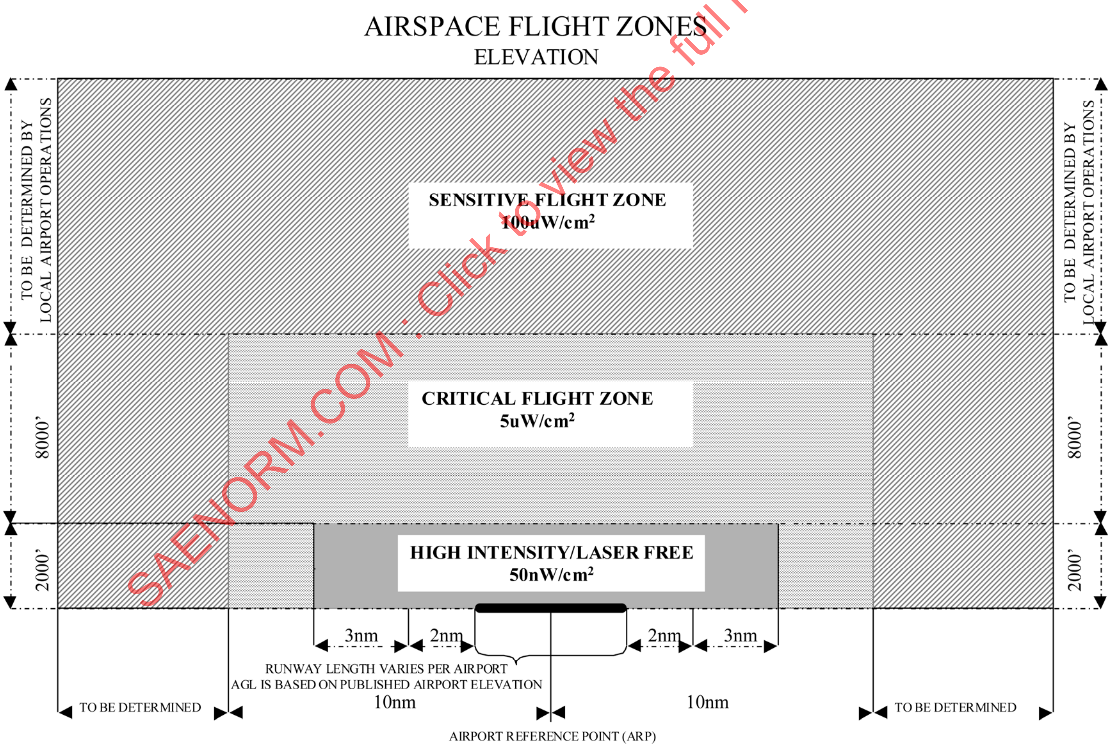

FIGURE 3

Eight conditions were identified based on the following independent variables:

Synthesized Laser Power Variables - 4

0.0 μW/cm^2 for 1 second
0.5 μW/cm^2 for 1 second
5.0 μW/cm^2 for 1 second
50.0 μW/cm^2 for 1 second

Laser Alignment - 1 angle (on-axis)

Approach/Departure Maneuvers - 2

ILS approach to landing
Departure with steady-state turn.

The proposed design manipulated the two variables: A) laser power setting, in μW/cm^2; and B) flight maneuvers. All laser exposures during the experiment were 1 second in duration. The four selected levels of laser power settings (0, 0.5, 5, and 50 μW/cm^2) and two selected flight maneuvers (approach, departure) result in a 4x2 factor, within-subject design. Table 1 presents each of the experimental conditions tested in this experiment.

TABLE 1 - EXPERIMENTAL CONDITIONS

POWER	FLIGHT MANEUVER
0	Approach
0	Departure
0.5	Approach
0.5	Departure
5	Approach
5	Departure
50	Approach
50	Departure

During the experiment, each of the conditions was presented twice, resulting in a total of 16 trials (approximately 5 minutes/trial) for each pilot. Total flight simulator time scheduled was two hours, but most subjects completed the session in approximately 1 hour and 45 minutes. Levels of laser power setting were selected to effectively bracket the proposed standard of 5 μW/cm^2. It should be noted that the levels of laser power proposed are far less than workplace standards provided by OSHA. The zero power level was included to provide a baseline measure with which to compare pilot performance following laser exposure.

The order of the trials was randomized for each subject. Subjects were instructed to remain focused on the laser source as long as possible during the one-second exposure. All trials were videotaped to observe subjective reaction to each exposure.

This study examined the possible adverse effects of sudden, unexpected laser illumination on aircrew performance in a simulated operational environment. Such an illumination may evoke a startle response that could disrupt aircrews' performance or interfere with work patterns during critical phases of flight. This distraction could result in a major error, such as a missed procedure or failure to notice another aircraft. (Note: Startle response was tested by counterbalancing laser power setting and maneuver type for the first laser exposure trial across subjects.)

TABLE 2 - TEST SCENARIO MATRIX

SCENARIO	LASER PWR.	MANEUVER	PILOT ACTION	WIND SPEED/DIR	LASER TRIGGERED
010	0	APPROACH	30 DEGREE RIGHT	090/10	N/A
020	0	DEPARTURE	LEFT TURN	270/10	N/A
033	.5 UW	APPROACH	30 DEGREE LEFT	270/10	@ 100 FEET AGL
043	.5 UW	DEPARTURE	LEFT TURN	270/10	@ 15 DEGREE ROLL
052	5.0 UW	APPROACH	LEFT DOWNWIND	270/10	@ 025 DEGREE HDG
062	5.0 UW	DEPARTURE	LEFT TURN	270/10	@ 15 DEGREE ROLL
071	50.0 UW	APPROACH	30 DEGREE RIGHT	270/10	@ 100 FT. AGL
081	50.0 UW	DEPARTURE	LEFT TURN	270/10	@ 15 DEGREE ROLL
090	0	APPROACH	LEFT DOWNWIND	270/10	N/A
100	0	APPROACH	30 DEGREE LEFT	270/10	N/A
113	.5 UW	APPROACH	LEFT DOWNWIND	270/10	@ 025 DEGREE HDG
123	.5 UW	APPROACH	30 DEGREE RIGHT	090/10	@ 335 DEGREE HDG
132	5.0 UW	APPROACH	LEFT DOWNWIND	090/10	@ 100 FEET AGL
142	5.0 UW	APPROACH	30 DEGREE LEFT	270/10	@ 005 DEGREE HDG
151	50.0 UW	APPROACH	LEFT DOWNWIND	270/10	@ 025 HDG
161	50.0 UW	APPROACH	30 DEGREE RIGHT	090/10	@ 335 DEGREE HDG

5.5 Data Analysis

A multivariate analysis of variance will be conducted for each maneuver type (approach and departure) with laser power as the independent variable and a selection of two or three of the aircraft maneuver measurements considered most relevant to pilot performance as the dependent variables. Separate analyses of each maneuver type are necessary because of the difficulty with finding an equivalent measure of pilot performance across maneuvers. Reactions of the pilot during the laser exposure, was specifically recorded. The data was analyzed and compared with subjective evaluations by the Simulation Test Director (STD). The subjective evaluations by the STD involved cockpit procedures, crew coordination, and efficiency of communication. In addition, subject pilot questionnaires were solicited and analyzed.

Pilot performance was evaluated against a performance baseline in which no laser exposure occurs. The data was further analyzed to detect performance variations induced by exposure to the laser. But, preliminary evaluation shows little variability that can be associated with the exposures, except for missed approaches initiated close to the runway. Possible startle effects were evaluated by analyzing the first laser exposure for each subject as a separate analysis. Effects of repetition and/or fatigue were evaluated by comparing the first two and last two trials, all of which will have been baseline trials. Each subject was allowed up to 30 minutes of pre-test practice time to become familiar with the simulator and the cockpit environment, if needed.

5.6 Test Implementation

Testing took place at the FAA Boeing 727 full-motion Level C flight simulator, Mike Monroney Aeronautical Center, Oklahoma City, OK 73125. The simulator was equipped to monitor a variety of parameters during flight. All flight evaluations were conducted using approaches and departures on OKC runway 35R and 35L.

5.7 Laser Installation

A collimated beam of green light with a peak spectral irradiance at 532 nm wavelength was generated by a continuous-wave doubled Nd:YAG laser. The laser was positioned in the simulator computer room with 75 feet of fiber optic cable used to deliver the beam to the simulator visual system beam splitter. The fiber optic cable was routed with existing wiring into the simulator cab. Appendix 1 of this chapter shows a schematic of the laser installation for reference.

Laser irradiance levels were measured by placing a radiometer at the subject's viewing position prior to each experiment session. In addition, the laser output was controlled by a power/energy controller. A safety shutter opened allowing the beam to pass when the laser output was at a prescribed level. If the laser power increased or decreased more than 10% of its prescribed level, the shutter closed, blocking the beam. The shutter is normally closed and required a positive voltage to open it. A trained laser operator was present throughout the experiment to ensure that all laser safety precautions are observed.

Laser irradiance levels was measured by placing a radiometer (model 161 with radiometric filter, United Detector Technology, Hawthorne, CA) at the subject's viewing position. Laser output power was controlled by a laser power controller (model VIS, Cambridge Research & Instrumentation, Inc., Cambridge, MA) to attenuate the laser beam and achieve and maintain desired irradiance levels at the subject's eye.

5.8 Subject Pilots

Thirty-six (36) qualified pilots served as human test subjects. Subjects were both male and female. Most pilots were large aircraft qualified, without visual disqualifications from flying. Each subject participated in approximately 2 hours of simulator time plus approximately 1 hour for brief and debrief. All participants were solicited as paid volunteers. The U.S. Air Force pilots represented approximately 50% of the pilots. Informed consent was obtained from all subjects prior to participation.

Additionally, subjective evaluations of available Laser Eye Protection (LEP) were performed to assess their usability while performing normal flight operations in a “dark adapted” cockpit environment.

Every participant was given an ophthalmic exam to ensure normal vision and ocular health. Participants was required to have visual acuity corrected to at least 20/20, a normal Amsler grid, and no ocular pathology. Fundus or digital retinal photographs of both eyes were taken. The ophthalmic exam was repeated at the end of testing. Prospective subjects were interviewed regarding their ophthalmic medical history. Persons reporting a history of eye disease, hypersensitivity to light, or taking photosensitizing drugs were not accepted for participation. Anonymity was ensured by assigning each test subject a study number that was used as an identifier on all test data collected. A list of photosynthesizing drugs has been prepared for screening test pilot candidates with the assistance of the U.S. Air Force. Copies of the questionnaires and eye examination forms are attached as appendices.

5.9 Test Procedures

Subjects were exposed to laser pulses as defined in Figure 4. Seat height was adjusted for each subject to the aircraft pilot design eye position. Laser exposures were approximately equivalent for the expected variability in eye positions between subjects. Subjects were instructed to continue normal visual procedures and fly as efficiently as possible during the laser exposure.

Crews flew approach and departure maneuvers and the laser illuminated the cockpit during the maneuvers. The laser exposures occurred when the aircraft was at 100 feet, during final runway alignment, during steady-state turns on approach, and during a steady-state turn following takeoff. A simulation test director was in the cockpit with the crewmember and a qualified B727 co-pilot was provided. A cockpit operator initiated each test run from the pilot instructor's station.

5.10 Simulated Weather Conditions

All scenarios were developed with the terminal area replications having unlimited ceiling and visibility conditions. Wind conditions for the approaches and landings were either a crosswind of 10 knots (left or right) or a zero knot value.

5.11 Simulator Operating Concept and Procedures:

The simulation operating concept involved a subject flight crew of two (Captain and First Officer), a Simulation Test Director/Operator. An experienced First Officer was provided to share some duties with the Simulator Test Director. A representative from the Civil Aeromedical Institute also rode as an observer in the cockpit for most test sessions.

Operator logs were completed for each subject pilot with the Simulation Test Director recording or scoring an evaluation of the particular crew for each scenario flown. The evaluation considered the crew's use of: proper cockpit procedures, appropriate crew coordination, and efficiency of communications.

The cockpit operator initiated each test run from the pilot instructor's station in accordance with the Simulator Operating Instructions in current use at the B-727 simulation facility.

5.12 Initial Simulator Conditions

Gross Weight	154,000 lb	Visibility	Unlimited
C.G.	25%	Ceiling	Unlimited
Fuel Freeze	Set Visual Control Panel	Turbulence	8%

5.13 Simulator Operator's Control Page

A separate control page was constructed on the instructor's console display to initiate and control each scenario. Scenarios have been automated to the extent possible to eliminate operator error and provide a more efficient process.

5.14 Success Criteria

The purpose of the evaluation was to validate that the 5 µwatt illumination values do not cause flash blindness, glare, startle or after-imaging that would lead to unsafe operation of the aircraft, or reactions by the pilot that lead to unsafe conditions. Observation of pilot performance by experienced and trained operators and pilots, and review of pilot questionnaires and operator log sheets were used for initial findings.

5.15 Data Collection

Data was collected and saved to files to the FAA's off-line data collection facility. Variables currently identified for collection for this research that will be analyzed, include:

Time*

Test Number*

Latitude*

Longitude*

Indicated air speed*

Radio altitude (ft)*

Rate of climb (ft/min)*

Pitch angle (degrees)*

Roll angle (degrees)*

Yaw angle (degrees)*

Total thrust (lbs)*

Ground distance (ft)*

Localizer (Centerline) deviation (ft)*

Glideslope deviation (ft)*

On ground flag

Flap Position

Spoiler deployed flag

Laser illumination flag*

Laser light detection*

*NOTE: These are primary parameters for use in the evaluation of pilot performance.

5.16 Test Plan Numbering Convention

To ensure clear identification of each test run, a unique six-digit run number was entered for each scenario run. This run number is composed of the scenario number, test pilot subject number, and indication if the run is a repeat run. This number was unique for each test and was recorded as a variable on all data collected.

Efforts were made to automate the testing procedures and simulator setup as much as practical. This was to enhance the repeatability and quality of the data collection needed for subsequent analysis and evaluation.

5.17 Medical Risk Analysis

As in previous human laser experiments, the laser radiant exposure level was not to exceed 5% of the MPE for an individual exposure. The MPE for direct ocular viewing of a 400 to 550 nm laser beam imaged as a point source for 1 s is 1.8t0.75 mJ/cm^2, where t = seconds, or

MPE = 1.8(1)0.75 mJ/cm^2

= 1.8 mJ/cm^2

The highest single planned exposure was 50 (J/cm^2). This is 2.8% of the MPE. The brightest laser exposures are similar in brightness to viewing a common D cell flashlight for a duration of 1 second at 7 feet.

A conservative approach to multiple exposures is to add up the radiant exposure (J/cm^2) for all exposures delivered over a 24 hour period, and use the MPE for the total exposure duration during the 24 hour period. The MPE for an exposure duration between 10 and 10,000 s is 10 mJ/cm^2 (ANSI Z136.1-1993). The planned cumulative exposure for each session is 222 (J/cm^2) over a total laser exposure time of 12 seconds. This amounts to an exposure, which is 2.2% of the MPE. No adverse effects were anticipated or obtained from the planned levels of exposure.

To further reduce the risk from laser exposure, persons who were taking photosensitizing drugs, are hypersensitive to light, or have a history of ocular disease were not allowed to participate.

5.18 Evaluation Results

A total of 38 test subjects were evaluated in the simulator test program. They ranged in age from 22 to 69 years old. There was 1 female test subject included, simply because we did not get any more female volunteers. Subjects all were given entrance and exit eye exams per the forms shown in the appendices. Each subject also completed pre-flight and post-flight questionnaires. In-flight questionnaires were completed by the observer during the tests. These questionnaires were based on the test subject's verbal responses to questions. All subjects received the same set of scenarios administered in a variable order.

5.19 Flight Performance

There was no apparent effect on pilot performance except for missed approaches triggered by exposure to the 50 µwatt illumination at 100 feet above the ground on final approach. This indicates that the 50 µwatts is too much during critical phases of flight. On the other hand, exposure to the 5 µwatt and 0.5 µwatt exposures received no noticeable response from the pilots. Even though the 5 µwatt illumination did not cause strong reactions, the pilots did consider them very bright and noted that longer exposures may have resulted in more noticeable reactions. Note that under the new standards there would not be any value greater than 5 µwatts closer than 10 nautical miles of the airport reference point.

There was a general fatigue effect that developed toward the end of the 2-hour test session. No one reported after-imaging or physical effects such as soreness or burning to the eyes. The 50 µwatt exposures did get a number of comments about how bright the light was, and on several occasions the pilots stated that if any of those exposure had lasted any longer, they would have resulted in more missed approaches.

5.20 Aversion Reactions

Common aversion reactions were squinting, blinking and head movement in reaction to the 50 µwatt and, to a lesser extent, the 5 µwatt exposures. Several pilots noted that slightly ducking the head enabled continued vision below the aircraft glare shield.

5.21 Protective Eyewear

While we had limited protective eyewear available, we subjectively evaluated the effects of the use of this eyewear in a night- adapted cockpit. The two types on hand offered excellent protection from the 532 nanometer wavelength laser used. One offered an optical density (O.D.) of 4.5 to the 532 nanometer which allowed calibration and setup while wearing the eyewear, the other provided an O.D. of 7 at 532 nanometers which virtually eliminated any sight of the beam except for peripheral effects. Even at the lower O.D., wearers reported substantial attenuation of ambient light. It was necessary to remove, or “look around”, the glasses in order to read panel labeling, frequency settings and other non-lit readouts on a dark flight deck. The comments from the pilots indicated that they did not feel comfortable wearing the glasses, especially if faced with a critical situation.

5.22 Conclusion

The proposed new U.S. standards shown in 7400.2E are valid and safe for terminal area operations. Even at the 50 µwatt level there were no after-images or flash blindness, although the 50 µwatt exposures completely obliterated the out-the-window visual scene when it was on. The 5 µwatt did not cause problems with the 1-second exposures, but would need to be evaluated if longer exposures were proposed for low altitude (less than 1000 feet) applications. The 50 µwatt level should not be allowed in any terminal area application.

SUBJECT NO.	**DATE OF EXAM**	**BIRTHDATE**

NAME:

EYE COLOR: BLUE GRAY GREEN HAZEL BROWN DARK BROWN OTHER

MEDICAL HISTORY:

DATE OF LAST EXAM: **COLOR VISION (DVORINE PIP)** ________/14

CURRENT Rx DATE:

	SPH	CYL	AXIS	PRISM	ADD
O.D.					
O.S.					

CURRENT CONTACT LENS Rx (If applicable)

COMPUTERIZED

	SPH	CYL	AXIS
O.D.			
O.S.			

VISUAL ACUITY (Snellen):

	Distant W/O	Distant WITH	Near W/O	Near WITH	Intermediate W/O
O.D.	20/_____	20/_____	20/____	20/____	20/____
O.S.	20/_____	20/_____	20/____	20/____	20/____
O.U.	20/_____	20/_____	20/____	20/____	20/____

PUPIL DIAM: H-Illum ____mm L-Illum ____mm

STEREOPSIS: ________/10

DOM EYE: R L

AMSLER GRID: R L

GLARE TESTING

W/O GLARE	WITH GLARE	**LOW CONTRAST**
O.D. 20/______	O.D. 20/______	O.D. 20/______
O.S. 20/______	O.S. 20/______	O.S. 20/______

PUPILS:

EXTERNAL EXAMINATION:

EOM:

SUBJECTIVE REFRACTION:

O.D. ______________________________ 20/_____

O.S. ______________________________ 20/_____

O.U.

ADD: O.D. ________________________ 20/_____

O.S. ________________________ 20/_____

O.U.

OPHTHALMOSCOPY:

C/D ____________________________________

Macula: ____________________________________

Hemorrhages/Exudates: ______________________

SLIT LAMP:

Cornea: ______________________________

Lens: ______________________________

CORNEAL TOPOGRAPHY: O.U.

VISUAL FIELDS: O.U.

RETINAL PHOTOGRAPHY: O.U.

Van B. Nakagawara, O.D.

ATTACHMENT 1 - PRE-FLIGHT EYE EXAMINATION

Date: ____________ Subject # _______________

Name: __________________________________ Phone number/contact: ________________

Age: ________ Sex: M F

EXPERIENCE:

1. What is your estimated flight experience in the 727-200 for the last six months? _________hrs

2. What is your estimated total flight experience in the 727-200? __________hrs

3. Total Flight Hours (all aircraft) ____________.

4. Aircraft Types _______________ Hours: _______________
   _______________ _______________
   _______________ _______________
   _______________ _______________

5. Have you previously experienced laser or high intensity light exposure while operating an aircraft? (circle one)
   a) Yes
   b) No
   c) Don't Know

If you answered (a) to question 3, answer questions 4 through 7. If you answered (b) or (c) to question 3, answer questions 8 through 10. Please answer the following questions on a scale of 1 to 5 where 1 = 'not difficult at all', 2 = 'slightly difficult', 3 = 'moderately difficult', 4 = 'difficult', and 5 = 'very difficult'. Circle the appropriate number.

How difficult was it to…	not diff. … very diff.
4. control the operation of the aircraft?	1 2 3 4 5

HOW DIFFICULT WAS TO PERFORM THE FOLLOWING FLIGHT MANEUVERS SAFELY?

5. Take off.	1 2 3 4 5
6. Normal Cruising.	1 2 3 4 5
7. Landing.	1 2 3 4 5

How difficult would you expect it to be to perform the following flight maneuvers safely after laser exposure?

8. Take off.	1 2 3 4 5
9. Normal Cruising.	1 2 3 4 5
10. Landing.	1 2 3 4 5

ATTACHMENT 2 - PRE-FLIGHT QUESTIONNAIRE