Acta Avionica

Volume XXV, 48 – No.1, 2023, DOI: 10.35116/aa.2023.0002

DESIGNING OF A NEW AIRPORT PROTECTION ZONE AGAINST LASER ILLUMINATION

Tomáš HOIKA*, Zbyšek KORECKI
University of Defence in Brno, Kounicova 65, 602 00, Brno, Czech Republic
**Corresponding author.* E-mail: tom.hoika@seznam.cz

Summary. Cases of laser irradiation of aircraft have become more frequent in the last 15 years and pose a greater threat to civil aviation security and the associated military aviation due to the availability and price of lasers. Based on studies by the Federal Aviation Administration (FAA) and the opinion of Czech experts on this issue, protection zones have been established around airports. However, they are not effective enough and laser irradiation has become more frequent until the outbreak of the coronavirus epidemic and the decline of aviation. Based on laser illumination statistics in the Czech Republic and an assessment of the danger of lasers at specified distances around airports, a new protective zone was proposed. The protection zones against laser illumination were defined by a rectangle around circles with a radius of 7 NM and the centers on the final approach track.

Keywords: glare, illumination, laser, protection zone, NOHD

1. INTRODUCTION

There are increasing reports of incidents of lasers targeting aircraft in flight around the world. Laser illumination is a very dangerous act for the flight personnel, as the laser, which looks like a small point of light on the ground, spreads over the cockpit glass at height and illuminates the entire interior of the cabin.

Danger to flight operations is not only from commonly available portable lasers in the hands of attackers who intend to hit the aircraft cabin and its crew, but also stationary laser devices, for example:

- sources of laser radiation in amusement parks for public entertainment,
- astronomical lasers, which are used to highlight objects in the night sky,
- other stationary lasers that are used for research purposes. [1]

Pilot vision requirements vary according to the specific phase of flight. Approximately 90 % of the information required for a safe landing is received by the pilot visually, which makes the approach, landing and takeoff the most difficult parts of the flight, as the operational requirements are also the most demanding.

During approach the plane is at a relatively large distance from the airport, but the height above the ground decreases and the plane is thus relatively easily visible from the ground and therefore easier to target. The same is true for landing and take-off, but the distances from the airport are shorter, and the offender thus has a high risk of being caught due to the quick reaction of the airport security guarding the airport perimeter or other security forces that participate in this protection. At the same time, these three phases are considered high-risk, when the entire crew must concentrate on individual actions and the reaction time is very short. [2]

The purpose of this study is to determine the zone around airports where it is highly probable that an attacker with a laser will be located and where it is also likely that the laser irradiation will cause such damage to the crew that may endanger the safety of the flight.

2. CONSEQUENSES OF ATTACKS

At night, the pilot's eyes are adapted to the dark, and in low light, this can lead to deactivation of the rod receptors in the eye and impaired vision. In particular, exposure of the eye to an intense light source certainly leads to deterioration of visual information. This effect can last from a few seconds to minutes, and the adaptation back to the dark can take 30 min or more. The most common effect of laser exposure is glare, or darkening of an object in the field of view. It is distinguished between different types of glare, namely distracting glare, limiting glare and blinding glare. Distracting glare distracts attention and impairs visual comfort, while blinding glare already prevents the ability to see even after the person is no longer exposed to the source of glare. Other effects of exposure to a laser beam are flashblindness, and then an afterimage, i.e. a transient image left in a person's visual field. An afterimage is created because, when watching an object, the eye adapts to the brightness of its environment, and when the brightness changes suddenly, it remains adapted to the original image. [3] [4] [5] [6]

Whether it is the above-mentioned immediate consequences, such as the exposure of the aircraft crew to negative visual effects after laser irradiation, this exposure can also hypothetically have longer-term effects and can even result in an aircraft crash. As a result of the laser exposure, the crew may become so confused or impaired that they lose control of the aircraft, which means laser exposure can be only part of a chain of negative events that results in an accident. [1] [7]

The effect of the laser on the eye and the way it is damaged depends on the wavelength, the output of the laser and the duration of exposure to it. The eyes are generally more at risk than the skin because the lens does not have an outer covering of dead cells compared to the skin. The combined optical gain of the cornea and lens is approximately 100,000 times, so in the retinal region, irradiance of 1 mW/cm^2 can increase to 100 W/cm^2. A lesion resulting from the impact of laser radiation on the retina can spread due to the release of various harmful substances by damaged neurons. The affected area may continue to expand for several hours or days after it begins to subside. In the case of absorption of sufficient energy of laser radiation by the retina, thermal precipitation occurs in the vicinity of the photoreceptors. The surrounding area of the entire retina will also be affected by swelling due to heat exposure. A greater amount of radiation energy can lead to internal bleeding in the choroid and retina [21]. For the visible spectrum, there is a natural protection where the eye closes itself (blink reflex) when it detects very high light output or sees a very bright object. If the radiation level is greater than 1 mW/cm^2, the eye is damaged even before it can close. [2] [8]

3. CURRENT AIRPORT PROTECTION ZONES

Airport protection zones were designed based on research by the FAA in the vicinity of airports, in order to ensure the safety of aircraft against the dangerous effects of lasers. Based on consultation with laser and aviation experts, it has been determined that 100 μW/cm^2 is the level at which a pilot can experience flashblindness or afterimages and therefore noticeably affect the pilot's visual performance. Similarly, a level of 5 μW/cm^2 has been established as the level at which significant glare may occur [3] [4]. The FAA has therefore established protected areas that must be protected according to Flight safe exposure limits (FSEL) when using a laser near an airport or flight path:

• Laser free zones (LFZ) – the maximum intensity of laser radiation in this area is limited to 50 nW/cm^2. [3]

• Critital flight zone (CFZ) – is an airspace adjacent to the LFZ, in which radiation is limited to a level that does not cause glare and the maximum intensity of laser radiation in this space is limited to 5 μW/cm^2. [3]

• Sensitive flight zone (SFZ) – outer airspace in which radiation is limited to a level that does not cause short-term blindness or afterimage effects. The maximum intensity of laser radiation in this space is limited to 100 μW/cm^2. [3]

• Normal flight zone (NFZ) – an airspace that is not defined as SFZ, CFZ or LFZ, but in which laser radiation capable of damaging vision must not occur. The maximum intensity of laser radiation in this space is limited to 2.5 mW/cm^2. [3]

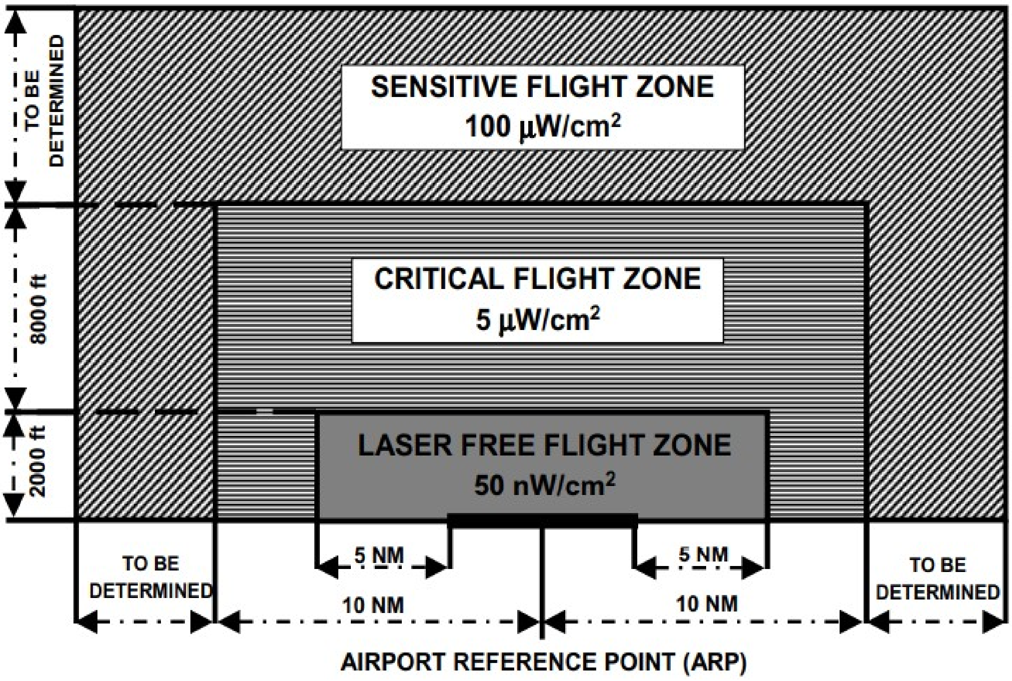

Figure 1 Profile of a single-runway airport and protection zones according FAA [3]

4. NOMINAL OCURAL HAZARD DISTANCE

The Nominal Ocular Hazard Distance (NOHD) represents the minimum distance of the observer's eye from the source of laser radiation at which sight damage already occurs. To determine this distance, the wavelength and time characteristics of the laser are needed, i.e. the corresponding pulse duration or irradiation time. For example, a common military range finder and a laser target illuminator emit their energy in very short pulses (on the order of nanoseconds). Such impulses cause skin lacerations rather than burns. Conventional laser markers, on the other hand, emit their energy as continuous laser radiation, which causes burns rather than lacerations of the skin [9].

In order to calculate the NOHD for continuous lasers, the radiated power is also needed, and the maximum operating should be included in the calculation. Pulsed lasers require the energy of a radiation pulse. The maximum operating energy of the radiation pulse should be considered for the hazard assessment. [9]

The divergence φ is also needed for the calculation. The increasing distance of the spread of laser radiation significantly reduces the danger of the laser. The divergence should be defined by the points of the beam at which the power or energy reaches a value of $1/\ \varphi$ of the peak value of the beam intensity. If there is an outer bundle waist, then the divergence should be taken from the narrowest part of the bundle waist [9].

Next, the shape of the beam is needed. That is, if the laser is rectangular, circular or elliptical. This must be known to determine the correct equation for the calculation. The influence of the atmosphere is neglected for the determination of NOHD.

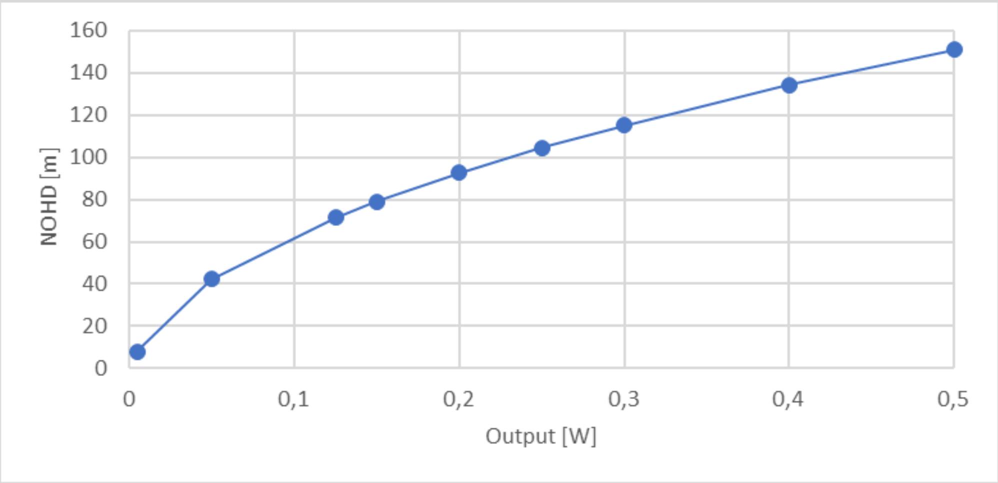

Figure 2 Dependence of NOHD on laser output

For an illustrative calculation, beam divergence of 1 mrad, exposure time t = 0.25 s and laser output 150 mW will be chosen. An exposure time of 0.25 s was chosen as this is the reaction time at which lid closure occurs. The output shape of the laser was chosen circular and the output width of the beam $\propto_{min}$ was chosen to be 8 mm. The formula for calculating the maximum permissible exposure (MPE) is obtained from the knowledge of the wavelength of the green laser (532 nm) and the exposure time. MPE can be expressed in several different ways, usually MPE is expressed in $J \cdot m^{-2}$ or $J \cdot cm^{-2}$.

$$MPE = 1{,}8.t^{0{,}75}.10^{-3}[J.cm^{-2}] \tag{1}$$

Legend:
t time of exposure

The maximum permissible exposure (MPE) for the green laser at the given time is 0.63x10-3 $J \cdot cm^{-2}$. For one exposure, the exposure value can be found by dividing the MPE, by the exposure time t_e:

$$E = \frac{MPE}{t_e} \tag{2}$$

Legend:
MPE maximum permissible exposure
t_e time of exposure

$$E = \frac{0{,}63x10^{-3}}{0{,}25} = 2{,}52x10^{-3}J.cm^{-2} = 25{,}2W.m^{-2} \tag{3}$$

For MPE = 0.63 x 10-3 $J \cdot cm^{-2}$ for time of 0.25 s, the illumination is E = 2,52 x 10^{-3} W/cm^2.

Table 1 Exposure limits for various visual effects [10]

Visual effect	Illumination limit [W/cm²]
Eye damage	2.5×10^{-3}
Flashblindness, afterimage	1×10^{-4}
Glare	5×10^{-6}
Distraction	5×10^{-8}

The desired NOHD value is determined from MPE and irradiance (E) by the equation:

$$NOHD_E = \frac{1}{\varphi}\left[\sqrt{\frac{4.P}{\pi.E}} - \propto_{min}\right] \tag{4}$$

Legend:

φ divergence

E illumination

$\propto_{min}$ beam width

After substituting into the formula, it turns out that the NOHD for the use of a green laser with a power of 150 mW is 79.07 m.

$$NOHD_E = \frac{1}{0{,}001}\left[\sqrt{\frac{4.0{,}150}{\pi.25{,}2}} - 0{,}008\right] = 79{,}07m \tag{5}$$

If the same calculation was performed, but for a laser with a power many times greater and still freely available in the Czech Republic and European countries, i.e. with a power of 1000 mW, then the NOHD is 215.94 m and flashblindness(oslepení) will only occur at a distance of 1129 m.

Table 2 Eye hazard distance for green laser (532 nm) depending on output

P [mW]	NOHD [m]	Flashblindness, afterimage [m]	Glare [m]	Distraction [m]	Safe zone [m]
5	8	71	349	3561	3561 <
50	42	244	1121	11278	11278 <
125	71	391	1776	17837	17837 <
250	104	556	2515	25229	25229 <
500	150	790	3561	35683	35683 <

4. NEWLY DESIGNED PROTECTION ZONE

The increasing popularity and availability of high-powered lasers is contributing to the increasing frequency of reports of laser attacks on aircraft. In the Czech Republic there were relatively few incidents of laser irradiation compared to the USA or the UK, and this problem was not paid attention until a total of 9 laser attacks were committed in 2009 and 34 attacks in 2010, which were classified as a direct threat to flight safety. The number of cases of exposure increased until the outbreak of the Corona virus epidemic in 2019. [1]

Table 3 The number of laser irradiation incidents between 2016 and 06/02/2021 in the Czech Republic

Year	Description	Number of flights	Total
2016	Approach	24	32
	Departure	5	
	En route	3	
2017	Approach	30	39
	Departure	5	
	En route	4	
2018	Approach	27	61
	Departure	4	

	En route	30	
2019	Approach	21	36
	Departure	2	
	En route	13	
2020	Approach	8	11
	Departure	1	
	En route	2	
2021	Approach	5	5
	Departure	0	
	En route	0	
Total	Approach	115	184
	Departure	17	
	En route	52	

In most cases, laser exposure occurred during approach phase of flight. Specifically 62.5 % of crews reported laser exposure during the approach, which makes this part of the flight the most risky in terms of laser exposure in the Czech Republic.

An interesting result of the processing of reports about laser exposure was the fact that in more than a third of the cases, the source of radiation was reported from populated areas. From 2016 to the end of 2020, 37.02 % of attacks were carried out from cities. This fact can be attributed to lasers used in clubs, pubs and concerts around cities, and therefore may not be intentional exposure. Nevertheless, it can be determined from this that a certain percentage of attackers irradiate planes from their homes or adjacent streets so that they can hide in time and not risk escaping through open spaces around airports, where their position can be relatively easily determined using thermal imaging.

Table 4 Number of laser exposures from populated areas in the years 2016 to 06/02/2021 in the Czech Republic

Year	Number of attacks	Number of attacks from cities	Percentage
2016	32	11	34.38 %
2017	39	16	41.03 %
2018	61	15	24.59 %
2019	36	12	33.33 %
2020	11	7	63.64 %
2021	5	1	20.00 %

It also follows from the aircraft irradiation reports that a green laser was mainly used, in 66.3 % of cases overall.

Table 5 Colors of lasers that irradiated aircraft in the period from 2016 to 06/02/2021

Year	Colour of laser	Number of attacks	Percentage
2016	Green	26	81.25 %
	Blue	2	6.25 %
	Other	1	3.12 %
	Unknown	4	12.50 %
2017	Green	31	79.48 %
	Blue	3	7.69 %
	Other	0	0
	Unknown	5	12.82 %

2018	Green	31	50.81 %
	Blue	5	8.19 %
	Other	0	0
	Unknown	25	40.98 %
2019	Green	20	55.50 %
	Blue	4	11.11 %
	Other	1	2.77 %
	Unknown	11	30.55 %
2020	Green	9	81.80 %
	Blue	1	9.09 %
	Other	0	0
	Unknown	1	9.09 %
2021	Green	5	100 %
	Blue	0	0
	Other	0	0
	Unknown	0	0
Total	Green	122	66.30 %
	Blue	15	8.15 %
	Other	2	1.08 %
	Unknown	46	25 %

The green laser used by the vast majority, which has a wavelength of 542 nm, is the most dangerous for the aircraft crew, as the green beam can be up to 28 times brighter during the day than the equivalent red beam due to the sensitivity of the photoreceptors in the eye to green light, and at night the human eye is up to 250 times more sensitive to green radiation than to red. [1]

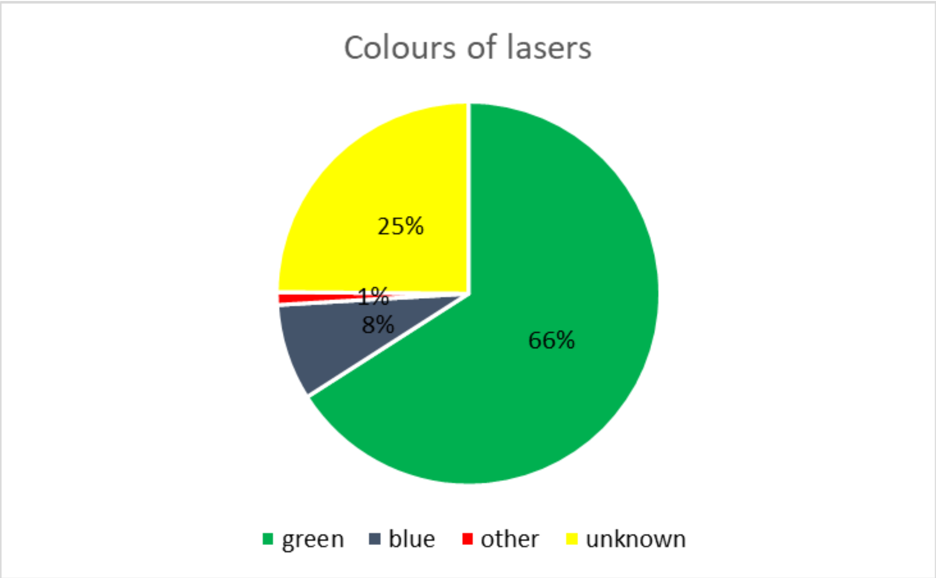

Figure 3 - Comparison of the frequency of the color of the lasers with which the aircraft was irradiated from 2016 to 06/02/2021

Analyzing data on laser exposure reports between 2016 and 6/2/2021, it was found that the average distance between the laser source, and therefore most likely the attacker, and the aircraft is 6.23 NM during approach.

Table 6 Average distance between laser source and aircraft by phase of flight

Year	Description	Average distance
2016	Approach	5.74
	Departure	2.35
	En route	10
2017	Approach	6.46
	Departure	1
	En route	1
2018	Approach	4.92
	Departure	5.1
	En route	26.83
2019	Approach	7.77
	Departure	6
	En route	10.75
2020	Approach	6.49
	Departure	-
	En route	5
2021	Approach	7.8
	Departure	-
	En route	-
Total	Approach	6.23 ± 0.66
	Departure	3.88 ± 1.27
	En route	9.65 ± 2.30

After adding the measurement uncertainty and adding a buffer space of 0.2 NM is created a distance of 7 NM.

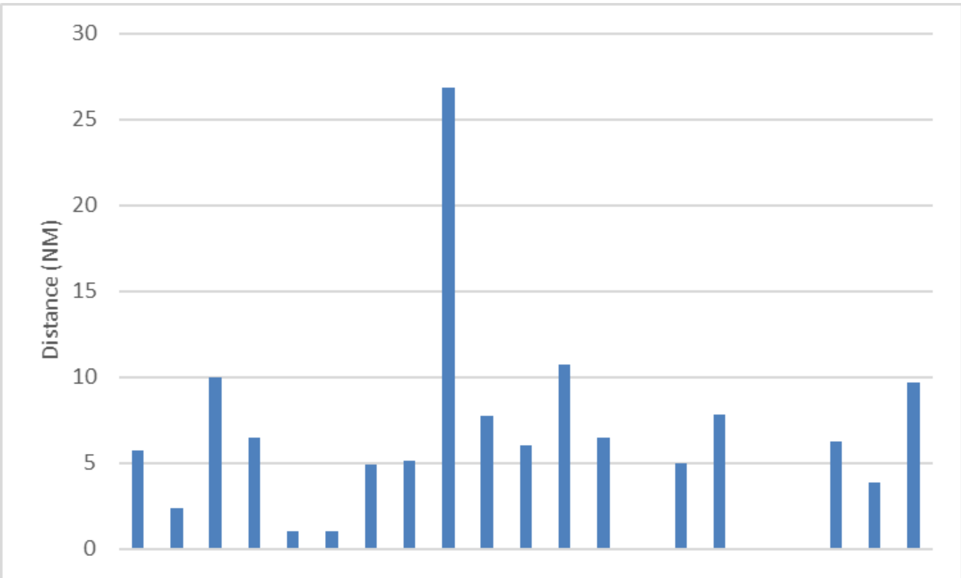

Figure 4 The average distance between the laser source and the aircraft

On average, the laser source when illuminating aircraft is located within 7 NM of the final approach track in up to 65 % of cases and, for example, in 2018 even over 78 % of cases were from this area.

Table 7 Illumination count below 7 NM

Year	Illumination count below 7 NM
2016	60 %
2017	55 %
2018	78.57 %
2019	66.66 %
2020	80 %
2021	50 %
Total	65.03 %

A distance below 7 NM around the approach routes of the airport is advantageous for the attacker, not only because the area around the airport provides the attacker with a good observation position and a convenient hiding place for a quick escape, but at the same time at a distance below 7 NM it is already possible to have an effective negative effect on the aircraft crew even with lasers with a relatively low output. For example, if the attacker is at a distance of 7 NM from the aircraft and uses a commercially available laser with a power of 150 mW, the value of the radiation intensity is 5.11×10^{-7} W/cm^2 – see Figure 5.

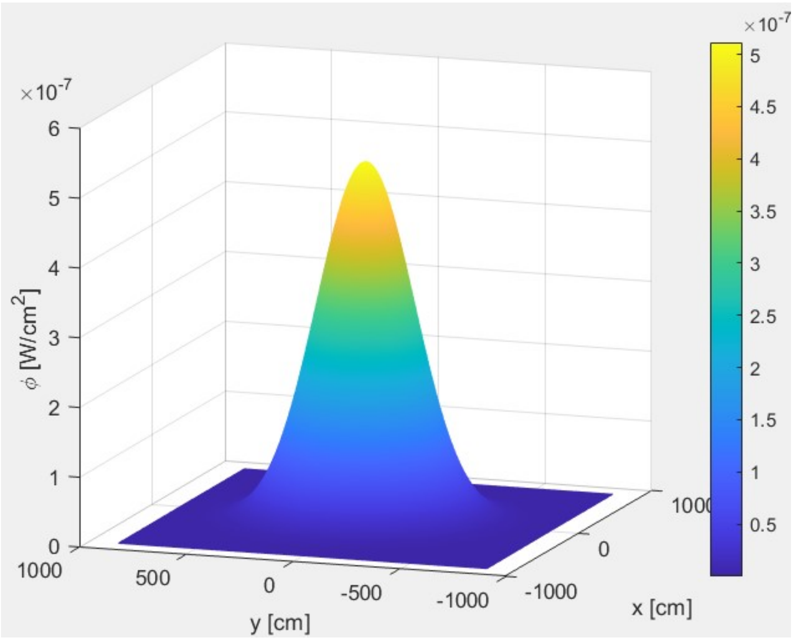

Figure 5 Graph of the intensity of irradiation at a distance of 7 NM by a laser with an output of 150 mW

The visual effect for the aircrew is disturbing glare at this irradiance value. The laser beam is approximately 8 m wide at this distance, as can be seen in Figure 6.

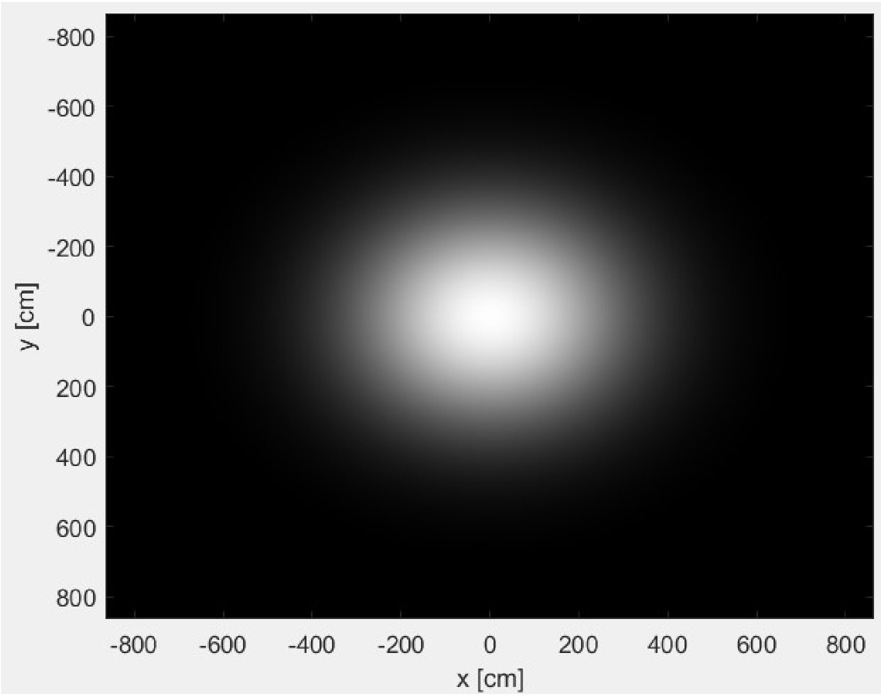

Figure 6 A 150 mW laser beam from the pilot's point of view at a distance of 7 NM

If the attacker has an advantageous position compared to the plane and the plane approaches the attacker up to a distance of 2 NM, the radiation intensity will be 6.27x10^{-6} W/cm^2, which corresponds to the visual effect of glare. At this distance, the width of the beam is approximately 2 m, which at least makes it difficult for an attacker to target the cockpit of the aircraft.

If the similar case is taken, but the attacker would use a commonly available 1 W laser, then the radiation intensity value at a distance of 7 NM would be 3.41x10^{-6} W/cm^2, which again corresponds to disturbing glare and a beam width of approximately 8 m. At a distance of 1 NM, however, the value would already correspond to blindness, since the radiation intensity would be 1.67x10^{-4} W/cm^2 – see Figure 7. At this distance, the width of the beams corresponds to approximately 1 meter.

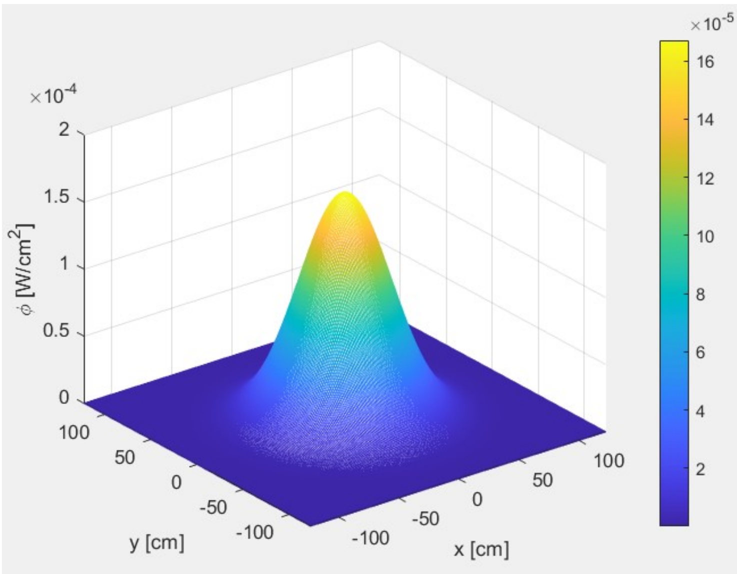

Figure 7 Graph of the intensity of irradiation at a distance of 1 NM by a laser with an output of 1 W

Furthermore, it was calculated for what theoretical maximum time it is possible for the attacker to influence the crew of the aircraft. In this case, it means hitting the pilot's eyes. Of the 2,492 cases of irradiation in the United States from the beginning of 2004 to the end of 2008, the cockpit was irradiated with a laser in 1,676 (67.3 %) cases, from which it can be concluded that the attackers are primarily trying to hit the cockpit of the aircraft and have the crew irradiation as their main goal. [6]

To calculate the time to influence the aircraft, the final angle between the attacker and the axis of the aircraft, under which the attacker is able to hit the interior of the cockpit and therefore the crew is needed. Other input data needed are the initial distance between the attacker and the aircraft, the initial angle between the attacker and the axis of the aircraft, and the speed of the aircraft. The speed of the aircraft during the entire approach was set at 185 $km.h^{-1}$ (100 kt).

In the specific case, when the distance 7 NM is chosen for the initial distance between the attacker and the aircraft and an initial angle of 1 degree from the axis of the aircraft, then using trigonometric functions i is found that in this case the attacker could irradiate the crew of the aircraft with a laser after 248.583 s. If a smaller distance of 5 NM is chosen as the initial distance, then the attacker will be able to affect the crew for 177.559 s. The time the attacker can act decreases as the initial angle between him and the axis of the aircraft increases and as decreases the starting distance. Even if an initial distance of 5 NM is chosen, the time is long enough to completely prevent the pilot from landing and noticeably impair vision

After evaluating the possible probability of radiation of the aircraft crew at a distance of 7 NM and less from the final approach route, after evaluating the intensity of radiation and possible effects on the crew and evaluating the time for which an attacker can act on the crew, it is determined distances of 7 NM and less as dangerous for the crew and flight safety during approach. Therefore, the distance of 7 NM can be used to mark out a protective zone against laser illumination by the laser, not around the airport, but around the arrival routes themselves. The protection zone was determined by a rectangle that describes circles with the mentioned radius of 7 NM with centers at the beginning of the final approach route, in the middle and at the MaPt (Missed approach point) – see Figure 8. The maximum intensity of laser radiation in this space should be limited to 50 nW/cm^2, or to the value of disturbing glare. The buffer zone extends vertically 1000 ft above the final approach route.

Figure 8 also shows protection zone LFZ marked in green, which is approximately 8.5 times smaller than the proposed new zone.

Figure 8 Satellite image of single RWY airport with marked circles with a radius of 7 NM forming a protective zone around the final approach tracks

Conclusion

Attackers have used more modern and powerful lasers over the years, and attacks may become more dangerous in the future, at least until now there has been no development in the professionalization or coordination of these attacks.

In the future, these protection zone may make it easier to find an attacker or source of illumination if a pilot reports to Air Traffic Control unit that someone is trying to interfere the safe conduct flight by laser.

The risk of increasing number of laser illuminations of aircraft will gradually increase due to the development of aviation, the growth of air traffic and the easy availability of lasers. Correct reporting is important to minimize the risk of air accidents and other incidents in air traffic. It is necessary to constantly identify threats in aviation, which undoubtedly include the increasing number of laser illumination of aircraft, and the ability to correctly interpret the collected data. On this basis, it is possible to develop new procedures and improve existing ones.

ACKNOWLEDGEMENT

The authors wish to express their deep gratitude to the Head of the Incident Investigation and Internal Audit Department of the Air Navigation Services of the Czech Republic, Ing. Jan Sedláček for providing data on laser irradiation of aircraft and for consultations regarding this issue

At the same time, we would like to thank doc. Ing. Teodor Baláž, Ph.D. for the hours of explaining the operation of lasers, for helping with calculations and providing many documents on the topic of the article.

REFERENCES

[1] RIND, Pavel. *The effect of a laser attack on the work of the pilot* [online]. Brno, 2011 [cit. 2021-12-14]. https://dspace.vutbr.cz/handle/11012/521.

[2] NAJMAN, Jan. *Laser attacks in air transport*. Praha, 2015.

[3] NAKAGAWARA, Van, Ronald MONTGOMERY a Kathryn WOOD. *Laser Illumination of Flight Crewmembers by Altitude and Chronology of Occurrence* [online]. Aerospace Medical Association, 2011, **82**(11), 6 [cit. 2021-05-13].

[4] NAKAGAWARA, Van, Ronald MONTGOMERY, C. CONOR, Leon MCLIN a Archie DILLARD. The Effects of Laser Illumination on Operational and Visual Performance of Pilots Conducting Terminal Operations. Oklahoma City: FAA Civil Aerospace Medical Instutute, 2003, 14.

[5] NAKAGAWARA, Van a Ronald MONTGOMERY. The Effects of Laser Illumination on Operational and Visual Performance of Pilots During Final Approach. Oklahoma City: Civil Aerospace Medical Institute, Federal Aviation Administration, 2004.

[6] NAKAGAWARA, Van, Ronald MONTGOMERY a Kathryn WOOD. The Illumination of Aircraft at Altitude by Laser Beams: A 5-Year Study Period (2004–2008) [online]. In: . Washington: Office of Aerospace Medicine Washington, 2010 [cit. 2021-05-13]. Dostupné z: https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/2010s/media/201021.pdf

[7] MARKOVÁ, Barbora. Lasers and their biological effects. Hradec Králové, 2006.

[8] LASER INSTITUTE OF AMERICA. American National Standard for Safe Use of Lasers: ANSI Z136.1 – 2007. Orlando: Laser Institute of America, 2007. ISBN 978-0-912035-65-9 & ISBN-10: 0-912035-65-X.

[9] ČOS 051636, Czech defense standard - Assessment of the safety of laser operation in military training areas. Prague: Office for Defense Standardization, Cataloging and State Quality Assurance, 2005, 40 p.

[10] American National Standard for Safe Use of Lasers in Educational Institutions: American National Standard. Z136.5 – 2009. Orlando: Laser Institute of America, 2009.

Received 03, 2023, accepted 06, 2023