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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.

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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.