LASER SAFETY CONCEPTS FOR AVIATION

Paper #902

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Abstract

This document is a review of laser safety concepts that are relevant for pilots and aviation officials.

In recent years, there have been about 10 laser/aircraft incidents per night reported to the U.S. Federal Aviation Administration (FAA). Visual interference from visible laser beams, during critical phases of flight, is considered the most significant hazard. This can be distraction (a mental interference), glare (cannot see past the light until it is removed), and flashblindness (visually interfering afterimage that can last seconds or minutes). Eye injury is a secondary concern. Due to various factors, in aviation incidents the chance of even temporary injury to the eye is considered extremely low.

Laser illuminations are not usually a single, fixed brightness but instead a series of flashes due to the difficulty of keeping a hand-held laser aimed at a moving aircraft. Helicopters are more susceptible to laser interference due to spending more time at lower altitudes and slower speeds. On the other hand, helicopters can remain in the area in order to direct police to the source of the (very visible) beam.

Laser protective eyewear, to reduce the intensity of light, may be appropriate for pilots flying into a known or suspected laser area. It is vital to select eyewear that does not block instruments or airport lighting; testing on the aircraft to be used is necessary.

If lased, follow procedures such as "fly the plane." First, block the light, resist the urge to rub your eyes, inform ATC, and report the incident to FAA.

Information is given about the possibility of injury. For example, being lased while inside the Nominal Ocular Hazard Distance does not necessarily mean that injury occurred.

Introduction

When a pilot sees a laser beam aimed toward an aircraft, he or she may be adversely distracted. If the beam enters the pilot's eyes, this can additionally cause visual impairments such as glare, flashblindness and/or afterimages, one or more blind spots, blurry vision, and significant loss of night vision acclimation. A few pilots have even reported feeling a sense of shock when they are unexpectedly illuminated by bright laser light.

These "visual interference hazards" during critical phases of flight are the primary concern of laser/aviation safety experts.[1] During critical flight phases such as landing, takeoff, low-level flying or an emergency, laser distractions or vision blocking could contribute to an accident.

A secondary concern is temporary or permanent eye injuries (retinal burns). Fortunately, as discussed later in this document, during aviation incidents the laser beam's power at the pilot's eye is so weak, and exposures are so brief, that the chance of even a temporary injury is extremely low.

Important Principles for Pilots to Remember

From 2011 to 2014, there were about 3,500 to 4,000 incidents in the U.S. of pilots reporting laser illuminations. This is roughly 10 incidents per night.

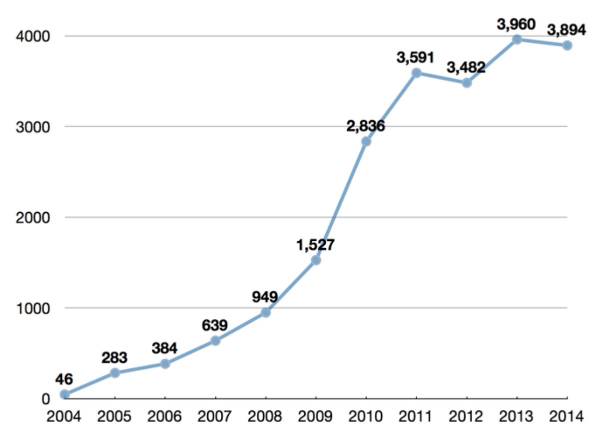

Figure 1: Number of laser illumination incidents reported to the U.S. FAA, 2004-2014

If you are a pilot, you should prepare for a laser incident by keeping these general principles in mind:

1. **The primary hazard for pilots is visual interference** during critical phases of flight. *Distraction* can be mentally controlled – don't pay so much attention to the waving laser beam that you forget to fly the plane. *Glare* and *flashblindness* are more serious since the light is blocking part of your vision. Follow the laser illumination procedures listed later in this document.

2. In addition to the interference, **a sudden laser flash can startle you**. The surprise can cause a feeling of shock or a headache, even though only a bright light is illuminating your body. Avoid rubbing your eye too vigorously; this can cause a painful temporary corneal abrasion.

3. **Do not unduly worry about eye damage**. It is highly unlikely that a consumer pointer or handheld would cause eye damage to a pilot in flight. At aviation distances – over, say 200 feet -- not enough light is deposited on the retina for a long enough period to cause a retinal injury. The U.S. FAA and U.K. CAA have had no documented cases of permanent eye injuries in over 20,000+ incident reports. If you do have any concern after a flight, schedule an eye exam -- preferably with a retinal specialist who has some laser knowledge or experience.

4. If you are a police, medical or other first responder pilot you may want to **consider laser protective glasses developed especially for pilots**. Do not wear them routinely but keep a pair nearby in the cockpit for times when lasers are active or likely.

The remainder of this document goes into more detail on these and other points.

Visual Interference Hazards

It should first be noted that not all laser light in airspace poses a risk to flight operations. For example, in May 2005, NORAD began using a laser Visual Warning System in the Washington, D.C. Air Defense Identification Zone.[2] An eye-safe laser beam, one that flashes red-red-green and is visible up to 25 miles away, is aimed directly at aircraft in the ADIZ when the pilot cannot be reached by radio.

The primary concern of laser/aviation experts[3] is when unauthorized laser light interferes with pilots' vision or otherwise adversely affects their ability to safely operate the aircraft. The photos in Figures 2-4 were taken in an FAA simulator. They illustrate examples of the three main visual interference hazards.

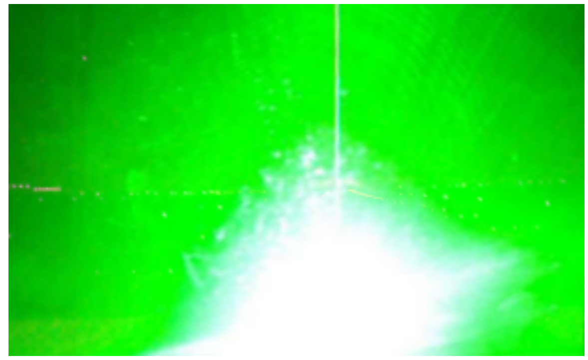

Figure 2: Temporary flashblindness[4]. The light is so bright it causes afterimages that last even after the light is off. This is the most serious problem, causing vision-impairing afterimages.

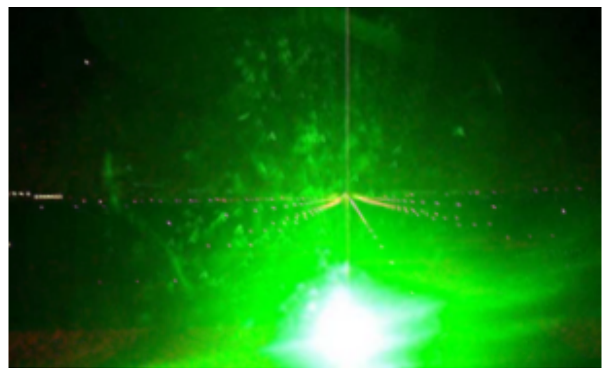

Figure 3: Glare. It is difficult to see past the light, as long as it remains on. This also blocks a pilot's vision, but only as long as the beam is directly in his or her eyes.

Figure 4: Distraction. The light is brighter than background lights. Distraction is a mental interference, since vision is not blocked. However, distraction during critical flight phases could lead to loss of situational awareness. Pilots can successfully counter distraction by focusing their attention on the task of flying.

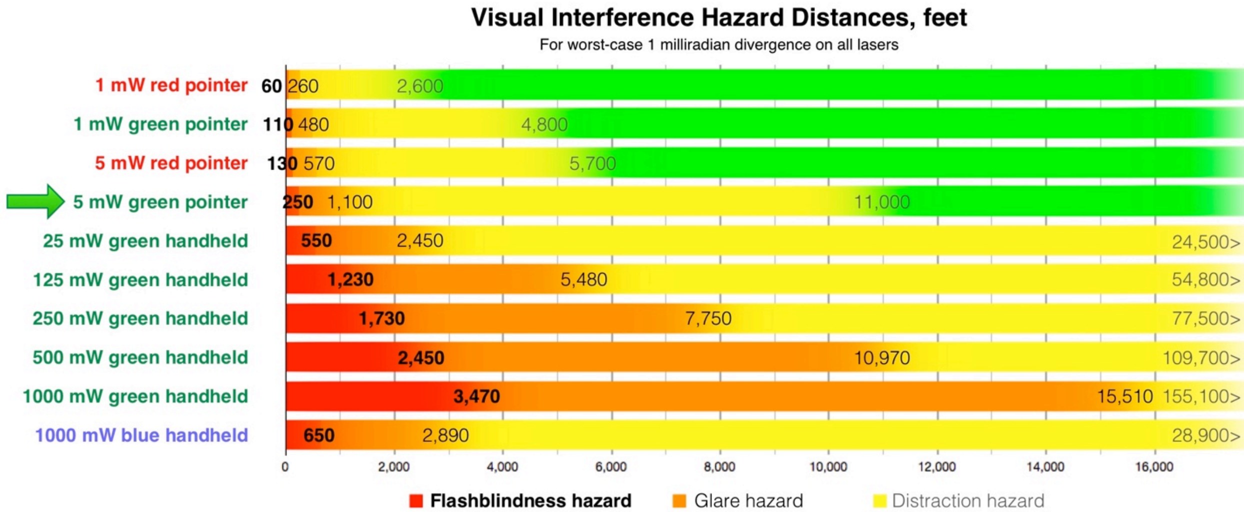

Figure 5: Visual interference hazard distances for selected lasers. Note that for comparison purposes, the chart assumes all lasers have a tight, 1 milliradian beam. Generally, higher power handheld lasers will have increased divergence, which means their real-world hazard distances will be less than what is shown here.

Figure 5 shows the distances over which lasers can cause flashblindness, glare and distraction. For example, the green arrow points to the visual interference hazard distances of a 5 milliwatt green laser pointer. (This is the most powerful laser that can legally be sold as a "pointer" under U.S. Food and Drug Administration regulations.)

Here is how to interpret the line to the right of the green arrow: A 5 mW green laser pointer is a flashblindness hazard from 0 to 250 feet (red zone), a glare hazard from 250 to 1,100 feet (orange zone), and a distraction from 1,100 to 11,000 feet (yellow zone). Beyond 11,000 feet (green zone), it is not a visual hazard; the FAA has determined that the laser's light would be no brighter than other city and navigation lights visible at night.

One of the key concepts the hazard distance chart illustrates is that the beam's color is an important factor determining how much it can interfere with vision. That's because the human eye is most sensitive to green light. The curve in Figure 6 shows the eye's response to color.[5] A 532 nm green laser beam – the most common type sold to consumers – will appear much brighter than a 633 nm red beam or a 455 nm blue beam of equivalent power.

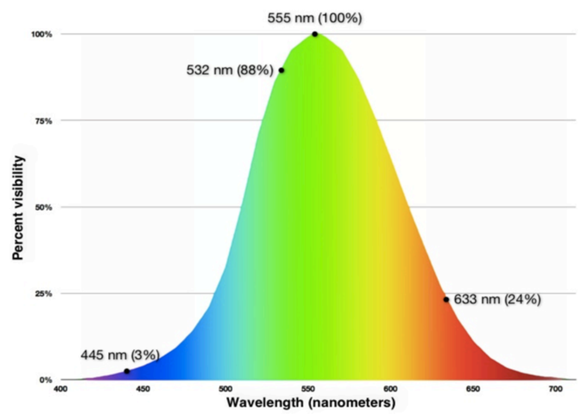

Figure 6: Human eye response to color.
The curve plots the data used in the FAA's Advisory Circular 70-1, which is used to evaluate laser hazards in airspace.

Another way to consider this is that a green laser beam will be a visual interference hazard over a longer distance than red or blue beams of equivalent power. Figure 7 shows this comparison for red and green beams. As the highlighted area shows, a 5 mW red laser pointer can cause glare up to 570 feet away, while an otherwise identical 5 mW green pointer can cause glare up to 1,100 feet. Again, this is because the human eye is more sensitive to green light than to an equivalent amount of red light.

Figure 8 shows a similar comparison between green and blue laser beams. A 1000 mW green handheld is a glare hazard up to 15,510 feet away, while the exact

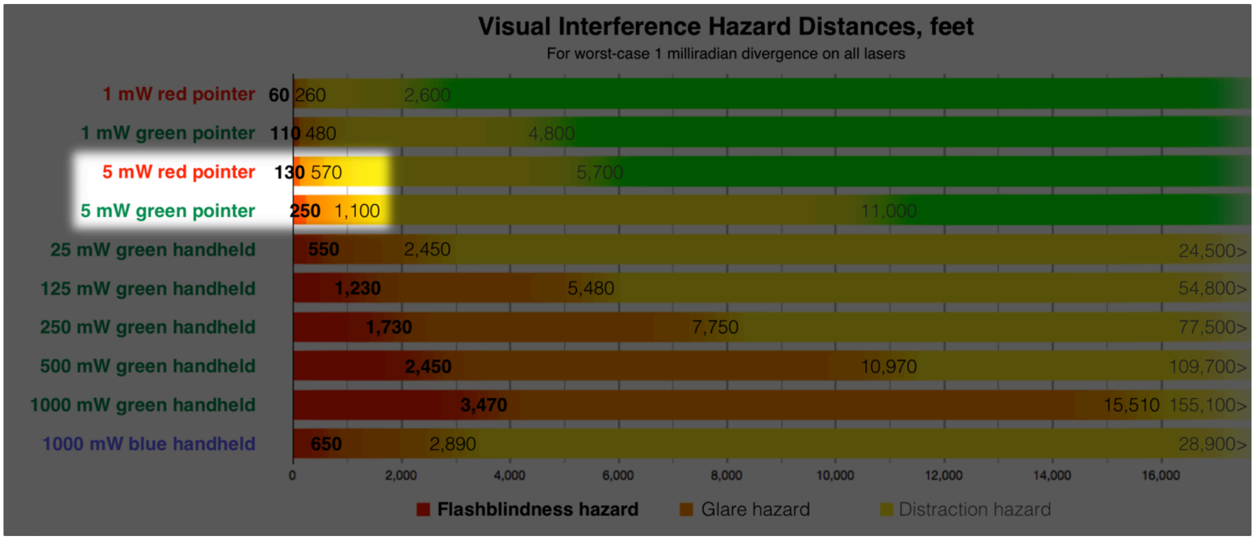

Figure 7: Red vs. Green Visual Interference Hazard Distances. The highlighted area shows that red laser light is a visual interference hazard over shorter distances than green laser light of the same laser power.

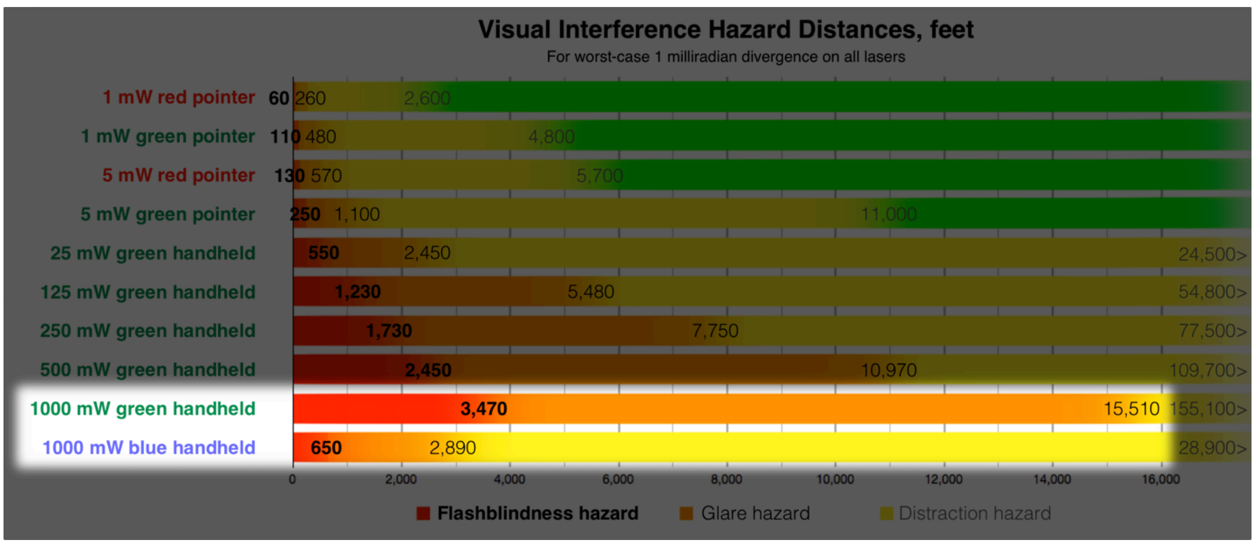

Figure 8: Blue vs. Green Visual Interference Hazard Distances. The highlighted area shows that blue laser light is a visual interference hazard over shorter distances than green laser light of the same laser power.

same laser but emitting blue light is a glare hazard to 2,890 feet -- that's only 18% of the green glare distance.[6]

Unfortunately for pilots, green lasers are the most common and also have the longest visual interference distances, compared to otherwise identical red or blue lasers. This explains why about 95% of incidents reported to FAA involve green laser light.[7]

Phase Of Flight And Altitude As A Hazard Factor

Visual interference is generally considered to be a hazard only during critical phases of flight: takeoff, approach and landing, and critical or emergency maneuvers. During cruise or other non-critical phases, there is enough time to react and recover from even a severe flashblindness incident.

The vast majority of incidents take place below 10,000 feet above ground level.[8] This is because the lower the aircraft's altitude, the easier it is for a person on the ground to see the aircraft and thus aim towards it.

Laser Eye Injuries – A Remote Possibility

Laser/aviation safety experts consider laser-caused eye damage to pilots, while possible, to be extremely rare. As of January 2015, there have been no documented cases of permanent eye injuries in any of the over 20,000 laser incidents reported to the U.S. FAA[9] and the U.K. CAA[10], according to these agencies' experts.[11] There have been a handful of temporary eye injuries that healed with no detrimental effect on vision; the pilots involved returned to flight status.[12]

This section contains a summary of laser eye hazard information. Additional details are in Appendix B.

Hazards close up are not the same as over a large distance

Laser beams spread out as they travel. Close to the laser, where the beam is narrow, all of the light may be able to enter the pupil and cause damage. But after travelling hundreds or thousands of feet, the beam is many inches or feet across. Only a fraction of the entire beam will enter the pupil. Thus, a beam that is an eye injury hazard close up may well be non-injurious at flight distances and altitudes.

There are additional factors as well, such as the difficulty in keeping a handheld laser steady on a moving target that is hundreds or thousands of feet away. In most incidents, the beam is not constantly kept on the pilot's eyes. This reduces heat buildup that can cause thermal injury to the retina.

At what distance can a laser start to cause eye injuries?

To determine a given laser's injury potential, scientists calculate its "Nominal Ocular Hazard Distance" or NOHD. This indicates, for a given laser's power and beam divergence (spread)[13], the distance at which the chance of eye injury is "vanishingly small"[14] or is a "negligible risk for injury.[15]" For example, the NOHD of a standard 5 milliwatt laser pointer with 1 milliradian divergence is 52 feet. In contrast, the NOHD of the most powerful handheld laser currently available, 2000 milliwatts (2 watts) with 1.75 milliradian divergence, is 593 feet.[16]

However, being inside the NOHD – closer to the laser than scientists recommend – does NOT mean certain injury or blindness. The NOHD was developed with a kind of built-in "safety factor" or "reduction factor." This is a complex topic. But in general, there are two major considerations:

- The level of concern is not where there is severe damage or blindness, but instead the level at which the smallest medically detectable changes could be seen in the eyes of laboratory animals, 50% of the time (even in a single eye, sometimes a given exposure caused a detectable change, sometimes it did not). In setting exposure limits, scientists took into account the light levels that caused a 50% chance of a minimally detectable change to the eye.

- Scientists then added on a "reduction factor" to reduce the chance of eye change or injury. For visible light, this was set to be approximately 10 times lower than where changes were seen in studies.

Thus, as a rough approximation, the MPE is 10 times less than where minimal injuries may occur. In turn, this means that roughly the square root of 10, or 0.316 times the NOHD, is where minimal injuries may occur. Beyond this point – in other words, the last 2/3 of the NOHD -- the chance of an injury continues to decline further.[17]

This is why it is called the Nominal Ocular Hazard Distance and not something like the "Actual Ocular Hazard Distance."

Certainly, if it is possible to control a laser exposure and/or distance, a person exposed to laser light in their eyes should be beyond the NOHD.

The problem is that pilots, among others, may be exposed involuntarily to laser light while they are within the NOHD.[18] They naturally may worry about potential injury. Knowing how the MPE levels and NOHD distances were set, with a "safety factor", may help alleviate fears of having a serious or debilitating injury.

In the real world, the conservative values set for the MPE and NOHD helps explain why there have been no documented permanent eye injuries in FAA and CAA incidents. Almost always, pilots are exposed well beyond the distance at which even the most powerful laser is likely to cause a vision-affecting eye injury.

More detailed analysis needed when balancing risk vs. benefits

There may be agencies such as police and rescue units, in which it is necessary to balance the risk of laser hazards with the benefits of stopping a laser perpetrator or rescuing someone while others are aiming lasers at the aircraft. Such agencies should work with laser experts to do a detailed analysis of real-world lasers currently being sold, taking into account factors such as those discussed above.

It is likely that when public safety is at risk, pilots and officers can, while still minimizing risk, approach a laser closer than a simple worst-case NOHD chart would initially indicate.

Non-eye Physical Effects

In about 0.1% of laser incidents[19], a pilot has reported a physical reaction to being suddenly and brightly illuminated. This has been described as being a "shock" or even a physical impact, and it may cause a headache.[20]

However, a laser beam is composed of coherent but otherwise ordinary light. Like a lamp's light or a flashlight's beam, the light from a ground-based laser cannot be felt on the pilot's skin since it is so widely spread out at aircraft distances. Also, a beam of such light would not cause any physical force or impact.[21]

This infrequent phenomenon – which must be a psychological reaction – is nevertheless a potential flight hazard if misinterpreted by a worried pilot. Remember that a laser beam in an in-flight situation cannot cause heat on the skin, electrical shock, or physical force.

What A Laser Illumination Looks Like

Laser incidents are not static events. The pilot normally sees a beam moving around, with one or more bright flashes if the beam actually enters the cockpit and the pilot's eye. The beam intensity will vary widely, because it is almost impossible for someone to steadily handhold a laser onto a moving target at aircraft distances and speeds.[22]

The aircraft windscreen refracts and spreads out the laser light. This is a significant cause of veiling glare – it may seem as if the entire windscreen is lit up. (Fortunately for eye safety, this same effect also helps spread out the beam, reducing the intensity of any light that directly enters the pilot's pupil.)

Figure 9 shows 20 frames taken at ½ second intervals from a police helicopter video.

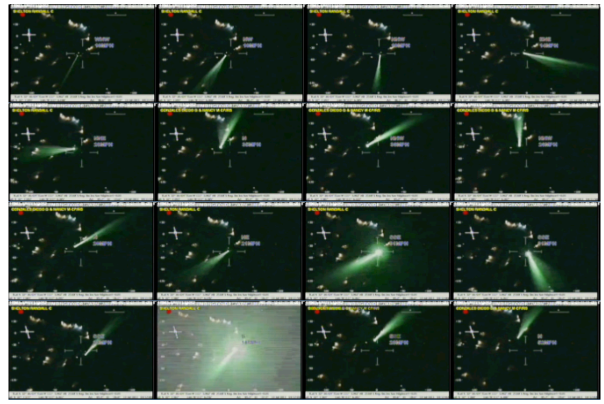

Figure 9: Frames from a video showing a laser being aimed at and near a police helicopter

In 19 of the frames, the laser is being waved around close to the aircraft. In one frame – one instant out of 10 seconds – the laser has actually hit the windscreen. Notice that it is not a direct hit into the camera lens, since the beam is still aimed to the lower left.[23] But the windscreen has spread out the beam, causing glare that makes it more difficult to see features on the ground.

Normally, such veiling glare only lasts a fraction of a second because of the difficulty of keeping a handheld beam aimed precisely at a moving target. If the beam enters the eye directly and is strong enough, it can cause flashblindness, in which case the pilot will experience an afterimage lasting from a few seconds to many minutes – like looking into a camera's flashbulb.

Fixed Vs. Rotary Wing

Helicopters are at greater risk for laser attacks. They fly at lower altitudes more often than fixed wing aircraft, and they can hover over the same spot, increasing their exposure potential. In addition, the rotor noise can cause annoyed persons on the ground to aim a laser to "get back" at the aircraft.

One compensating benefit is that it is much easier for a helicopter pilot to stay in the area, in order to identify the source of the laser beam. The pilot must avoid direct beams in his or her eyes while determining the perpetrator's location. For civilian pilots, it is usually best to report the approximate location to ATC, who will relay this to authorities. A law enforcement helicopter can then be sent to safely determine the exact location and to assist ground units.

Probability Of Laser Exposure

In 2014, there were 3,894 laser incidents reported to the FAA. This is an average of 10.7 incidents each night.

In 2012, there were 3,482 incidents, which were reviewed in more detail to determine eye effects. In 35 of these incidents (1%), adverse eye exposure was reported. Regarding vision effects, there were 21 reports of temporary flashblindness, two reports of blurry vision, one report of blind spots, and one report of temporary peripheral vision loss. Regarding physical effects, there were nine reports of eye discomfort or pain, and three reports of headache. Four persons sought medical attention. In two of the eye exposure cases, the flight was affected (the co-pilot took over in one case; in the other, the pilot requested a vector away from the area). And in four cases, the pilot reported laser light in the eyes with no adverse effect. The FAA's Civil Aerospace Medical Institute reviewed these cases and determined that none of them was an "injury".[24]

Based on FAA ATADS flight data on airport operations[25], the chance of a pilot seeing a laser beam on any given flight in a single year is about 1 in 15,000. In about 28% of incidents, the beam enters the cockpit, making the chance of a cockpit illumination about 1 in 54,000 flights per year. And in about 1% of incidents, the beam causes adverse eye or body effects. This means the chance of being illuminated so it causes such effects is about 1 in 1,500,000 flights.

If And When To Use Laser Protective Eyewear

Some companies are producing laser safety glasses for pilots. These are designed to attenuate one or more specific wavelengths (colors) of laser light, while still permitting cockpit instrument and airport lights to be seen.

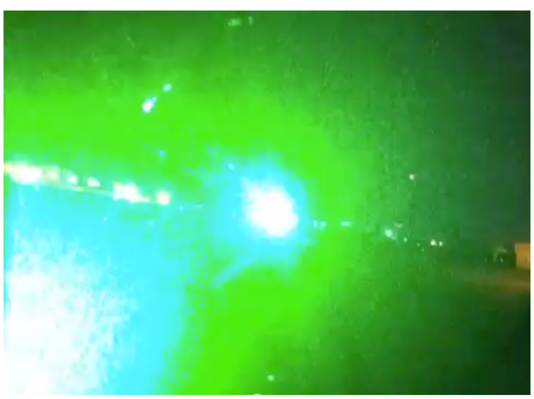

Figure 10: Laser aimed into camera, with no protective eyewear.

Figure 10 is a photo taken from the pilot's seat of a helicopter sitting on an airport ramp. A 70 mW, 532 nm (green) laser is aimed almost directly into the camera's lens from 128 feet away. The camera is within the laser's Nominal Ocular Hazard Distance – it would be a potential eye hazard if the beam directly entered a person's pupil. Note that as the laser beam hits the windscreen, the light spreads out, making it almost impossible to see past the glare; this is similar to what would happen in flight.

Figure 11: Laser aimed into the camera, with OD 3 protective eyewear over the lens.

Figure 11 is a photo of the same setup, but the camera's lens is almost fully covered by the lens of laser protective eyewear that has an optical density at the laser's wavelength of 3 (1000x attenuation). (Note part of the curvature of the lens edge at lower left, allowing a small amount of laser light to reach the camera.)

In general, laser protective eyewear is most appropriate for police, rescue, medical and other first responder pilots. They have the greatest likelihood of encountering laser beams, and of having to perform operations despite being illuminated. But because eyewear also will reduce the visibility of certain wavelengths (colors) of displays and ground lights, it is critical to determine whether it is suitable for a given mission and aircraft.

For pilots who wish to have laser protective eyewear available, there are some key points and cautions:

1. **Choose from laser protective eyewear designed specifically for pilots**. Laboratory eyewear and consumer "blue blockers" or standard sunglasses are not appropriate or safe.

2. **The glasses first must be safely tested,** on the ground and while at cruising altitude, on the actual equipment being used. The glasses should still allow sufficient color rendition and sufficient color discrimination of cockpit instrumentation and airport lights.

3. **Laser attenuation glasses should NOT be routinely worn.** Instead, keep them readily available during flight so they can be deployed and worn in the event of a laser illumination or if laser activity has been reported in the area.

4. **Glasses that attenuate green laser light should be sufficient** in most cases. Over 90% of FAA-reported incidents involve green laser light at 532 nanometers.

5. Glasses that attenuate two or more wavelengths, such as green-plus-red or green-plus-blue, are available. However, the more wavelengths that are attenuated, the greater the **possibility of reduced color discrimination of cockpit instruments.**

6. **It is not necessary for the glasses to fully block the laser's light.** Simply attenuating the light by one or two orders of magnitude (Optical Density 1 or 2) can be sufficient to prevent flashblindness and reduce glare.

7. Informal tests have shown that for single-wavelength green (532 nm) protection, OD 3 blocks too much light (both laser and instrument panel); for example, it is not possible to track the laser beam to its source. Thus, **for green protection an OD of 2 or 2.5 is suggested**. For attenuating red or blue, a lower OD such as 1 or 1.5 is suggested. As stated above, **testing on the actual equipment to be flown is essential** to ensure that, whatever the OD, it does not adversely affect visibility of instruments and airport lights.

Laser Illumination Procedures[26]

"Fly the plane" first. With two pilots, the one who was not exposed should look at the instruments -- not out the window. If the plane is in a critical flight phase such as landing or takeoff, determine whether it can it be flown without looking outside (for example, on an automated final approach). Determine whether a go-around might be prudent.

Do not look directly towards the light. Instead, look a bit away from it. Be prepared to look completely away and warn the other pilot if the beam or light returns.

Block the light if possible with a clipboard, visor or your hand. You can sometimes maneuver the aircraft to block the light.

Turn up the cockpit lights. Light-adapted eyes are less prone to the effects of a laser.

Resist the urge to rub your eyes. This can irritate the eyes and cause tearing, or a corneal abrasion.

Inform ATC as soon as possible and in particular if a decision has been made to diverge from the cleared flight path.

After landing, **report the incident to the FAA**. This webpage has more information: http://www.faa.gov/aircraft/safety/report/laserinfo/

Seek qualified eye care if you have any concerns. An eye doctor with experience in retinal examinations, and especially one who has knowledge of laser injuries, is best.

APPENDIX A: Frequently asked questions

What is the difference between a laser pointer and a handheld?

It is a matter of legalistic terminology. Under U.S. FDA regulations, lasers sold as "pointers" or for pointing purposes must be under 5 mW.[27] It is legal to sell any lasers above 5 mW, including battery-powered portable handheld lasers, as long as 1) they have all safety features required for their power (laser classification), 2) they are properly certified to FDA, and 3) they are not sold as "pointers" or for pointing purposes. Often, a pointer and a higher power handheld can look identical. From the standpoint of a pilot who has been illuminated, it does not matter if the laser is legally a pointer or a handheld.

What about the visibility of laser beam colors other than red, green and blue?

Lasers with yellow, orange, deep violet, or other color beams are relatively rare for consumer pointers or handhelds. All would appear dimmer than a green laser beam of equivalent power and divergence. From a flight safety standpoint, the main issue is not the color; it is how bright the light appears to the pilot and thus how much visual interference could occur.

Do atmospheric conditions such as fog or smoke affect laser illuminations?

Visible laser light will be more scattered and diffused if there is fog, smoke, dust, rain, snow or other substances in the air. This reduces the amount of light that can reach a pilot's eyes, compared with clear air conditions. When a beam travels through even clear air for many tens of thousands of feet, the atmosphere can lessen, or attenuate, its power; however, the effect of atmospheric attenuation decreases with altitude.

Despite this, laser/aviation experts generally ignore atmospheric attenuation, or its inverse, scintillation (where beams can shimmer, focusing them stronger and weaker for brief milliseconds). For one thing, attenuation and scintillation effects roughly cancel each other out. For another, in terms of mitigating hazards, attenuation and scintillation effects cannot be relied upon so it is usually best to use a worst-case, clear-air approach.[28]

The charts in this document use standard safety calculations and assume no atmospheric attenuation.

What is the difference between a laser incident, illumination, hit, strike and attack?

When referring to FAA laser incident reports, these terms describe the same thing: someone unauthorized has aimed a laser beam at a pilot. "Incident" is a general term indicating that something occurred that may or may not have had adverse effects.

- "Illumination" emphasizes the scientific aspect: that it is only light which is touching the aircraft.
- "Hit" and "strike" imply a physical blow and are scientifically inaccurate although some pilots have reported feeling physical effects when unexpectedly illuminated by laser light.
- "Attack" implies deliberate intent to cause adverse effects; this may not always be true since many incidents are due to ignorance.

Why do people aim at aircraft?

Currently, the main problem is ordinary people who do not understand the hazards to aircraft and are not trying to cause harm or trouble. There are four reasons that such persons may believe that aiming at aircraft will not cause problems:

1) They may think that the laser beam can't reach the aircraft, in part because a beam aimed into the air appears as if it ends after a few hundred feet. The photo below depicts this effect.

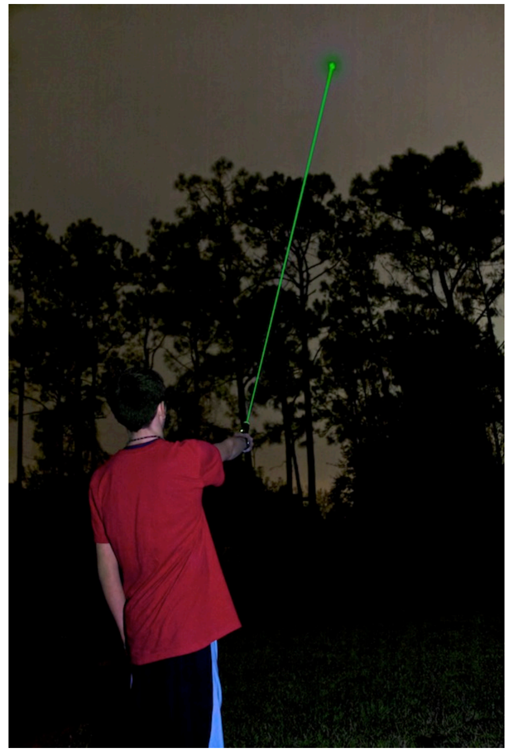

Figure 12: A laser beam can appear to stop in midair

Air close to the ground – the "Planetary Boundary Layer" – contains dust and other particles that scatter light, making the beam visible. As the beam emerges into clear air, from the ground it appears to stop in mid-air.[29]

2) They may think the laser will only hit the underside or rear of the aircraft.

3) They may think that at worst, the laser will appear to be a small dot on the windscreen, like when they play with their cat or dog. They do not understand that the beam can spread out to fill the windscreen and totally obscure the view.

4) They may believe that, like a flashlight, the light intensity is rapidly diminished by distance.

These people can hopefully be reached with education programs, and through hearing in the media about persons prosecuted for aiming at aircraft.

Unfortunately, there are also a large number of people who simply don't care if they interfere with aircraft. They may deliberately intend to distract pilots; perhaps to stop airborne police missions. They may be upset by aircraft noise. They may be doing this for anti-social "fun," figuring that the chances of getting caught are small. Ironically, sometimes persons like this who are caught, are also charged with other crimes such as drug possession – the laser literally pointed them out to police attention.

Is aiming at aircraft illegal?

Yes, many people have gone to jail for violating federal or state laws. The FBI, FAA and local prosecutors take this very seriously.

Some laws are specific such as U.S.C. Title 18, Chapter 2, Sec. 39A which makes it illegal to aim a laser pointer at an aircraft or its flight path. Violations can result in up to 5 years in prison and a fine of up to $250,000. Some laws are more general, such as U.S.C. Title 29, Subtitle VII, Part A, Subpart iv, Chapter 465, Paragraph 46505 which bans interference with flight crew member.

Under 49 U.S.C. Section 46301(a)(5)(A), FAA may seek a maximum civil penalty of $11,000 per violation for aiming a laser at an aircraft in violation of 14 C.F.R. 91.11. From June 2011 through mid-September 2013, the FAA has opened 129 civil enforcement cases against persons who aimed lasers at aircraft.[30]

Many states also have laws against aiming at, or interfering with, aircraft.[31]

Can lasers be banned on the ground?

For various reasons, restricting laser possession or usage may be difficult. At the federal level it would require new laws from Congress. Banning, licensing or taxing consumer lasers may not make a significant impact for years, since there are already millions of lasers in circulation. Also, it is easy to make a handheld laser using diodes removed from common electronic devices such as DVD drives and laser video projectors.

Some limitations do seem to be working. In February 2013 the resort town of Myrtle Beach, S.C. restricted laser pointer sales to devices below 1 mW, and banned the sale of pointers to minors. In mid-summer 2013, a local official reported "remarkably fewer complaints" and that the ordinance "made a huge difference."[32]

However, this has not been the case in Australia. In 2008, the country enacted import controls and strict bans on laser possession. A 2013 study[33] showed that this has not reduced the number of Australian aircraft lasings; in fact, they went up 27% over three years. It also decreased consumer safety since imported high-powered pointers were mislabeled as being of low power, in order to evade import inspection.

The Australian experience demonstrates that pilots must be vigilant even if consumer lasers are restricted or banned. There would still be some misuse incidents, so pilots must be prepared.

How can pilots help ensure safety?

Pilots need to know that they are the last line of defense. They should familiarize themselves with what lasers can and cannot do. Read material similar to this paper, from the FAA and others. Watch the FAA's video "Aircraft Laser Illumination"[34] and other online videos filmed from police helicopters, to get an idea of what a laser illumination looks like from the air. Keep in mind the laser illumination procedures discussed above.

A laser incident is very manageable and will not cause safety issues, if a pilot has advance knowledge about how to react and recover from an exposure.

APPENDIX B
Laser eye hazard considerations for pilots and aircrews

Because pilots are understandably concerned about *any* eye damage, this section goes into more detail about the potential harm from consumers misusing visible laser beams in the aviation environment.

How visible laser light can harm the eye

The retina is the part of the eye that could be damaged by consumer laser beams. Visible light passes through the transparent lens and cornea, and is absorbed by the retina. Normally, retinal tissue will dissipate any heat build-up. But enough light, kept long enough on the same area, can cause a retinal burn. This burn may be minor and visually unnoticed. It may heal in the same way as a small skin burn. Or, if the power and time-on-target are substantial, the burn may cause a permanent spot in the visual field – again, this is highly unlikely with consumer lasers in aviation incidents.

For visible light lasers, the retinal hazard is based primarily on the beam's power entering the eye, which is related to its divergence (spread). More power means more damage potential. A tighter beam means light is more concentrated on the retina, which further increases the damage potential.

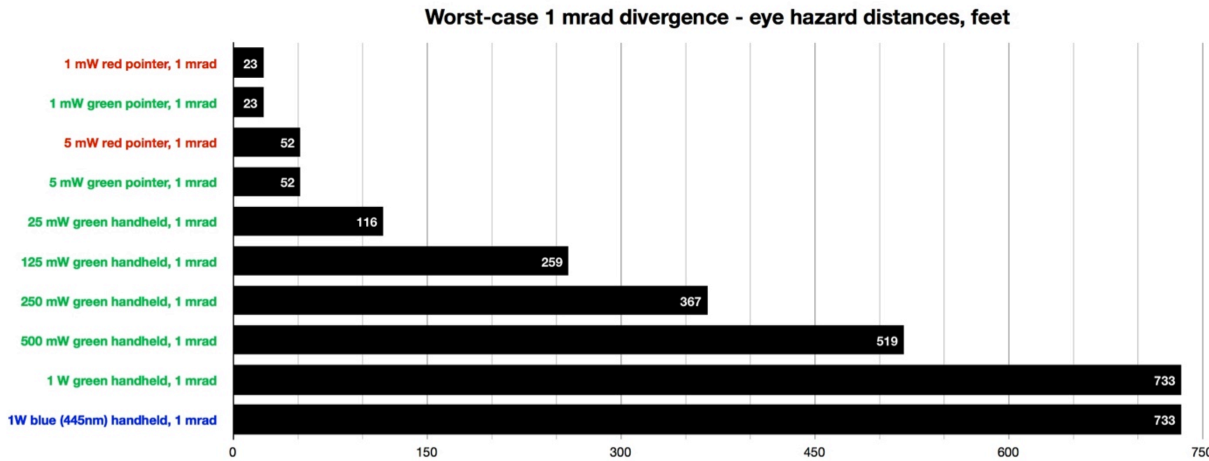

Figure 13: Nominal Ocular Hazard Distances for selected lasers. Note that for comparison purposes, the chart assumes all lasers have a tight, 1 milliradian beam. Generally, higher power handheld lasers will have increased divergence, which means their real-world hazard distances will be less than what is shown here.

Laser beams spread out over distance

Keep in mind that laser beams do spread out. A beam that can pop a balloon at 2 feet may not be able to do so at 10 feet and may in fact be completely eye-safe at 500 feet since the beam's power is less concentrated at a distance. Videos of people bursting balloons within a few inches or feet of a laser, are not very relevant when considering the safety of pilots much further away – hundreds or thousands of feet in the air.

Let's look at the eye damage potential from ten lasers ranging from 1 mW to 1000 mW (1 watt).

For comparison purposes, we will assume they all have a tight beam of 1 milliradian, or about 6/100 of a degree. Such a beam would be 1/10 inch in diameter at one foot from the laser. It would expand to 6 inches across at 500 feet, and would be 63 inches at one statute mile.[35], [36] The more the beam spreads out, the smaller the fraction of the original laser power that will enter a person's pupil.[37]

Figure 13 shows the eye injury hazard distance – called the Nominal Ocular Hazard Distance or NOHD[38] – for ten lasers of various powers, assuming for comparison purposes that they all have a 1 milliradian divergence.

If a person is beyond the NOHD, it is not considered hazardous to momentarily look directly into the laser's beam.[39] For example, for the 1 mW pointers, the NOHD is 23 feet (top two bars). For the 1 watt handheld lasers, the NOHD is 733 feet (bottom two bars). If a person were standing around 23 feet from a 1 mW pointer, or around 733 feet from a 1 watt laser, it would be possible to briefly look directly into the beam without harm – not that this is suggested or recommended![40]

Recall that for visual interference hazards, different colors have different hazard distances. But for eye hazards, the laser beam color does not matter -- only the beam power (strength) and divergence (spread). In the chart below, the red and green 1 mW lasers have the same NOHD of 23 feet. Similarly, the red and green 5 mW lasers both have an NOHD of 52 feet, and the green and blue 1 watt lasers both have an NOHD of 733 feet.

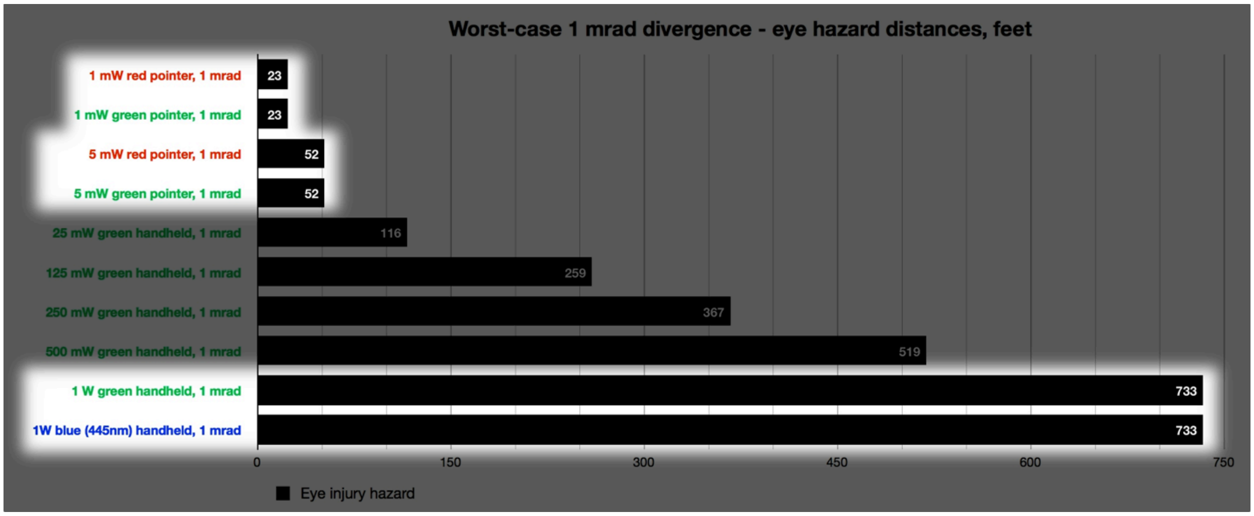

Figure 14: Nominal Ocular Hazard Distances for selected lasers, showing how the NOHD does not depend on the laser beam's color (unlike visual interference distances; compare with Figures 7 and 8).

The NOHD is widely used to determine how far away a person should be from a laser, so that the risk of injury is considered vanishingly small. This is fine for situations where the exposure can be controlled; when possible, persons exposed to laser light should not be within the NOHD.[41] But what about uncontrolled incidents such as aircraft lasings, where a pilot may be inside (closer than) the NOHD distance? What does the NOHD tell us about the potential for eye damage?

Looking more closely at what NOHD means

A laser exposure while inside the NOHD does not necessarily mean instant or severe eye damage. Laser safety experts included a safety factor when establishing the NOHD. As discussed in the main text, that is why it is called the *Nominal* Ocular Hazard Distance, and not something like the *Actual* Ocular Hazard Distance.

If the NOHD is color-coded to show danger as red and safe as green[42], eye hazards are approximately as shown in Figure 15. Yellow is used to indicate the light has a roughly 50/50 chance of causing the smallest medically detectable retinal change[43], under laboratory conditions where the laser and eye are both held steady.[44]

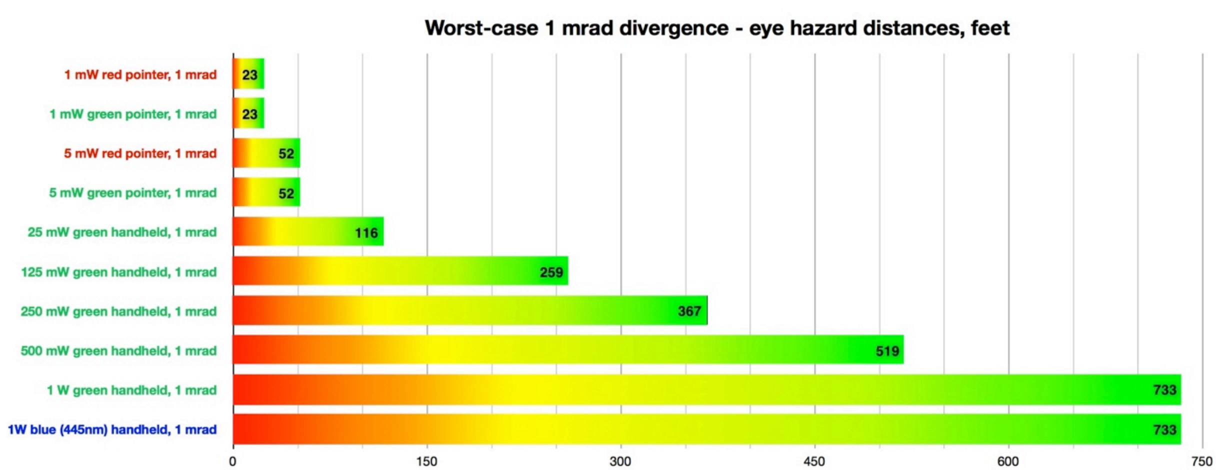

Figure 15: Nominal Ocular Hazard Distances for selected lasers. This shows the same data as Figure 13, but is color-coded to indicate how the hazard decreases with distance. As with Figure 13, for comparison purposes the chart assumes all lasers have a 1 milliradian divergence; in the real-world, higher powered lasers will have a greater divergence and thus the NOHD will be shorter (see Figure 16).

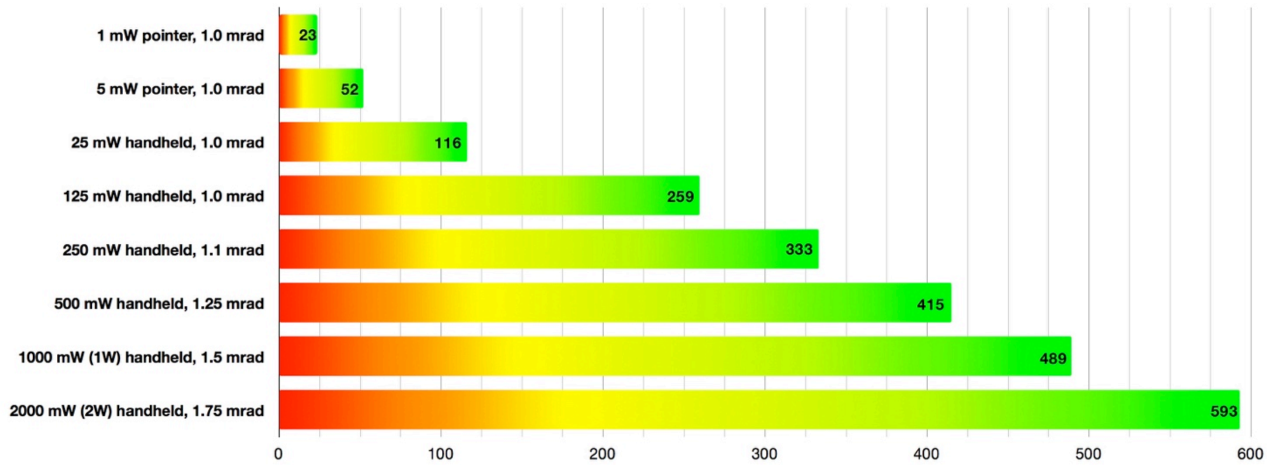

Figure 16: Real-world Nominal Ocular Hazard Distances for selected handheld lasers. Previous figures (13-15) assumed for comparison purposes that all lasers had the same beam divergence. This is not the case with real-world handheld lasers, where higher powered lasers almost always have higher divergences. The data in this chart, therefore, is more realistic regarding the hazards to pilots and others exposed to handheld lasers. See text for an indication of what the color coding indicates.

For example, the yellow spots of the 1 watt lasers in Figure 15 are at 232 feet – a little less than one-third of the 733 foot NOHD distance. A basic interpretation of this is as follows:

> *A person who is 232 feet away from this laser, and who is exposed under worst-case conditions of a stationary laser beam and non-moving eye, would have roughly a 50/50 chance of sustaining a retinal burn or spot that would be barely detectable by an expert. Unless the spot was in the fovea (center of vision), it would be unlikely to be noticed by the person or otherwise cause long-term loss of visual function. As the person moves even further away from the laser, the chance of noticeable or adverse injury decreases, until at the NOHD of 733 feet, it is considered negligible by safety experts.*[45]

Higher-power lasers' beams usually spread faster

Finally, there is one other important factor that makes real-world high-powered lasers less hazardous than the charts in this document indicate. For comparison purposes, the previous figures (13-15) assume that all lasers have a tight 1 milliradian beam. But high-powered lasers usually have wider-diverging beams of 1.5 milliradians or more.

This spreads out the beams' power thus reducing the NOHD. The result is that real-world high-powered lasers have a greater margin of safety, compared to the same laser with a theoretical 1 milliradian divergence. Figure 16 shows the hazard distances of real-world lasers based on higher powers having higher divergences.

APPENDIX C: A technical note about laser hazard calculations

This document is necessarily simplified and general. Keep in mind that laser safety is complex. Some common assumptions are not always true. Here are two examples.

Doubling the laser power does not double the hazard distances

Doubling the power of a laser does not make the hazard distances twice as long. Take a look at Figure 15, the "Worst-case 1 mrad divergence" NOHD chart. A 500 mW laser with 1 milliradian divergence has an NOHD of 519 feet. You might think that doubling the power to 1000 mW (1 watt) would make the NOHD twice as long, 1038 feet, but this is not true – the NOHD is 733 feet, or only 1.4 times longer.

Mathematically stated, the NOHD increases as the square root of the power increase. In practical terms, this means that as consumer laser powers increase, the hazard distances do not increase as fast. This is a welcome bit of good news for pilots.

Doubling the apparent brightness does not double the hazard distances

The calculations work the same way for color. Figure 8 compares a 1 Watt green laser with a 1 Watt blue laser. The 1000 mW green at 88% apparent brightness has a glare hazard distance of 15,510 feet. In comparison, the 1000 mW blue laser with 3% apparent brightness has a glare hazard distance of 2,890 feet.

While there is an 88/3 or 29 times difference in the apparent brightness, this results in only a 15510/2890 or 5.4 times difference in the glare interference hazard distances. (As before, the visual interference distances increase as the square root of the apparent brightness increase.) Thus, although the green laser beam looks much, much brighter than the blue beam, there is not as much difference in the distances at which it is a hazard.

Laser beam hazards are not always intuitive

The general lesson to be drawn is that laser beam hazards are not always intuitive. A laser that lights cigarettes up close can be eye-safe further away. Conversely, a laser that is relatively weak can be a visual interference hazard hundreds of feet away. Pilots, regulators, reporters and others involved in this issue should be careful that they are understanding the correct laser safety principles in a given situation; for example, in flight at aircraft distances vs. on the ground at close range.

Acknowledgements

The author wishes to thank the many persons who contributed data and suggestions, and especially to Ricky Chitwood of the U.S. Federal Aviation Administration, who encouraged development of a document specifically to address the detailed concerns of pilots and aviation officials who may not have a laser safety background.

Meet the Author

Patrick Murphy has been a member of the SAE G10T Laser Safety Hazards Committee since the mid-1990s. In this capacity, he helped develop the regulations and forms used by the U.S. Federal Aviation Administration to evaluate outdoor laser operations. During 2013, he helped write the FAA's Laser Beam Exposure Questionnaire, and proposed guidance for pilots from which much of this paper comes. He is editor of the website LaserPointerSafety.com, which seeks to be an independent resource for users, regulators, pilots, media and others concerned with handheld portable lasers.

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[1] Throughout this document, "laser/aviation safety experts" refers to the consensus of groups such as the SAE G10T Laser Safety Hazards Subcommittee and the ANSI Z136.6 Outdoor Laser Use standards subcommittee. SAE G10T, in particular, has helped define laser/aviation safety parameters and the resulting FAA procedures.

[2] From "Visual Warning System for the Washington, D.C. area" by NORAD and USNORTHCOM Public Affairs, May 24, 2005. Online at: http://www.norad.mil/Newsroom/tabid/3170/Article/1159/visual-warning-system-for-the-washington-dc-area.aspx

[3] See note 1.

[4] Figure 2, the temporary flashblindness photo, shows the instant of maximum flashblindness when the laser beam strikes the eye. The afterimage would be a blob centered where the laser was, which gradually fades away. Total vision would not be blocked as the photo indicates, but of course the afterimage would be a serious impediment to clear vision. A GIF animation is online which gives a better sense of the initial flash, and the dying-away afterimage; see the three GIFs on the Wikipedia page "Lasers and aviation safety", http://en.wikipedia.org/wiki/Lasers_and_aviation_safety

[5] The eye's color response curve is different for photopic (day) vision and scotopic (night) vision. The curve shown here is taken directly from the data used by the FAA in evaluating laser usage in airspace, and thus is valid for pilots flying at night. Safety experts on the SAE G10-T Laser Safety Hazards Subcommittee determined that, because pilots have instrument lights on, their night-flying vision is not scotopic but is closer to photopic. For the data, see Table 5 of FAA Advisory Circular 70-1, available online at www.faa.gov/airports/airport_safety/wildlife/guidance/media/Lasers_AC.pdf

[6] See the second bulleted item in Appendix C, "A Technical Note about Laser Calculations". It describes how, although the green beam appears 29 times brighter than the blue beam, there is only a 5.4 times difference between the two beams' hazard distances. This is a reminder that laser safety calculations are not always intuitively simple.

[7] Based on an analysis of the FAA Weekly Laser Reports for the year 2011, as presented to the SAE G10T Laser Safety Hazards Committee in January 2012.

[8] Ibid.

[9] Personal communication to Patrick Murphy in fall 2011, by Dr. Van Nakagawara O.D. At the time he was head of the Vision Research Team at the FAA's Civil Aerospace Medical Institute. Dr. Nakagawara is former chair of the SAE G10-T Laser Hazards Subcommittee and has authored numerous papers on laser light effects on pilots and aviation. Since Dr. Nakagawara's statement, the FAA's Weekly Laser Report has not listed any cases of permanent eye damage, as of the Dec. 31 2014 report.

[10] Civil Aviation Authority Safety Notice SN-2012/005, issued 13 April 2012: "So far, there have been no documented cases anywhere in the UK where civil aircrew have suffered permanent eye damage as a result of a [laser] attack." Since that time, CAA has not reported any permanent eye damage incidents.

[11] This information is for pilots in civil airspace. Military pilots in hostile areas have been exposed to deliberate laser attacks. It is not publicly known if any of these attacks caused permanent eye injuries. In a 1997 case, a military observer claimed eye injury from an alleged laser aimed at his helicopter from a Russian merchant ship, the *Kapitan Man*. The cause of the observer's eye abnormalities was disputed – he lost a 2002 court case against the ship's owner -- so even this is not a proven case of permanent laser injury to a person in an aircraft. See "Case 5" in "Assessment of Alleged Retinal Laser Injuries"," *Archives of Ophthalmology,* August 2004, pp. 1210–1217, which concluded, "The patient had real complaints, but they were caused by preexisting autoimmune problems rather than by laser injury."

[12] Personal communication to Patrick Murphy from Dr. Nakagawara, fall 2011.

[13] Wavelength also becomes a factor when calculating the NOHD for lasers emitting non-visible beams. For lases with visible beams, the NOHD does not vary depending on the wavelength. For example, a given laser will have the same NOHD regardless of whether it emits red, green, blue or other visible wavelength light.

[14] Personal communication to Patrick Murphy from Dr. David Sliney, fall 2011.

[15] Jean, Mathieu and Schulmeister, Karl, "Validation of a Computer Model to Predict Laser Induced Thermal Injury Thresholds of the Retina", in Proceedings of the International Laser Safety Conference, 2013, page 235.

[16] The careful reader may note that here it is stated that a 2 watt laser has an NOHD of 593 feet, while the NOHD bar graphs later in the document show a 1 watt laser having an longer, more hazardous NOHD of 733 feet. This is because the 2 watt laser example uses a real-world divergence of 1.75 milliradians, while for the 1 watt laser the bar graph uses a tighter 1 milliradian divergence. The bar graph is comparing various lasers' powers so we hold the divergence of them all constant at 1 mrad – even though in the real world, consumer lasers above roughly 500 mW have divergences closer to 1.5-2 mrad (and thus shorter NOHDs).

[17] This discussion is not meant to be exhaustive or conclusive. The closer one looks at ED_{50} studies, the setting of MPE levels, differences in eyes, scintillation effects, etc. the more difficult it can be to draw a conclusion about the possible effect of any given exposure on any given person. The purpose of the discussion is to give a high level overview for persons who were already involuntarily exposed to laser light, or persons in public safety professions. For pilots or others exposed, the discussion helps them better judge the likelihood of being injured – how much they should be concerned. For example, a pilot who was at 600 feet AGL when exposed to laser light would have a small concern for eye injury even if the laser were eventually found to be a powerful 1 watt laser (see Figure 16, bottom line on the chart.) For persons in public safety professions, the discussion helps form policy about when pilots or others should continue with a public safety operation despite the risk of laser exposure. For example, if a Coast Guard helicopter is at 600 feet from shore when flashed by a laser, the risk of eye injury may be less than the benefit of continuing an operation such as a rescue mission.

[18] Of course, in the air during an incident a pilot would not know the power and divergence of the laser, and thus the irradiance, MPE and NOHD would not be able to be calculated. They also may not know the distance precisely. If the laser is recovered and is accurately tested by an expert familiar with laser metrology (not just relying on the label information), then the NOHD can be calculated. In many cases it may be sufficient to obtain a "ballpark figure", to tell a pilot whether a given laser is likely to cause an exposure above the MPE. For example, an inexpensive red bullet laser costing a few dollars would nominally have an NOHD of 52 feet; as long as the pilot was beyond this distance, the exposure was likely below the MPE.

[19] Out of 3,482 laser incidents reported to the FAA in 2012, three involved headache. No 2012 incident involved a "shock" though this has been reported in previous years.

[20] A pilot illuminated on January 15 2010 reported a "burning/warm feeling in right eye" although there are no pain receptors in the retina and the laser exposure was not powerful enough to cause heating of body tissue. The pilot later said this "may have been caused by the fact that I was rubbing my eye." He also reported "emotional effects" of fear and anger. See the ALPA laser conference presentation at http://bit.ly/17k6iwq.

[21] The beam from a powerful laser, aimed by hand at skin within a few inches or feet, can be felt as heat and may cause a burn. Similarly, at a microscopic level light pressure can affect micron-sized particles and even atoms as is done with "optical tweezers." But for pilots who are hundreds or thousands of feet away from a pointer or handheld laser, these effects cannot be felt. Laser light at this distance is so diffuse it cannot be felt and does not exert a force.

[22] The reader is invited to try this himself or herself. At night, use a low-powered laser to aim at a road sign, car rear light, license plate or other retroreflective material at a distance of a few hundred feet or greater. (Of course, check that there are no persons near or behind the target, and that this would not cause distraction or concern.) It is difficult to hold the beam steady on a head-sized target area. A moving target is even more difficult to track.

[23] The software used to extract frames only had a ½ second resolution. When looking at YouTube videos or similar, often the direct laser hit will only last a frame or two, meaning 1/30 to 1/15 second. Now, this is still disconcerting and hazardous. But the key point is that a still photo of a frame-filling laser light is not the entire incident, but reflects the worst moment. Similarly, TV news reporters often will film from inside a helicopter on the ground, while someone a

few yards away aims a laser at the camera; this is not realistic. What is realistic are videos of incidents as captured by police and news helicopters. These show what actual lasers, from real-life perpetrators, look like.

[24] Analysis of the 35 incidents in the 2012 FAA Weekly Laser Reports where the field "Injury Reported" was starred. In a few incidents, a single pilot listed multiple symptoms, or more than one pilot was affected. This is why there are 43 reports from the 35 incidents.

[25] Based on FAA Air Traffic Activity Data System report of 52,522,825 U.S. airport operations from Dec. 2010 to Dec. 2011.

[26] Tips based in part on information in FAA Aviation News, July/August 2009, p. 31 and FAA AM-400-10/3 "Laser Hazards in Navigable Airspace", pp. 3-4.

[27] More specifically, lasers used for pointing are classified by FDA as "demonstration" and/or as "surveying, leveling and alignment" lasers. This gives the FDA authority over the maximum power of these lasers. As of early 2015, the FDA does not appear to have authority to limit the maximum power of general-purpose lasers, including battery-operated handheld lasers. A few states and localities have limitations on the possession, sale and use of pointers and/or handheld lasers.

[28] Laser safety experts have debated the pros and cons of factoring in atmospheric attenuation and/or scintillation. There may be some situations where it is necessary to take these into account. But for general aviation safety purposes, regarding consumer misuse of lasers at relatively low-altitude aircraft at night, in relatively clear air, it is simplest and safest to assume no attenuation and no scintillation.

[29] The reader is invited to try this demonstration. It works best with relatively powerful lasers such as 50 mW or more. Briefly aim the laser upwards into a clear area of the night sky, where there is no air traffic. You should see that the beam looks like a shaft that appears to end. This effect can vary depending on location (humid seashore air vs. dry desert air) and atmospheric conditions. Seeing this effect in person gives a greater understanding of how someone might think that a beam somehow "stops" in mid-air and would not reach an aircraft.

[30] Based on paragraph 4 of a press release from the FBI San Juan Field Office, released September 17 2013. It is available online at http://www.fbi.gov/sanjuan/press-releases/2013/federal-bureau-of-investigation-and-federal-aviation-administration-join-forces-against-aircraft-laser-strikes-in-puerto-rico-and-the-u.s.-virgin-islands.

[31] A selected list is at www.laserpointersafety.com/rules-general/uslaws/uslaws.html

[32] Jason Rodriguez, "Green lasers along Grand Strand not as prominent as last summer", Myrtle Beach Online (published by the Myrtle Beach *Sun News*), July 2, 2013.

[33] "Laser Pointer Prohibition - Improving Safety or Driving Misclassification", Trevor Wheatley, School of Engineering and IT, UNSW Canberra, Australia, Proceedings of the 2013 International Laser Safety Conference, pages 48-54, published by the Laser Institute of America.

[34] The FAA's official 21-minute version is at http://www.faa.gov/about/initiatives/lasers/hazards/. There are shorter versions, condensing the main information, at YouTube and other websites; these can be easily found using the search terms "FAA aircraft laser illumination video".

[35] To calculate beam diameter at a distance, multiply the beam divergence in radians by the distance; the result is the diameter in the same units as the distance. Note that 1 milliradian is 0.001 radians. For example, to find the size in inches of a 1 mrad beam at 500 feet, do the following calculation: 0.001 radians times 500 feet times 12 inches in a foot, or 0.001 x 500 x 12 = 6; the result is a 6 inch diameter beam. For increased accuracy, add in the initial beam diameter at the laser aperture, which is usually on the order of 1/10 to 1/4 inch – although this is not a significant additional amount when the beam is far from the laser.

[36] The formula provided here includes the majority of the beam within the stated diameter. Scientists use various methods to express the diameter of a laser beam, such as Full Width Half Maximum, 1/e and $1/e^2$. For pilot safety purposes, any of these methods will give a useful general idea of the diameter of a beam at a given distance. There may be some special circumstances when it is necessary to determine the exact amount of power within a specified area at a given distance. In these cases a laser safety expert should be consulted regarding which method is most appropriate.

[37] For laser safety calculations and standards, the size of a fully dark-adapted pupil is used; this is considered to be 7 mm in diameter. For semi-dark conditions such as an aircraft cockpit at night, a size of 5 mm would be more normal. Note that this further reduces the actual laser hazard since less light is entering the eye than is considered by scientists when they draw up safety calculations and standards such as the NOHD.

[38] The NOHD is directly derived from the laser safety concept of "Maximum Permissible Exposure". Laser light can be evaluated in terms of what exposure is so low that the chance of human eye injury is vanishingly small; this is the MPE. The NOHD is calculated for a given beam power and divergence, to determine the distance at which laser light entering the pupil is weaker (irradiance is less) than the MPE.

[39] The NOHD used in this document is for a ¼ second exposure to visible light. This is considered to be an unintended or accidental exposure, where a person would blink or move their head out of the way within ¼ second of the initial laser exposure. This is the situation for a pilot in a laser incident, of course.

[40] For one thing, the actual power of the laser may be stronger than indicated on the laser's label. Mislabeling of laser pointers due either to poor quality control or deliberate attempts to avoid import restrictions is a problem. See for example work done by Joshua Hadler at NIST (ILSC 2013 Proceedings, page 38), Woody Strzelecki of FDA/CDRH (ibid, page 180), and John O'Hagan, Michael Higlett and

Marina Khazova of the U.K. Health Protection Agency, now Public Health England (ibid, page 181-188).

[41] Or, said another way: when possible, persons should not be exposed to laser light in excess of the MPE.

[42] The exact shading of red-to-yellow-to-green in these charts was carefully determined, based on discussions with laser experts about how fast the chance of injury tapers off as distance increases.

[43] "Smallest medically detectable retinal change" refers to what can be seen by direct opthalmoscopic observation of the retina. Such changes are significant enough that a person might notice them in the edge of their visual field under special conditions such as looking at a blank wall or blue sky. If it were in the center of their visual field, they would probably notice a spot. Newer, more advanced instruments can detect much more subtle retinal changes; however, these would not necessarily cause any adverse change to a person's vision. Laser safety standards are based on the earlier, direct opthalmoscopic observations.

[44] This is a general description of the "ED_{50}", a concept in the laser safety studies indicating where an effect is seen in 50% of the subjects, or for a single subject, 50% of the time. Based on different studies which came up with different ED_{50} values, the Maximum Permissible Exposure for visible light exposures was set to be about ten times lower than typical ED_{50} levels. This ten-times reduction is sometimes referred to as a "reduction factor" or "safety factor". The NOHD is an area function, so the point where laser light intensity is ten times less is the square root of 10 times, or 0.316 of the NOHD. This is slightly less than 1/3 of the NOHD. While there is no single "ED_{50}" used to set laser light exposure standards, the concept of ED_{50} is a fundamental basis for these standards and thus is valid when discussing in general about how specific light levels were set. For the purposes of informing pilots, regulators and non-experts that laser hazards are not constant within the NOHD but in fact decrease as the distance from the laser increases, the color-coding in Figures 15 and 16 give a reasonable indication of the chance of laser injury. For more information on this, refer to Sliney, D.H., and Wolbarsht, M.L. Safety with Lasers and Other Optical Sources, New York, Plenum Publishing Corp., 1980.

[45] Human sensitivity to laser light varies from person to person. Also, it is in some sense probabilistic – a given exposure might or might not cause a detectable change to a given person's retina. Because of this, the scientific experts who developed laser safety standards could not cover 100.0% of all cases. For example, there may be an outlier such as a person whose retinas are especially sensitive to damage by visible light. But the standards are considered to provide safety for the vast majority of persons, in the vast majority of laser exposure situations.