Laser dazzler emitting three-colour radiation

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Abstract—The article presents a laser dazzle generating three overlapping laser beams of different colours, and an analysis of the possibility of dazzling people with this radiation. The analysis considers the eye's photopic sensitivity and the additivity of three radiation beams. Such an analysis, to the knowledge of the authors, has been presented for the first time. The dazzling possibility is presented for four different dazzle levels and three levels of ambient luminance. It has been shown that in some conditions it is possible to damage the eye without causing the assumed dazzle effect.

Each radiation detector has a specific allowable range of exposure to radiation. Within this range, the response to detected radiation is not distorted. If radiation exceeds a certain level, the response is distorted, and the information received is unreliable. The human eye is a special type of detector. It detects visual radiation from the environment and enables humans to function adequately. There are two major types of photoreceptors in eyes, rods and cones. Rods are activated by dim light, shades of gray. The cones are activated by colors and bright lights. Rods give people night vision, while cones work to colorize the world around. The eye has three types of cones, and each type is sensitive to different ranges of wavelengths.

When the level of radiation reaching the retina is too high, the so-called dazzle effect appears, resulting in temporary impairment of human performance. A very good example of the dazzle effect is the exposure of the eye to sunlight on a clear day. When one looks directly at the Sun, there is a temporary glare that manifests itself as visual impairment. It takes some time for the quality of vision to recover.

One of the ways to dazzle a person is to use visible light radiation with sufficiently high radiance (brightness). Lasers are the source of such radiation. They are particularly suitable for dazzling applications due to the generation of high power from a small area and in a small solid angle.

The dazzle effect has many applications, both positive and negative. A positive application may be to dazzle an enemy or an adversary in a situation of armed conflicts or counter-terrorist activities. Dazzling allows to disrupt the opponent's activity and, as a result, overpower him while keeping him alive. This makes it possible to minimize fatalities, protect the innocent and limit collateral damage [1]. By contrast, all kinds of attempts to dazzle passenger plane pilots are negative applications, which can even lead to an air crash. In 2019, pilots reported 6,136 incidents of laser illumination to the US Federal Aviation Administration [2].

When considering dazzling, the potential for permanent damage to the eye must be considered. Such threats appear more and more often, mainly due to easy access to markets offering laser devices and a decrease in their prices [3–10]. The possibility of eye damage during exposure to laser radiation has been described in the relevant standards, where the Maximum Permissible Exposure MPE has been defined, for which the probability of damage is very low [11–12]. Based on the MPE, the Nominal Ocular Hazard Distance NOHD can be derived, which defines the distance from the radiation source at which the intensity of a single laser beam becomes safe without exceeding MPE.

In a similar way, the Nominal Ocular Dazzle Distance NODD can be determined, which defines the distance from the radiation source at which the intensity of a single laser beam does not cause dazzling [13]. In this case, the intensity does not exceed the Maximum Dazzle Exposure MDE, the values of which were first proposed by C.A. Williamson and L.N. McLin [14].

One way to counteract the dazzle effect is to isolate the eye from the radiation that causes it. This can be achieved by using appropriate optical filters that suppress this radiation. In such a situation, it is necessary to have knowledge about the wavelength of incoming radiation to use filters with appropriate transmission characteristics. It is worth noting that when such filters are used, a certain area of radiation reaching the eye is cut out, which affects the quality of vision, especially colour vision. To make it difficult to counteract the dazzle effect, dazzling can be performed with several beams located in different bands of visible radiation. In such a case, an attempt to counteract dazzling by applying optical filters may turn out to be ineffective as such filters may significantly reduce colour vision and prevent the normal operation of people who use them.

The dazzler presented in this article makes it possible to dazzle humans with laser beams of three radiation bands (red, green, and blue). The laser dazzler wavelengths along with the cone types, their spectral ranges and peaks of absorption are presented in Table 1.

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Tab.1. Laser dazzler wavelengths along with the cone types, their spectral ranges, and peaks of absorption.

Cone type	Spectral range [nm]	Peak of absorption [nm]	Laser dazzler wavelength [nm]
S	400–500	420–440	440
M	450–630	534–555	520
L	500–700	564–580	635

In such a situation, counteracting the dazzle effect with appropriate filters becomes less rational due to the need to suppress the radiation bands of three basic colours.

The NOHD can be determined based on the values of the MPE, beam power P, its divergence Ø (in the case of a circular beam) and its diameter w at the output aperture in accordance with the formula [15]:

$$NOHD = \frac{\sqrt{\frac{4P}{\pi MPE}} - w}{tg\emptyset} \quad (1)$$

In most cases, the beam diameter is small and has a negligible effect on the NOHD, so it can be ignored. Similarly, the angle of divergence in most cases does not exceed a few miliradians, so the approximation tgØ = Ø can be introduced, and Eq. (1) will take the form:

$$NOHD = \frac{\sqrt{\frac{4P}{\pi MPE}}}{\emptyset} \quad (2)$$

When the beam is characterized by an elliptical cross-section and hence it has two different divergences in two planes α and β, respectively, then Eq. (2) takes the form:

$$NOHD = \sqrt{\frac{4P}{\pi\alpha\beta MPE}} \quad (3)$$

The MPE values are defined in the standard IEC 60825-1: 2014 for different wavelength ranges and different exposure times [12]. For laser dazzlers, applied in a hostile engagement scenario, one could assume persistent viewing when the person being dazzled intentionally looks at the dazzle beam for a relatively long time. For such an assumption, following the standard, the MPE value relates to exposures from 10 to 30,000 s. On the other hand, natural aversion to bright light may significantly decrease this exposure time to one quarter of a second. According to the standard for visible radiation in the wavelength range 400–700 nm and for the exposure time of 0.25 s, the MPE is equal to 25.46 W/m2.

Equation (3) can be used to derive the NODD except that the MPE should be replaced by the MDE. Thus, the NODD can be found using the following equation:

$$NODD = \sqrt{\frac{4P}{\pi\alpha\beta MDE}} \quad (4)$$

The standard MDE values for four different dazzle levels and three ambient light levels were first proposed by C.A. Williamson, L.N. McLin [14]. The dazzle level describes the size of the dazzle field (expressed as angular size of the visual field that is obscured within an observer's field of vision) caused by a laser eye dazzle event. It is schematically shown in Fig. 1, where the green field is the visible area while the blue field is the area obscured by dazzling. The standard values of the MDE are presented in Table 2.

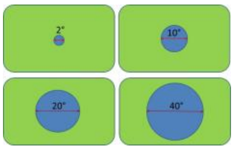

Fig. 1. Four different dazzle levels.

Tab.2. Standard values of the MDE for different dazzle and ambient light levels [13].

Dazzle level	MDE [μW/cm^2]		
	Night	Dusk/Dawn	Day
2	0.001	0.6	40
10	0.04	30	2000
20	0.16	120	8000
40	0.6	450	30 000

The above values were defined for the maximum eye's photopic sensitivity V(λ) equal to 1 (for a wavelength of 556.1 nm) [16]. To determine the MDE for other wavelengths, the values from Table 1 should be divided by the appropriate value of V(λ). The values of V (λ) for a few basic wavelengths λ are given in Table 3.

Tab.3. Values of V(λ) for a few basic wavelengths [14].

λ [nm]	440.0	520.0	635.0
V(λ)	0.0503366	0.718089	0.24169

Equations (1)–(4) are appropriate when dealing with a single laser beam. In the case of the emission of three overlapping laser beams of different powers and divergences, Eqs. (3) and (4) will take the form [15]:

$$NOHD = \sqrt{\frac{4}{\pi MPE}\left(\frac{P_1}{\alpha_1\beta_1} + \frac{P_2}{\alpha_2\beta_2} + \frac{P_3}{\alpha_3\beta_3}\right)} \quad (5)$$

$$NODD = \sqrt{\frac{4}{\pi}\left(\frac{P_1}{MDE_1\alpha_1\beta_1} + \frac{P_2}{MDE_2\alpha_2\beta_2} + \frac{P_3}{MDE_3\alpha_3\beta_3}\right)} \quad (6)$$

The equations presented above are true only for the areas common to all laser beams.

The additivity of spectral sensitivity of the eye for visible radiation was assumed here, however it has not been firmly proven for laser exposure [17, 18].


Fig. 2. Developed Laser dazzler emitting three-colour radiation.

The developed dazzler generating three overlapping beams of red, green and blue radiation with different parameters is shown in Fig. 2. The figure also presents the dazzle when it is attached to a rifle. The parameters of the generated beams are shown in Table 4.

Tab. 4. Parameters of the generated beams.

λ [nm]	P [mW]	α [mrad]	β [mrad]
520	574	2	2
440	1825	2	5
635	520	3	7

For the parameters presented in Table 3, the NOHD and the NODD were calculated. The calculation results of the NOHD are shown in Table 5 while those of the NODD are shown graphically in Figs. 3–5 for each beam separately and in Fig. 6 for all beams together.

Tab. 5. Calculation results of the NOHD.

λ [nm]	NOHD [m]
520	85
440	96
635	35
Three beams together	132

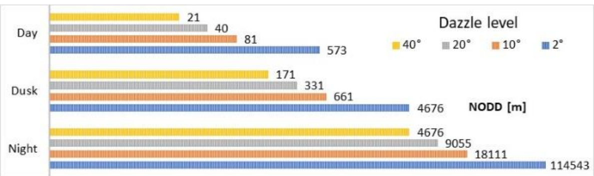

Fig. 3. Calculation results of the NODD for 520 nm laser beam.

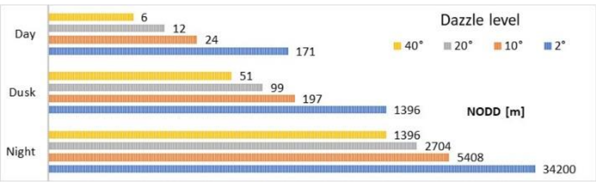

Fig. 4. Calculation results of the NODD for 440 nm laser beam.

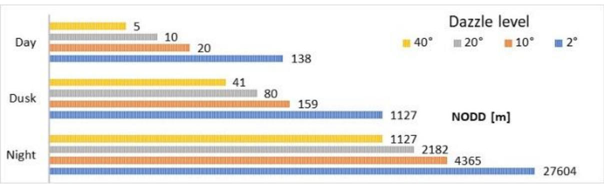

Fig. 5. Calculation results of the NODD for 635 nm laser beam.

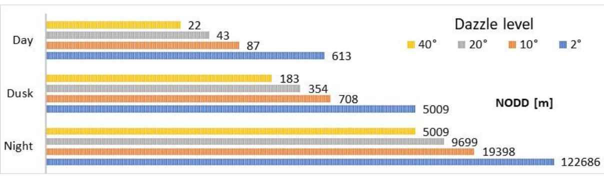

Fig. 6. Calculation results of the NODD for three beams together.

The presented calculations show that depending on the dazzle and ambient light levels, the NODD values vary to a very large extent. For the green radiation, the NODD value varies from 21 m for a 40° dazzle level at day ambient light to over 114 km for a 2° dazzle level at night ambient light. For the red radiation this range is 5 m and over 27 km, and for blue radiation 6 m and over 34 km, respectively. The highest values of the NODD are characteristic for green radiation due to the highest value of the V(λ). The use of three beams simultaneously slightly increases the NODD value in relation to the corresponding value for the green radiation. For the green beam for a dazzle level of 40° at night ambient light, the NODD is over 114 km, while under the same conditions, but using three beams simultaneously, the value of the NODD increases only to over 122 km. It can also be seen that for day ambient light level and 10°, 20° and 40° dazzle levels, for all beams together and separately, the NOHD exceeds the NODD. A similar situation occurs in dusk/dawn ambient light level and the dazzle level of 40° for the blue beam. In such a situation, at the distance below the NOHD, the dazzle effect may occur simultaneously with eye damage, while at the distance between the NODD and the NOHD, the eyes may be damaged without any dazzle effect.

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