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Factors in the evaluation of laser beam effects upon pilot performance

In the attempt to ameliorate the rare instances where a laser beam intercepts an aircraft, there have been several control measures suggested, including irradiance limits at a known range. This particular technique, while noteworthy, does not address all of the issues identified with the effect of a laser beam intercepting an aircraft. For example, a proposed limit of 100 microwatts/centimeter squared at 1.6 kilometers (1 mile) acts as a restriction on low divergence beams from Argon and Copper Vapor lasers, yet does not significantly affect the frequency doubled Nd:YAG laser, which has much higher divergence. There are other factors, including photometric response, atmospheric scattering, and duration of exposure, that should also be considered.

Photometric Comparison of Common Display Lasers

It has been suggested that the evaluation of non- injurious laser effects upon vision should be considered in photometric terms, rather than radiometric. While the conversion of irradiance into illuminance is fairly straight forward, a simple correction factor may be all that is needed. As the Argon laser is the dominant laser in use at this time, we can normalize its photometric response to a value of 1. For establishing the relative efficacy of the three different lasers used for display, I compared the total photometric efficacy versus the power per laser line, as follows:

Argon Laser			
Laser line	**Power**	**Efficacy**	**Equivalent @ 555 nM**
528 nM	1.0	84%	0.84
514 nM	7.5	60%	4.5
501 nM	1.5	33%	0.495
496 nM	2.5	27%	0.675
488 nM	6.5	19%	1.235
476 nM	2.7	12%	0.324
472 nM	1.2	9.1%	0.109
465 nM	0.75	7.3%	0.055
457 nM	1.35	5.7%	0.009
TOTAL	**25 W**		**8.24 W @ 555 nM**

Copper Vapor Laser			
Laser line	**Power**	**Efficacy**	**Equivalent @ 555 nM**
510 nM	15	50%	7.5
578 nM	10	88%	8.8
TOTAL	**25 W**		**16.3 W @ 555 nM**

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ND:YAG Laser			
Laser line	**Power**	**Efficacy**	**Equivalent @ 555 nM**
532 nM	25	88%	**22 W @ 555 nM**

This illustrates that equivalent power beams from these three lasers have different effects upon vision, in roughly a 1:2:3 ratio. I recommend that this be adopted as a correction factor for the presently adopted exposure limits at 100 and 5 uW/cm^2, as these limits were developed for Argon laser exposures. This correction can be applied as a multiplying factor for the emitted power of the laser, so a Nd:YAG laser emitting at 40 W would have a brightness equivalent of (40 x 3) = 120 watts, with a corresponding increase in hazard range.

Atmospheric Scattering Effects and Extended Sources

Laser Displays are viewed by the atmospheric scattering (Mie scattering) of the beam, providing low level diffraction and reflection into audience areas. This effect is strongest along the path of the beam. In laboratory tests, viewing both 5 and 100 uW/cm^2 sources, atmospheric scattering was not a factor, as the range was short (3-5 meters). Viewing the source caused typical point source imaging to occur, approaching the d=f x theta approximation, which images the laser source upon a very small area of the retina. While this small area would be strongly affected, the effect on total visual acuity is minor. A spot of 20 to 100 microns on the retina may have a sustained afterimage, but the rest of the retina can “compensate” for this loss.

With a long beam path, the forward scattering in the beam becomes a significant effect. While the point source will always be apparent, the forward scattering of the enlarged beam will begin to act as an extended source. The larger the relative spot size at the point the beam is viewed, the larger the extended source, with a resultant greater effect upon the total visual acuity. The more area of the retina that is affected, the greater the impact upon visual task performance.

This effect has not been quantified, but it has been strongly suggested by some of the aircraft illumination reports. This also explains the discrepancy between laboratory tests where 5 uW/cm^2 is “no problem”, and field tests where 1.5 uW/cm^2 is “really bright”. The perception of brightness is a function of area as much as illuminance.

This leads to the conclusion that a high divergence beam of sufficient power will create an extended source effect at a distance, rendering a greater disruption to visual acuity than a low divergence beam, creating a smaller source and a lesser disruption.

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We can quantify the effect as a function of beam divergence:

Laser type	Divergence (Radians)	Range	Beam Diameter	Irradiance
Argon	0.001	16 km (10 miles)	1600 cm	1.25 E-5 W/cm^2
CVL	0.0005	16 km	800 cm	5.0 E-5 W/cm^2
Nd:YAG	0.006	16 km	9650 cm	3.45 E-7W/cm^2

If irradiance was the sole function affecting visual acuity, the Nd:YAG laser should have virtually no effect at this range, even accounting for the higher photometric efficacy. The hypothesis of extended source effects should be considered, particularly in that the larger area of vision that is affected, the more severe the reduction of visual task performance.

Exposure Duration as a Function of Divergence

The unintentional illumination of aircraft by laser light is a transient effect. Even if the beam is static, the aircraft is moving. Duration of exposure is a function of four factors:

1. Beam divergence.
2. Range from source.
3. Angle of intercept.
4. Velocity of aircraft.

The duration of exposure will have two effects: one, the amount of energy entering the eye, and hence the cumulative exposure; second, the duration of the actual illumination event. The cumulative exposure issue is significant, as the collected energy will primarily determine the degree of physiological effect upon the eye, in much the same manner as a cumulative exposure can exceed the AEL, based on duration. The duration of exposure also has a more psychological effect, in that the longer the illumination event, the greater the distraction and disruption of normal task processing. This can be illustrated as the difference between a camera flash, and a camera floodlight. A short duration flash leads to quick recovery, and a long duration flood of light will continue to disrupt the task as long as it is present.

Given that beam divergence is the only factor affecting exposure duration that can be controlled, we can compare the common lasers with this function:

Laser type	Divergence (Radians)	Spot Size @ 16 km	Exposure Duration @ 6705 cm/sec
Argon	0.001	1600 cm	0.24 seconds
CVL	0.0005	800 cm	0.12 seconds
Nd:YAG	0.006	9650 cm	1.44 seconds

The duration values are based on an aircraft velocity of 6705 cm/sec (150 mph) and a 90 degree intercept angle. If divergence is fixed, duration will be proportional for any intercept angle and aircraft velocity.

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If the duration is multiplied by the irradiance and the photometric correction factor, we find:

Laser type	Irradiance	Duration	Photometric Correction	Effective exposure
Argon	1.25 E-5	0.25 sec.	1	3 uJ/cm^2
CVL	5.0 E-5	0.12 sec.	2	12 uJ/cm^2
Nd:YAG	3.45 E-7	1.44sec.	3	1.5 uJ/cm^2

This would explain most of the physiological effects of a laser exposure. However, it is interesting to note that the exposure duration of both the Argon and CVL lasers is below the recognized time of the aversion response, whereas the Nd:YAG laser is substantially above this time. An exposure to the Nd:YAG would probably cause a blink reflex, with the associated psychological delay in recovery.

Summary

The issue of controlling the inadvertent exposure of aircraft to laser light is not a simple issue. There are several factors involved in assessing the magnitude of the effect upon visual task performance, and can only be answered by experimentation. “Quick-fix” solutions, such as broad irradiance/range limits may pose no solution at all and leave open the possibility of future exposures that meet the guidelines, yet have significant effects on vision. This has been illustrated recently by exposure incidents that would have fully complied with the proposed irradiance/range guidelines, yet presented an illumination level and duration that the pilots involved found unacceptable. Moreover, the calculated exposure of this incident (Miami, FL January 1996) is below the new FAA 7400.2 limits for the Critical Zone, suggesting that either some factors were disregarded in the development of the present levels, or that the pilots reported an incident that did not cause an impairment.

Suggested Course of Action

While the photometric correction factors are well documented in the literature, the issues of forward scattering creating an extended source, and exposure duration require some study. It is important to all parties that a resolution to this situation be found that is effective, practical, and based on sound scientific evidence. Unlike the proposed FAA test program that is “bogged down” in bureaucratic paperwork, testing the issues of extended sources and exposure duration do not require the involvement of pilots, aircraft simulators, and tens of thousands of dollars. A test program of 100 volunteers performing a visually intensive task using standard psychophysical experimentation protocols should be sufficient to document the effects of wavelength, apparent source size, and exposure duration. Once this is clearly defined, the means of control should be obvious. Moreover, the parameters for maximum permissible exposure for visual intensive task operation will be derived experimentally, rather than from anecdotal evidence.

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