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Laser Irradiation in Aviation transport

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The high level of security and safety areas in air transport is due to the continuous detection of threats and risks and the adoption of measures to cut them. The media significance of aviation attacks and the potential threat to passengers and crew leads responsible national and international authorities to carry out measures across states.
The active operation of the pilot is most important in the phases when the pilot performs manual control or when dealing with emergency and emergency situations. Laser attacks on aircraft are most often recorded in phases take-off and landing up to a height of 400 feet. In recent years, attacks have also occurred against aircraft at high flight levels of 9 - 10 km. Lasers have a power of about 1W and are used on automatic monitoring devices.
The pilot's higher vulnerability is during the landing phase when illumination from the left side into the cockpit can significantly affect the pilot's ability to maneuver manually.
Lasers are devices that emit coherent radiation in the optical spectral band $\lambda = 532\text{nm}$. Green lasers emitting at a wavelength are most often used to attack aircraft. A more detailed division is given by the harmfulness of laser radiation.
Radiation harmfulness is assessed according to the Maximum Permissible Exposure (MPE).
MPE can be expressed in two quantities, the highest power density (W/m3), or the energy density of the light source (J/cm2). In case of influence on the pilot in selected phases of flight, it is eyes exposure MPE.
The theoretical description of the effects of lasers during the approach to landing will be supplemented by maps of protection zones with the laser devices prohibition according to regulation L-14.
The analysis will be performed for international non-public controlled airports of the Czech Republic with IFR operations.

Key words: **Laser, aircraft, airplane illumination.**

Introduction

GREEN laser $\lambda = 532$ nm attacks on aircraft are on the rise worldwide and are becoming a phenomenon due to the availability of laser equipment.

Laser attacks on aircraft pilots are extremely dangerous, especially during takeoff and landing phases.

The increasing number of laser interactions against aircraft may be due to the affordability of laser devices, with technological developments continuously increasing power in the range of 1-5 mW to 5 Watts.

The power of the laser device given by law should be in the range of 5 mW.

So far, there has been no fatal accident due to the use of a laser, but it is clear that the accident chance with fatal consequences has an increasing trend.

The danger of lighting the cockpit is due to the pilot distraction in the last phase of flight.

The pilot's reaction may cause a deviation from the direction of landing, which could endanger other arriving aircraft. On the other hand, a helicopter deviating from the course could hit a power line or a building.

The power intensity required to endanger the pilot is in nW over a relatively short distance.

Determining position of the laser attack source is critical information that a pilot from a moving aircraft cannot decide. The positioning of the laser source must be performed by an automated system.

The energy E of electromagnetic radiation of wavelength λ has a frequency f. The relation is expressed by the equation:

$$\lambda = \frac{c}{f}, \quad E = h \cdot f \tag{1}$$

where $h = 6{,}626 \times 10^{-34}$ J. $s = 4{,}135667\ 696\ldots\times 10^{-15}$ eV Hz^{-1} (Planck's constant).

The light emitted from the laser device may pass through the material or be absorbed. Of course, light can change characteristics.

Depending on the material used, light reflection can range from 4% to 90%.

The protection of human vision against radiation is governed by the standard ČSN EN 207 - Personal eye protection - Filters and means for eye protection against laser radiation (laser goggles) and – ČSN EN 60825-1 Safety of Laser products – Part 1: Equipment classification and requirements.

The standard specifies the resistance of a material to the action of a wavelength of 10,6 μm (which is a CO_2 laser) in continuous mode (CW) or 100 pulses in pulse mode (Q-switch) for 10 seconds.

The protection range of the goggles is L1 (lowest protection) to L10 (highest protection).

The transparency of the human eye for electromagnetic radiation is in the range of 370 nm to 1400 nm. UV light below 350 nm is absorbed on the surface of the eye, damaging the cornea or lens.

The visible spectrum in the range of 380 nm to 780 nm acts on the retina that triggers a “blink reflex” reaction when the eye closes itself.

However, radiation with a power greater than 1 mW, irreversible damage to the eye occurs earlier.

For infrared radiation in the range of 780 to 1400 nm, there is no natural protection or reflex, and retinal damage occurs. The cornea is damaged by overheating or by curvature and detachment.

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The color of the rays is an important factor against the human eye because the human eye is most sensitive to green light.

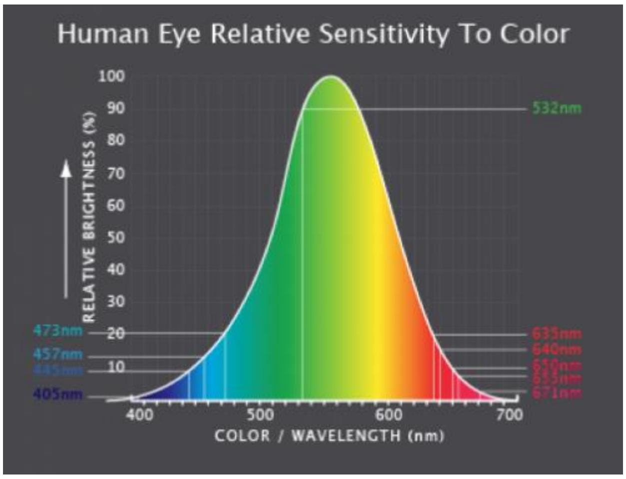

Figure 1: Human eye response to color [1]

Fig.1 shows the graph of V_{λ} a color eye's response.

The 532 nm green laser beam has the highest equivalent power, which is higher than the other beams.

Due to the power of the available lasers, most laser attacks occur up to a height of 3048 meters (10,000 feet).

Standard ČSN EN 60825-1 ED.3, Safety of laser products - Part 1: Equipment classification and requirements, describes the associated hazards in the assessment of laser risks and for the implementation of measures necessary health protection measures.

Methodology

The research carried out in two experiments.

The first step is to select publications. The criterion for choice for the first experiment is the phrase "air transport security and safety" of publications indexed on WoS. The selection resulted in 382 publications. Authors filtered and used from these publications only publications with 25 or more citations.

The second approach was practical measurement in the premises of MTA Jince and evaluation of airport sectors LKNA.

The relationship between frequency and wavelength of light is expressed by the equation

$$\lambda = cT = \frac{c}{f} \text{ , it follows that } f = \frac{c}{\lambda}. \quad (2)$$

The calculation of the frequency f, the energy of one photon E_1 and the number of photons emitted per second N is then performed according to the formulas :

$$E_1 = h \cdot f = \frac{h \cdot c}{\lambda} \text{ and } N = \frac{P}{E_1} = \frac{P \cdot \lambda}{h \cdot c} \quad (3)$$

Laser light detection technology is a special device with spectrometers for measuring wavelength, power meters for measuring irradiation, and fast photodiodes for detecting pulse length.

The calculation of the location of the remote laser source is based on knowledge of the location of the detection system and the direction from which the laser signal was sent.

To determine the location of the laser source, GPS telemetry data, a digital magnetic compass, will be used to locate the distance of the laser source.

Furthermore, calculations and graphs of the evaluation of laser safety sources of the US Federal Aviation Administration were used, which are used to evaluate laser operations in the outdoor environment (Advisory Circular 70-1).

The possibility of eye damage is calculated according to the Nominal Ocular Hazard Distance (NOHD).

Lasers of this power output and wavelength have a nominal ocular hazard distance of around 1,000 ft (304.8 m) [2].

The axial intensity (W/m²) at a distance z from the laser source is given by the formula:

$$I = \frac{4P_0 \exp(-z \cdot \mu)}{\pi (2w + z \cdot \theta)^2}, \quad (4)$$

where the Gaussian beam has power P_0, the radius of intensity w is 1/e² given in meters, the divergence θ (rad), and the absorption velocity μ are usually neglected

$$\theta_0 = \frac{\lambda}{\pi . \omega_0} \quad (5)$$

Subsequent calculation of NOHD assumes replacement with NOHD and size I by the M.P.E.

$$NOHD = \frac{\sqrt{\frac{4P_0}{\pi \cdot MPE}} - 2w}{\theta} \quad (6)$$

In general, for visible lasers of small portable devices, the maximum allowable exposure is 2.54 mW/m².

NOHD, as a standard concept of laser safety, uses the "nominal" value at which the laser is considered safe for the eyes. It does not express the actual geographical distance. The risk of eye injury decreases with the distance from the laser source.

The maximum allowable exposure for flash blindness is 0.1 mW/cm².

Table 1: Laser source distances with the possibility of eye damage [3]

	Distance [m]	Power
Nominal Ocular Hazard distance	250	MPE
Senzitive Zone Exposure Distance	500	100 μ W/cm²
Critical Zone Exposure Distance	2500	5 μ W/cm²
Laser free Exposure Distance		50 nW/cm²

According to current research, the maximum allowable exposure in the Critical Flight zone (CFZ) is 5 μW/cm².

The average CFZ is 18, 520 m, which is given to the Airport reference point (ARP).

ARP is the center of the airport, which is located in the geometric center of all usable runways.

ARP is calculated as the weighted average end of the runway coordinates [4].

For the Sensitive Flight zone, the permissible value is 100 W/cm².

SFZ is located in the distance range from ARP 18. 250 meters – 22, 300 meters.

The exposure distance of the zone without FAA lasers is used for scattering. The maximum allowable exposure in this area is 50 nW/cm².

The type of aircraft also determines the risk of affecting the pilot.

Due to the used heights and speeds, helicopters are more endangered than fixed wings.

Due to the tasks performed, they can move in a relatively small space, or be hung over one place and thus create conditions for increasing the exposure of the intruder.

At the same time, however, they can identify the location of the laser source.

Analysis Specific events - laser threats across Europe in the period 2013-2017

The level of laser threats to pilots in the EU is constantly declining.

However, the problem of the low level of cooperation between Eurocontrol member countries in adopting and implementing policies of the laser attack protection and processes remains.

Pilot's primary risk is, a visual distraction in critical phases of flight, in worse cases, glare, or temporary flash blindness, can occur [5].

Table 2: Basic overview of handheld lasers available on the market [6, 7]

Power [W]	Security class	Color	Beam range [m]
5mW	3A	green	200
50 mW	3A	green	5000
200 mW	3B	green	>5000
200 mW	3R	green	to 5000
700 mw	3B	green	> 5000
1W		green	>10000

Class 2, 3R, 3B, and 4 laser pointers, which are over-the-counter, may exceed statutory safety standards.

Due to technological development, the classification of lasers has been adjusted to classes 1, 1M, 2 and 2M (400-700 nm, blink reflex, 0,25 seconds); 3R (400 and 700 nm, max. 5mW); 3B (max. 500 mW) and 4 from the previous classifications of class 1, 2, 3a, 3b and 4.

Type (Power) of pointer	Flashblindness hazard	Glare hazard	Distraction hazard	NOHD
1 mW	60	260	2600	7
5 mW	130	570	5700	15
5 mW	76	335	3352	15
25 mW	167	746	7467	35
125 mW	375	1670	16703	79
250 mW	527	2362	23622	111
500 mW	746	3343	33436	158
1000 mW	1057	4727	47247	223
1000 mW	198	880	8808	223

Figure 2: Visual interference hazard distances for selected lasers.

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Table 3: Commercially sold handheld laser pointers

Laser (Wavelength)	Power (Watts)	Laser Hazard Ranges (meters)	
		NOHD[b] (m)	ED_{50} [c] (m)
Red (659.4 nm)	0.685	81	26
Blue (442.8 nm)	1.661	197	63
Green (523 nm)	0,05	100	
Green (530.7 nm)	0.455	76	24
Green (530.7 nm)	0.06057	18	6
Green (806.1 nm)	0.0001	0	0

NOHD[b] = nominal ocular hazard distance; eye safe viewing distance.

ED_{50}^{c} = eye Damage distance; Distance where probability of retinal damage is 50%.

An important factor is the size of occupational exposure limits MPEś, which is different for different types of lasers.

Table 4: Selected occupational exposure limits (MPEś) for some lasers [9]

Type of laser	Principal wavelength (s)	MPE (eye)
Argon ion	488 - 514,5 nm	3,2 mW/cm² for 0,1 s
Coper vapor	510, 578 nm	2,5 mW/cm² for 0,25 s
Helium-neon	632,8 nm	1,8 mW/cm² for 1,0 s
Gold vapor	628 nm	1,0 mW/cm² for 10 s

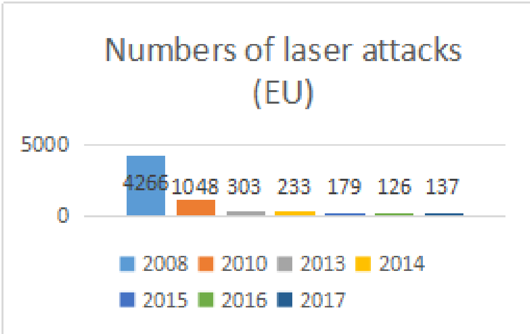
To convert MPEś in mW/cm², multiply by exposure time t in seconds, He-Ne or argon MPE at 0,1 second is 0,32 mJ/cm²

In general, it can be stated that the incidents of laser interference are higher in the summer, with laser illumination in the landing up phase.

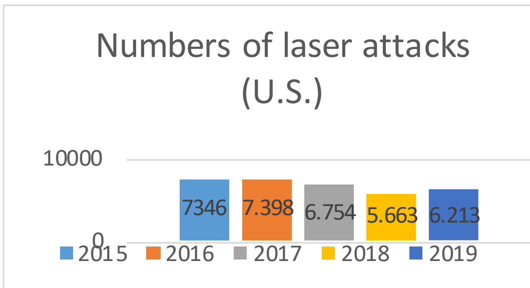
The alarming fact is that in several cases, there was laser interference at very high altitudes.

Implementation of laser distortion at high altitudes presupposes high performances. The length of laser illumination ranges from a few seconds to more than one minute. The length of laser illumination ranges from a few seconds to more than one minute.

Longer laser illumination of the cockpit presupposes the use of laser holders), which help keep up a more accurate flying target.

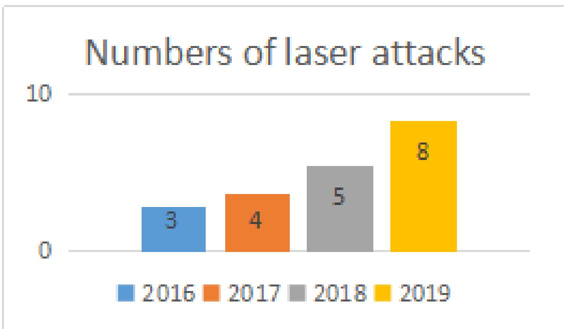


Graph 1: Number of laser attacks [10]



Graph 2: Number of laser attacks in US [11]

The trend of laser attacks shows an increase of 9.7% compared to 2018 and an 8% decrease compared to 2017.



Graph 3: Development of the number of blue laser attacks

Graphs 1, 2 and 3 show the trend of laser attacks in the European Union and the United States of America.

Lasers emit electromagnetic radiation with a wide range of wavelengths covering ultraviolet $\lambda = (100 \div 400)$ nm, visible $\lambda = (400 \div 780)$ nm, and infrared $\lambda = (780 \text{ nm} \div 1\text{mm})$ radiation. The wavelength can be considered as the basic division of lasers.

A more detailed division of lasers is provided by MPE, which assesses the effect on the human eye. MPE allows you to divide lasers into 7 hazard classes and expresses the energy density of the light source.

Energy density is given in W/cm^2 or J/cm^2.

Class 1 and 1M lasers are safe due to their low power. Laser class 2 and 2M are safe because they use the "blink reflex" of the human eye. The value of power in continuous mode is up to 1mW.

The effects of short-term exposure may be glare, flash blindness, and permanent visual stimuli when temporary visual impairment occurs.

Higher classes of lasers 3R, 3B, and 4 can already cause permanent eye damage.

Damage to the human eye depends on the wavelength of the laser, and in general, exposure to more than 1mW of radiation can cause damage to the eye.

Wavelengths of 405 nm, 532 nm, and 550 nm were used for illustrative calculation.

The optical power is 5 W, and the beam divergence is 0.7 mrad. The beam diameter at the source output port is 1 mm.

We assume that a laser pointer emitting at a wavelength of $\lambda = 532$ nm will be used for laser attacks on aircraft.

Lasers of this type work in continuous mode (CW) with a radiated power of about 50 mW, exposure time to laser radiation 0.25 s, which corresponds to the reaction time of the blink reflex

$$MPE = 18 \cdot t^{0,75} \left[\text{Jm}^{-2}\right],$$

$$t = 0,25 \text{ s;}$$

$$MPE = 6.36 \cdot \left[\text{Jm}^{-2}\right]$$

Point source $\alpha_{\min} = 0$.

$$NOHD_E = \frac{1}{0,001}\left[\sqrt{\frac{4 \cdot 0,005}{\pi \cdot 6,36}} - 0\right] = 100 \text{ m}$$

Direct view of a laser with a power of 50 mW poses a risk of damage to the visual organ up to a distance of 100 m from the radiation source.

Study of attacks using a laser

The pilot in the cockpit of the aircraft is potentially endangered against laser attacks during the landing up flight phase.

The correct determination of the attack elimination tool can be realized in several ways.

Many institutions have already performed testing of the laser effect in the landing phase.

The Federal Aviation Administration (FAA) in the United States of America presented the results of the use of a laser pointer with a power of 5 mW and a wavelength of 532 nm [12].

Visibility for different distances from the aircraft was examined.

The following images 3, 4, 5 and 6 [13] present a gradual deterioration in runway visibility.

Figure 3: View from the cockpit of the simulator

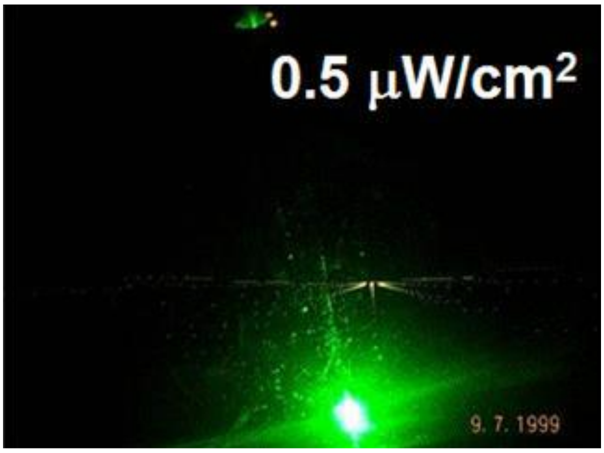


Figure 4: Laser at a distance of about 1128 meters

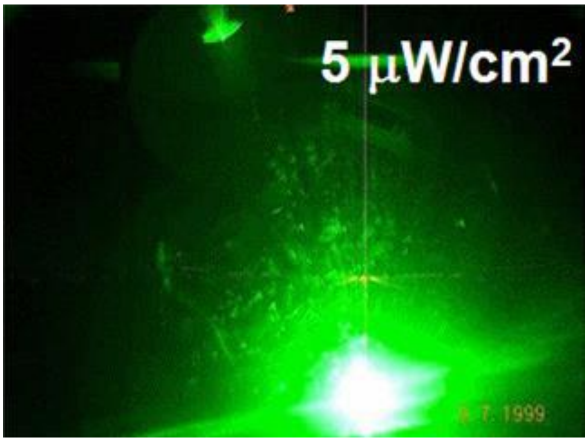


Figure 5: Glare 5mW laser at a distance of about 366 meters (approximately 107 meters). Runway fully covered

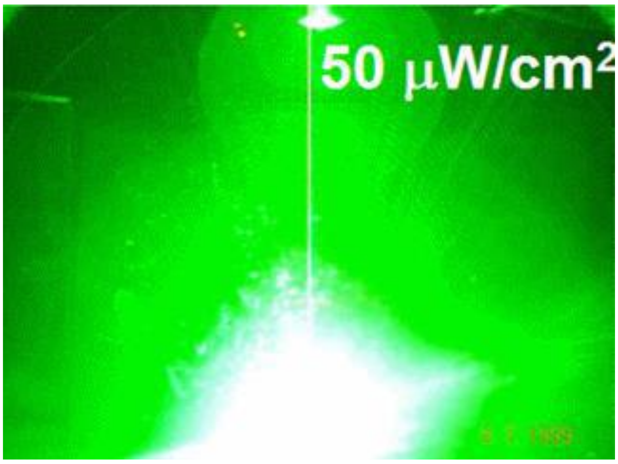


Figure 6: 5mW laser at a distance of 350 feet

The effect of the laser on the pilot according to the power and distance of the laser source (5 mW laser) causes:

Table 6: Health complications when irradiated 5mW laser

Level of threat	Distance [m]	Health complication	RWY visibility
1	1,200	Brief shock and distraction	Partially covered
2	366	Glare	Largely covered
3	100	Temporary sudden blindness	Fully covered

Blue lasers that use a wavelength of 445 nm or 450 nm have an output power of 6000 mW and 5000 mW, respectively. Evening visibility is given within 15 km.

If laser diodes with a rated power are connected (6 laser diodes with 4W each were assembled up to 24 W), a laser diode array with a power above the legally permitted limit will be created.

Protection zones of Náměšť nad Oslavou airport

Airport security zones are based on Regulation L-14, Title 2, which stipulates that airports shall establish security zones:

- OP with a ban on constructions,
- OP with height restriction of buildings,
- OP against dangerous and misleading lights,
- OP with a ban on laser equipment,
- OP with restriction of constructions of HV and VHV overhead lines,
- OP ornithological [14].

The protection zone with the prohibition of laser devices consists of two sectors - sector A, and B.

Sector A - is defined by a rectangle with a longitudinal axis identical to the runway centreline, with a width of 8,000 m, a length exceeding 10,000 m beyond the runway thresholds, and extending from the ground to a height of 600 m above the average altitude of the aerodrome operating areas.

In sector A, it is prohibited to permanently or temporarily place, hold or use laser sources or operate with them with a maximum permissible radiation dose exceeding 50 nW / cm^2.

Sector B - has the shape of a circle centered on the aerodrome reference point with a radius of 20,000 m and extends from the ground to a height of 2,400 m above the average altitude of the aerodrome operating areas.

In sector B, it is prohibited to permanently or temporarily place, hold or use laser sources or operate with them with a maximum permissible radiation dose exceeding 5 μW / cm^2 [15].

Due to the specifics of the deployment of military aircraft, the power of available lasers, and restrictions on movement in protection zones, it can be assumed that it is minimized to dazzle pilots. The FAA has defined two critical dimensions: 350 and 1,100 meters.

During the laser attack from this distance, the pilots were already dazzled, and the runway was covered.

Different shapes of cockpits and their location limit the possibility of enlightening the pilot.

In order to show one area size (one for 350 meters and one for 1,100 meters), a 45° angle was chosen as the maximum angle from which the laser beam would reach the cockpit windows.

The edges of the areas are given by the furthest point on the ground, from which the distance between this place, and the cockpit windows is 350 (1,100) meters, and the angle of the beam from the horizontal is not more than 45°.

At the level of the runway threshold, the edge is therefore at a distance of almost 350 (1,100) meters from the extended runway centreline, when it is necessary to calculate, that the cockpit is at a certain height above the ground.

Subsequent progression from the runway along its extended axis increases the angle at which it is necessary to aim at the aircraft in order to illuminate the cabin. The reason is the fact that the aircraft is located at a greater height above the ground.

The edge point is then the place from which the beam is directed at an angle of 45° - 247 and 778 meters from the extended axis of the runway.

The highly dangerous area with a critical size of 350 meters is shown in purple on the maps.

The hazardous area with a critical size of 1,100 meters is shown in blue.

Sector A, from regulation L-14, whose color is light green, is also available for display. The aircraft descent angle is standard 3°.

The Army of the Czech Republic uses four airports in the Czech Republic

a) Čáslav

b) Náměšť nad Oslavou [16]

c) Pardubice

The size of the protection zones of international non-public controlled airports of the Czech Republic with IFR operations are given in Table 8.

Table 7. Protection zones of international non-public controlled airports Náměšť nad Oslavou, Armed Forces of The Czech Republic with IFR operations

Zone type	
Protective zone of operating areas	3,780x600
Inner ornithological zone	3,780x600
Protection zone against dangerous and misleading lights	9,780x1,500
Outer ornithological zone	9,780x2,000
Protection zone with limited constructions of HV and VHV overhead lines	1,2780x2,000

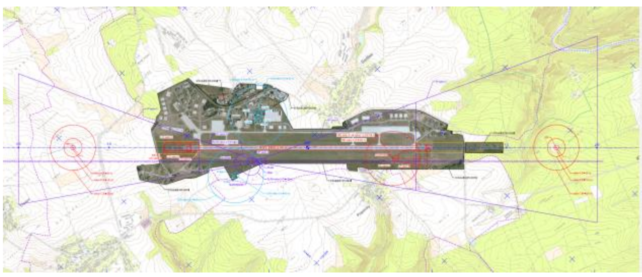


Figure 7. Schematic illustration of Naměšt nad Oslavou airport

Laser source due to the path and movement of the aircraft and the possibility of direct impact on the cabin of the aircraft

The practical experiment was carried out on MTA Jince on 11 September 2019 with the aim of:

- carry out an attack on a flying helicopter at various distances,
- verify the behavior of the helicopter crew after aiming the helicopter at the laser beam cone,
- verify the possibility of direct contact of the crew's eye with a laser beam,
- verify the effect of laser radiation on the helicopter's instrumentation.

Table 8: Experimental conditions in the locality of Jince.

Date of realization	11th 9. 2019 from 17:00 to 22:00 hours
Temperature	18ºC
Absolute humidity [g/m³]	14,7
Air pressure converted to sea level	1015,3 hPa
Wind	1,8m/s
Visibility	up to 3 km
Coordinates of point A	49.7594008N, 13.9463214E
Coordinates of point A	49.7650369N, 13.9558339E
Distance of point A-B	1,900 meters
Point altitude A	482
Point altitude B	484

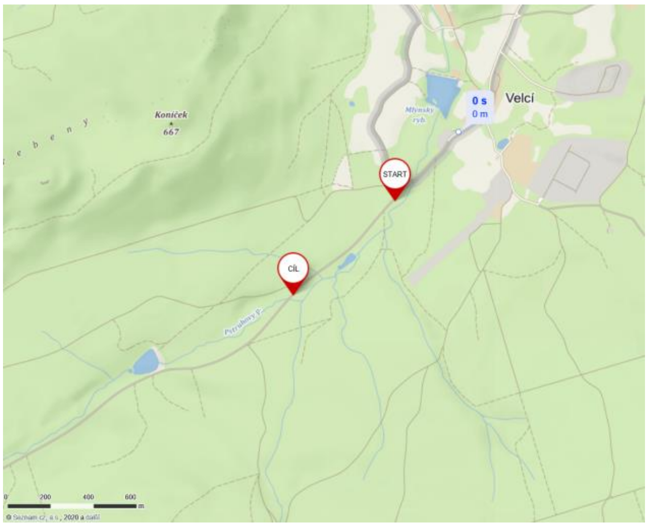


Figure 8. Space for the implementation of a practical experiment

In the direction A-B, an attack was carried out on a low-flying ACR helicopter at a distance of about 2,000 m.

The experiment was carried out in the time interval from 20:00 to 23:00 by selected technical means, see Table 10.

Table 9. Technical parameters of used lasers

Type of Green laser	λ [nm]	Performance stability	θ [mrad]
DPGL- 2050F	532	< 1%	1,2
Pointer	532	---	1

The relation was used to calculate the NOHD [1].

Table 10 Calculated distances for nominal ocular hazard distance

Laser power	Distance
50 mW	50 m
150 mW	86 m

A real attack on a low-flying ACR helicopter was carried out in order to demonstrate the irradiation of the helicopter with a hand-held laser with a power of 150mW in the direction A-B.

A helicopter moved in the area of point A at a height of about 300 m above the ground, at a speed in the range of 80-120 km/h.

The distance of the helicopter from the source was about 2,000 meters.

Longer-term maintenance of the beam at one point of the helicopter is relatively difficult. The shaking of the hands begins to manifest itself, which makes it difficult to focus the target at a long distance for a long time.

Figure 9. The intensity of the incident beam perceived from the cockpit at a distance of about 2,900 m

Aiming a flying subject at a distance of several hundred meters to almost 3 km is relatively easy to do with a commercially available laser pointer or hand-held laser.

Holding a laser beam on a moving target without a tripod is limited to a few seconds.

The possibility of endangering the human eye with a narrow beam of the laser beam is close to zero due to the divergence of the beam and the distance.

The target is hit across the board.

Influence of laser beam on aircraft construction

We will assume that the offender carries out the laser attack at a distance of about 500 m with a common laser pointer with a divergence of 1 mrad and a power of about 150 mW.

At a distance of 500 m, the beam will have a diameter of 0.5 m, which corresponds to the area of the circle, which will be formed on the target about 0.2 m².

The intensity of irradiation of the target will be about 0.75W/m², which is a value that can not cause any damage to the aircraft structure.

Influence of laser beam on aircraft electronics

During a practical experiment, the helicopter was equipped with a CCD camera and a thermal imaging camera.

Figure 10. Location of CCD and thermal imaging camera on EC 135

When a CCD camera is hit by an intense light source, so-called "blooming" occurs, a phenomenon in which a large amount of light falls on the pixels of the camera, and their capacity is exceeded.

Figure 11. Thermal imaging camera on EC 135 in pre-flight position

Subsequently, the scanned image is transmitted as a system of vertical lines of irregular length.

If the exposure to intense light is short in a few seconds, the CCD camera will fail for a short time. Prolonged exposure poses a risk of permanent damage to the camera. The same situation occurs with night vision devices. Night vision devices amplify residual light with $\lambda = (700 \div 1000)$ nm and convert it into visible light.

When irradiated with a strong light source, the night vision device may be taken out of service for a few minutes, or the internal electronic components of the night vision device may be permanently damaged and taken out of service completely.

Conclusion and proposal part

A typical aircraft is equipped with a set of interacting systems that are combined to enable

the aircraft to perform a particular role or set of roles [17]. Identifying the position of the laser source could simplify a separate instrument located in the cockpit of the aircraft. The instrument will be able to indicate position, altitude using GPS and, a 3-axis magnetic compass.

The laser source will be scanned by a camera sensor, which will allow the computer to identify the position and altitude of the source.

At the same time, information is sent to predefined recipients to perform the intervention.

Because smart phones already contain the functionalities, camera, compass, GPS, processor and display that are needed to locate the intruder (laser source), only a way to implement the new device into the dashboard must be found.

The results of the measurements indicate the fact that the risk of using laser radiation against the pilot in the conditions of the Air Force of the Army of the Czech Republic is addressed by the creation of protective zones.

Protection bands with sufficient reserve exceed the power capacity of mobile lasers.

Similarly, the results of NOHD in the field of eye injuries they prove that due to the power of lasers, the probability of causing injuries is only 1/3 of the length of the beam from the source.

Laser pilot illumination is a safety incident, and measures must be taken to eliminate the number of laser illumination of the pilot.

Measures taken to keep the pilot's attention in the critical phase of flight, landing, and take-off or to operate the helicopter must minimize the possibility of using laser sources by limiting suitable spaces or by acquiring pilot protection in the cockpit.

Due to the protection zones of military airports, it is necessary to mention that the probability of damage to the retina of the eyes is significantly eliminated.

Laser attacks by mobile means are aimed at the pilot, who cannot prevent the laser pulse from being sent, but since this is a controllable situation, it is possible to react by turning on the lights in the cockpit.

The implementation of flight procedures in laser lighting requires immediately informing the ATC and, depending on the flight phase of the flight, turning on the autopilot or performing a missed approach.

Pilot eye protection is also provided through laser protective eyewear.

The absorption spectrum depends on the structure of the compound from which the eyewear is made [18] while complying with the legislative requirements of the standard ČSN EN 207/208 Personal eye protection.

Optical density expresses the eye's ability to filter out the laser beam.

To calculate the optical density, we use this formula $D = \log \tau$, where D is the density, and τ is the transmittance, which expresses the amount of light of a certain wavelength that has passed through the sample.

Transmittance is defined: $T = \frac{I}{I_0}$, where I is the intensity of the light which has passed through the sample and I_0 is the intensity of the light which has entered the sample [20].

It should be borne in mind that the same protective device may not provide the same degree of protection against infrared and ultraviolet laser beams [21].

Technical possibilities for aircraft crew protection are goggles and protective glasses with special filters.

When assessing the quality of protective equipment against laser radiation, we evaluate the following parameters:

Optical Density: determines the extent to which the protective device absorbs incident radiation. If the indicated optical density is 6, the incident radiation is attenuated 10^6x,

Visible Light Transmission: the amount of daylight that is released by the protective equipment.

Recommended goggles should have an optical density of 6 - 8 and a polycarbonate filter, which provide protection against a laser with a wavelength of 532 nm (green laser).

The reflective protective layers of the cockpit windshield represent another possibility of protecting the crew from the negative effects of laser radiation.

These are very thin and soft layers made, for example, of MgO, which are vapor-deposited on glass.

The disadvantage is the reduction of the level of protection if the incident beam does not have a perpendicular impact on the glass. In the current situation, the cockpit windscreens are mostly at an angle of 30^o.

Another development in the field of pilot protection against laser attacks may be the use of a Fabry-Perot interferometer filter, which uses a multi-beam interference process to obtain wavelength selectivity.

The filter usually has one inlet, and one outlet port, and uses two highly reflective plates, which together form a resonant cavity creating a multi-beam interference process.

Diamond-like carbon (DLC) is widely used in the infrared protection window, but its ability to protect against laser radiation is limited. [19].

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