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14. Abstract

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Nominal ocular dazzle distance (NODD)

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OCIS codes: (140.3360) Laser safety and eye protection; (290.2648) Stray light; (330.4060) Vision modeling; (330.4595) Optical effects on vision.

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1. Introduction

The realm of laser eye damage is well documented, with international safety standards existing to provide guidance on safe exposure levels and appropriate eye protection requirements [1,2]. Such safety advice is built from a foundation of experimental data on laser eye damage thresholds [3] together with well-established modeling capabilities [4]. However, it is not laser eye damage but laser eye dazzle that is encountered most commonly in civilian and military domains today. The rise in power of handheld visible-wavelength laser "pointers" has been accompanied by a significant decrease in cost as demonstrated by a 5 mW green (532 nm) laser pointer costing $100 in 2003 but only $1 today, and over 1 W of power now being available for under $300 [5]. This has fueled a rising number of incidents of commercial aircraft being targeted by such devices, reported by the U.S. Federal Aviation Administration (FAA) as a 14-fold increase in laser dazzle incidents against its aircraft between 2005 (283 incidents) and 2013 (3960) [6]. Such events are of particular concern as they have the potential to cause catastrophic visual interference through pilot distraction during critical phases of flight such as takeoff and landing.

The domain of studying visual distraction by bright light sources precedes the onset of these laser dazzle events by many years. Understanding the effects of this "glare" on driving [7] and office work [8] are some of the applications that have been well characterized and understood. In such applications, the term "disability glare" is often used to describe the situation where glare reaches the point of disabling aspects of the visual task, chiefly by affecting visual detection and resolution [9]. In terms of detection, this represents the case where the contrast of a particular object has been reduced to below the eye's threshold, essentially masking it and rendering it no longer visible. In the context of this work, laser eye dazzle is defined as disability glare caused by a visible laser source.

A simple model is needed to allow the calculation of likely laser eye dazzle risks by non-experts. For laser eye damage calculations, the concept of Maximum Permissible Exposure (MPE) gives irradiance limits above which there is a risk of permanent

eye damage. The associated Nominal Ocular Hazard Distance (NOHD) translates the MPE into a safety distance for a given laser system. MPE and NOHD provide a robust framework for evaluating eye damage risks from laser systems, but no equivalents exist for eye dazzle. Only the ANSI standard for outdoor laser use [10] offers some quantitative advice, but this is not applicable universally to different applications or ambient light levels. Blick *et al.* [11] and Reidenbach [12] have advanced the understanding of laser dazzle with human experiments and simulations, but a complete model has not been the ultimate aim of their work. Such a model is required for a variety of safety applications such as for establishing acceptable exposure levels and distances for flight safety zones, informing eye protection requirements to reduce dazzle to an acceptable level during exposure, understanding the likely visual impacts during a laser dazzle event, and optimizing laser dazzler specifications to deliver the desired effects at the safest possible laser irradiance. This work aims to achieve these goals by simplifying and collating previously reported models and proposing two new calculations—Maximum Dazzle Exposure (MDE) and Nominal Ocular Dazzle Distance (NODD)—to complement existing standards for laser eye damage.

2. Scatter within the Human Eye

Fundamental to the understanding of laser eye dazzle is an understanding of the scatter experienced by light incident upon the eye. If laser light propagates perfectly from our cornea through to our retina, we would only experience a very small saturated spot in our vision that would obscure the appearance of the laser aperture itself—our vision around this spot might be completely unaffected. In reality, before laser light is detected by the retina, it encounters a number of scattering sources internal to the eye, which collectively produce intraocular scatter. This scatter serves to spatially spread out the illumination on the retina, directing photons across angles beyond the retinal image of the light source itself.

Intraocular scatter is caused by spatial variations in refractive index within the optical media [13] and occurs primarily during transmission through the eye's cornea and lens, and via reflections from the retina, which can be absorbed by different retinal areas [14–16]. There is also a smaller contribution from the ocular wall [17], comprising the sclera and the iris.

These internal scatter sources give rise to unfocused light, manifesting as glare across the scene, which is commonly referred to as "straylight." The levels of straylight are variable for individuals, with some common factors such as increased scatter with age, primarily because of yellowing of the lens [18], and reduced scatter experienced by individuals with dark-colored eyes, owing to greater pigment absorption and reduced ocular wall transmission [17,18].

In this work, human eye scattering is modeled by the standard CIE equations developed by Vos *et al.*

[19], but is calibrated with experimental data from laser exposures reported previously by the authors [20]. Internationally accepted standard equations for intraocular scatter have been developed over a period of almost 100 years. They have evolved from the simplistic Stiles–Holladay relation [21–24], which had limited angular coverage and no age or pigmentation dependence. This was initially refined to increase its accuracy at angles less than 5 degrees [25,26], and then extended to account for age and pigmentation [9,27,28]. The resulting "CIE General Disability Glare Equation" (sr^{-1}) is [19]

$$g_{\text{eye}}(\theta, A, p) = \frac{10}{\theta^3} + \left[\frac{5}{\theta^2} + \frac{0.1p}{\theta}\right]\left[1 + \left(\frac{A}{62.5}\right)^4\right] + 0.0025p, \quad (1)$$

where θ is the angle between the glare source and the line of sight $(0.1° < \theta < 100°)$, A is the age of the individual (years), and p is an eye pigmentation factor $(p = 0$ for black, 0.5 for brown, 1.0 for light, and 1.2 for very light eyes).

Previous work by the authors [20] has shown that this equation tends to overestimate laser eye dazzle effects at low ambient light levels $(<1 \text{ cd} \cdot \text{m}^{-2})$, and to underestimate them at higher ambient light levels $(>1 \text{ cd} \cdot \text{m}^{-2})$. Two calibration factors, S_1 and T_1, derived by this earlier work are therefore applied to the eye scatter function as follows:

$$f_{\text{eye}}(\theta, A, p, L_b) = S_1 L_b^{T_1} g_{\text{eye}}(\theta, A, p), \quad (2)$$

where L_b is the background luminance $(\text{cd} \cdot \text{m}^{-2})$, the values for S_1 and T_1 are given in Table 1, and f_{eye} is in units of sr^{-1}.

It is assumed that the equations are independent of pupil size, which has been shown to be a good approximation [29].

Figure 1 illustrates some example eye scatter functions in dawn/dusk conditions $(L_b = 10 \text{ cd} \cdot \text{m}^{-2})$ using Eq. (2). It can be seen that age has the strongest dependence at small angles $(<10°)$ as a 30 year old experiences considerably less scatter than a 70 year old. This shows why glare affects us more as we age, manifested by night driving becoming increasingly troublesome because of the scatter from oncoming headlights [28]. Beyond 10° the effects of pigmentation are increasingly significant, as dark eyes experience less scatter than very light eyes. For this example case, beyond around 35° degrees, eye pigmentation becomes more significant than age, as shown by the scatter for a 70 year old with black

Table 1. Calibration Factors for the Eye Scatter Equation

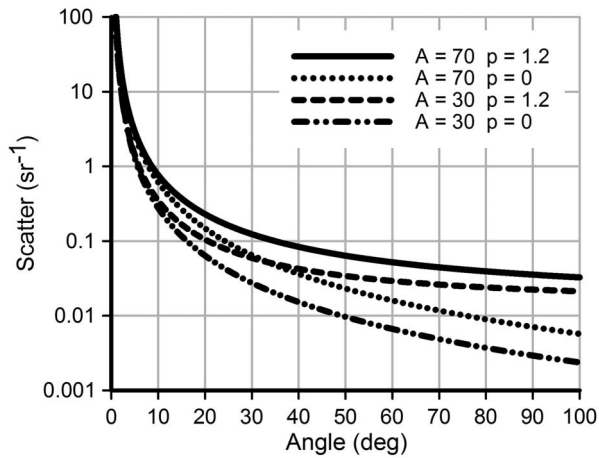| S_1	T_1
0.9239	0.6795

Fig. 1. Example eye scatter functions.

eyes being less than that of a 30 year old with very light eyes.

The work by Coppens *et al.* [31] has provided evidence that there is a wavelength dependence of straylight within the human eye, characterized by a Rayleigh λ^{-4} relationship with darker eyes. However, for lighter eyes this wavelength dependence is counteracted by the pigmentation contribution to the scatter function. The Coppens *et al.* study was conducted at only five different wavelengths and only in the central portion of the eye's response (457–625 nm). The present authors have chosen to implement a wavelength-independent eye scatter equation at the current time owing to the limitations of the Coppens data set. However, an extension to this model should be considered in future revisions as further experimental data become available.

3. Impact of Laser Scatter

With the intraocular scatter function now defined, it is possible to look at how laser scatter translates into dazzle within the eye and how that dazzle affects human performance.

A. Equivalent Veiling Luminance from a Laser Source

A light source at an angle θ with the eye's viewing direction produces an illuminance of E_l (lux or $\text{lm} \cdot \text{m}^{-2}$) at the front of the eye, causing a light veil on the retina with luminance L_v ($\text{cd} \cdot \text{m}^{-2}$) that reduces the contrast of the retinal image. This "equivalent veiling luminance" [26] represents dazzle for our purposes. These two quantities are related to the scatter function by the simple equation

$$f_{\text{eye}} = \frac{L_v}{E_l}. \tag{3}$$

To find the equivalent veiling luminance caused by a laser source requires knowledge of the appropriate scatter function together with the laser illumination in units of lux. Lasers are most commonly characterized by their power in watts or their irradiance in $\text{W} \cdot \text{m}^{-2}$, which can be converted to illuminance by use of the following equation:

$$E_l = 683 V_\lambda U, \tag{4}$$

where V_λ is the eye's photopic efficiency at the laser wavelength, λ, and U is the laser irradiance at the observer in $\text{W} \cdot \text{m}^{-2}$. The factor of 683 is the lumens per watt at 555 nm for photopic vision—the wavelength at which $V_\lambda = 1$ [30]. The resulting units of E_l are $\text{lm} \cdot \text{m}^{-2} = \text{lux}$.

Substituting Eq. (4) into Eq. (3) and then rearranging, the equivalent veiling luminance, L_v ($\text{cd} \cdot \text{m}^{-2}$), caused by a laser source is given by

$$L_v = f_{\text{eye}} 683 V_\lambda U. \tag{5}$$

B. Contrast Reduction

Figure 2 illustrates the impact of laser dazzle on the contrast of a target. For the illustrated case of positive contrast (i.e., the target luminance, L_t, is greater than the background luminance, L_b), the contrast without a laser present can be represented by the standard Weber contrast as follows:

$$C_{\text{orig}} = \frac{L_t - L_b}{L_b}. \tag{6}$$

For the situation where a laser is present, both the target and the background luminance are increased by the equivalent veiling luminance of the laser source, L_v, and the resulting contrast within the eye, C_v, becomes

$$C_v = \frac{(L_t + L_v) - (L_b + L_v)}{L_b + L_v} = \frac{L_t - L_b}{L_b + L_v} = \frac{L_b C_{\text{orig}}}{L_b + L_v}. \tag{7}$$

It can be seen that the effect of the veiling glare is to reduce the contrast by a factor of $L_b/(L_b + L_v)$. This highlights the strong dependence of the severity of laser dazzle on the ratio of the ambient luminance to the laser irradiance (and its resulting veiling luminance).

C. Human Performance Impact

This study uses the Adrian model of target visibility [32] to assess the impact of laser dazzle on human performance. The eye's threshold contrast for the detection of a target depends on the background luminance, L_b, and the angular size, α (deg), of the
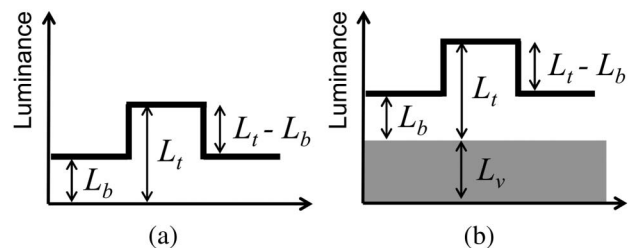

Fig. 2. Background, L_b, and target, L_t, luminance levels (a) in the absence of laser dazzle and (b) in the presence of laser dazzle with an equivalent veiling luminance, L_v.

Table 2. Lookup Table for Values of Ω Given L_b and α

| α (deg) | L_b (cd·m^{-2}) | | | | | | | | |
	0.0001	0.001	0.01	0.1	1	10	100	1000	10,000
0.01	3437.1	767.91	118.91	17.463	4.9341	1.6964	1.0151	0.9843	1.2305
0.1	38.400	9.1085	1.6274	0.2916	0.0951	0.0441	0.0305	0.0280	0.0303
0.2	10.784	2.7099	0.5487	0.1141	0.0409	0.0223	0.0165	0.0148	0.0149
0.5	2.3604	0.6775	0.1762	0.0469	0.0192	0.0128	0.0101	0.0089	0.0083
1	0.9098	0.3011	0.0978	0.0310	0.0137	0.0102	0.0083	0.0072	0.0065
2	0.4390	0.1694	0.0672	0.0243	0.0113	0.0090	0.0075	0.0065	0.0057
5	0.2379	0.1084	0.0516	0.0207	0.0100	0.0083	0.0070	0.0060	0.0052
10	0.1845	0.0911	0.0469	0.0195	0.0096	0.0081	0.0069	0.0059	0.0051
20	0.1603	0.0830	0.0446	0.0190	0.0094	0.0080	0.0068	0.0058	0.0050
30	0.1526	0.0804	0.0438	0.0188	0.0093	0.0079	0.0068	0.0058	0.0050
40	0.1489	0.0791	0.0435	0.0187	0.0093	0.0079	0.0068	0.0058	0.0050

target. Adrian fitted equations to a vast array of human subject trial data to replicate the average contrast threshold, C_{thr}, for detection according to the following equation:

$$C_{\mathrm{thr}}(L_b, \alpha, A) = \Omega \mathrm{AF}, \qquad (8)$$

$$\Omega(L_b, \alpha) = \frac{2.6\left(\frac{\phi(L_b)}{60\alpha} + L(L_b)\right)^2}{L_b}; \qquad (9)$$

for $23 < A < 64$, $\qquad \mathrm{AF}(A) = \frac{(A-19)^2}{2160} + 0.99;$
$$(10)$$

for $64 < A < 75$, $\qquad \mathrm{AF}(A) = \frac{(A-56.6)^2}{116.3} + 1.43,$
$$(11)$$

where AF is an age adjustment factor to account for the decrease in contrast threshold with age, A (years), and Ω contains the factors ϕ and L, which depend on the background luminance as given by

for $L_b \geq 0.6$ cd·m^{-2}
$$\phi = \log(4.1925 L_b^{0.1556}) + 0.1684 L_b^{0.5867}, \quad (12)$$

$$L = 0.05946 L_b^{0.466}; \qquad (13)$$

for $0.00418 < L_b < 0.6$
$$\phi = 10^{-0.072 + 0.3372 \log L_b + 0.0866 (\log L_b)^2}, \quad (14)$$

$$L = 10^{-1.256 + 0.319 \log L_b}; \qquad (15)$$

for $L_b \leq 0.00418$
$$\phi = 10^{0.028 + 0.173 \log L_b}, \qquad (16)$$

$$L = 10^{-0.891 + 0.5275 \log L_b + 0.0227 (\log L_b)^2}. \qquad (17)$$

For convenience in calculations, values for Ω and AF are provided in Table 2 and Table 3, respectively. For worst case scenario calculations (i.e., maximizing the extent of the dazzle), the value of L_b and α should be rounded down to the closest values in the table, and A should be rounded up to the nearest value. While Adrian's model was not validated above background luminance values of 1000 cd·m^{-2}, it is assumed here that the estimates above 1000 cd·m^{-2} are reasonable.

In order for laser dazzle to obscure a target in the scenario illustrated in Fig. 3, the equivalent veiling luminance of the laser source must be sufficient to reduce the contrast of the target to just below its detection threshold contrast. For calculation purposes, we will take this as the case where L_v causes the contrast, C_v, to be equal to C_{thr}. Equating and rearranging Eqs. (7) and (8) gives

$$C_v = C_{\mathrm{thr}},$$

$$\frac{L_b C_{\mathrm{orig}}}{L_b + L_v} = \Omega \mathrm{AF},$$

$$\Rightarrow L_v = \frac{L_b C_{\mathrm{orig}}}{\Omega \mathrm{AF}} - L_b. \qquad (18)$$

For simplicity, the eye's threshold contrast for detection before laser illumination [where the background luminance in Eq. (8) is L_b] is applied to the situation after laser illumination, where,

Table 3. Lookup Table for Values of AF Given A

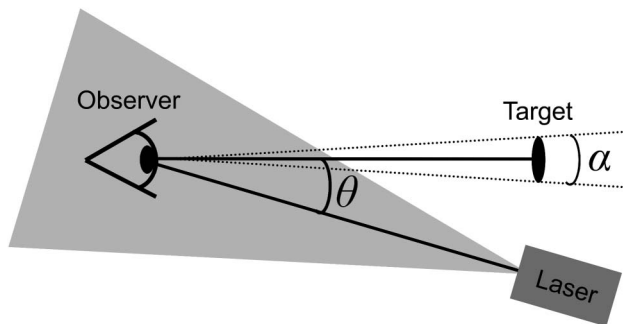| A	AF
≤ 23	1.000
25	1.007
30	1.046
35	1.109
40	1.194
45	1.303
50	1.435
55	1.59
60	1.768
65	2.037
70	2.974
75	4.341

Fig. 3. A schematic of a laser dazzle scenario with the observer on the left experiencing dazzle from the laser on the right. The target to be detected is represented by the solid ellipse with an angular size of α (deg). At a laser offset angle θ (deg), the target contrast is reduced to the eye's detection contrast threshold, C_{thr}, for this target for the given ambient luminance and laser-induced veiling luminance. At angles less than θ, the target is obscured from view and so θ represents the extent of obscuration for the target. θ is a half-angle as it applies equally to both sides of the laser axis, meaning the total obscuration spans 2θ.

strictly speaking, L_b in this equation should be replaced by $L_b + L_v$.

The equations presented here are for a 2 s or greater viewing time and are applicable to positive-contrast targets (i.e., the target is brighter than the background). They are valid for photopic, mesopic, and scotopic vision as they are based on experimental data acquired across these light levels. The threshold contrast is greater for shorter viewing times according to additional equations provided by Adrian. However, to reduce complexity, this additional factor has been ignored. Adrian also gave an adjustment for positive contrast, which is again neglected for simplicity.

4. Calculations

A. Maximum Dazzle Exposure

We propose a new value to be known as the Maximum Dazzle Exposure (MDE). The MDE is the threshold laser irradiance at the eye below which a given target can be detected. It can also be used as a measure of the minimum laser irradiance required to obscure a given target. This supplements the MPE, which determines the safe level of laser irradiance below which there is no risk of permanent eye damage. The MDE is applicable for continuous-wave laser sources and may also be calculated for the average power of repetitively pulsed laser sources.

The MDE in $W \cdot m^{-2}$ for a given target can be derived by equating L_v in Eqs. (5) and (18) and rearranging as follows:

$$f_{\text{eye}}683V_\lambda U = \frac{L_b C_{\text{orig}}}{\Omega AF} - L_b,$$

$$\Rightarrow \text{MDE} = U_{\text{threshold}} = \frac{\left(\frac{L_b C_{\text{orig}}}{\Omega AF} - L_b\right)}{f_{\text{eye}}683V_\lambda}. \quad (19)$$

To provide some general guidance as to the threshold laser irradiance for the obscuration of a target, Eq. (19) has been applied to a set of input parameters (Table 4) for a range of three ambient luminance levels (night, $0.01 \text{ cd} \cdot m^{-2}$; dawn/dusk, $10 \text{ cd} \cdot m^{-2}$; and day, $10,000 \text{ cd} \cdot m^{-2}$), two laser wavelengths (green, 532 nm, and red, 635 nm), and four obscuration angles (1 deg, 5 deg, 10 deg, and 20 deg). In all cases, the MPE should also be evaluated and should be taken as the exposure limit to prevent eye damage. Table 5 shows the results of the MDE calculations and denotes MDE values greater than $2546 \text{ μW} \cdot \text{cm}^{-2}$ as exceeding the 0.25 s MPE for visible lasers [1,2].

From these calculations, it can be seen that large obscuration angles (over 20 degrees) can be achieved at night luminance levels with around $10 \text{ μW} \cdot \text{cm}^{-2}$ of green or $50 \text{ μW} \cdot \text{cm}^{-2}$ of red laser irradiance. However, in dawn/dusk conditions, around $75 \text{ μW} \cdot \text{cm}^{-2}$ of green or $300 \text{ μW} \cdot \text{cm}^{-2}$ of red is required to achieve obscuration over just a 5 degree extent. At daytime luminance levels, only very small obscuration angles are possible without potentially damaging the levels of irradiance being required.

B. Nominal Ocular Dazzle Distance

We propose a new laser safety calculation to be known as Nominal Ocular Dazzle Distance (NODD). The NODD is the minimum distance for the visual detection of a target in the presence of laser dazzle. It also represents the maximum effective range of a laser dazzle system designed to prevent the visual detection of a target. This supplements the NOHD, which determines the range at which a laser can be viewed without the risk of permanent eye damage.

For a given laser system, the NODD is the range at which the laser irradiance matches the MDE for a given scenario. The average irradiance, U ($W \cdot m^{-2}$), for a circular laser beam at a range R (km) is given by

$$U(R) = \frac{\text{total power}}{\text{beam area}} = \frac{P}{\pi(R \cdot d/2)^2}, \quad (20)$$

where P (W) is the laser power at its source and d (mrad) is its divergence; atmospheric attenuation and the initial beam size are ignored. Setting U to be the MDE and R to be the NODD, this equation can be rearranged to give the following simple relationship:

$$R_{\text{NODD}} = \sqrt{\frac{4P}{\pi d^2 \text{MDE}}}. \quad (21)$$

Table 4. Input Parameters for the Example MDE Calculations

Parameter		Value	Units
Age	A	40	Years
Eye pigmentation	p	0.5	—
Target size	α	1.0	deg
Target contrast	C_{orig}	0.8	—

Table 5. Calculated MDE Values (Laser Irradiances) in $\mu W \cdot cm^{-2}$ required to Obscure a 1 Degree Target of 0.8 Contrast from a 40 Year Old with Brown Eyes

Obscuration Angle from Laser, θ (deg)	Laser Wavelength λ (nm)	Maximum Dazzle Exposure ($\mu W \cdot cm^{-2}$)		
		Night (L_b) 0.01 cd $\cdot$ m^{-2}	Dawn/Dusk 10 cd $\cdot$ m^{-2}	Day 10,000 cd $\cdot$ m^{-2}
1	532	<1	2	22
	635	<1	6	90
5	532	1	75	1075
	635	3	304	>MPE
10	532	3	322	>MPE
	635	13	1314	>MPE
20	532	12	1215	>MPE
	635	49	>MPE	>MPE

This equation can be used to calculate the NODD from a given MDE together with the laser power and divergence, and it has the same form as the standard equation commonly used to calculate the NOHD from the MPE [2]. The calculated NODD represents the minimum distance at which a target of size α can be detected beyond an angular extent of θ from a dazzling laser source. θ represents the maximum obscuration extent, and at the NODD, the target cannot be detected at angles less than θ.

To include an approximation of the atmospheric attenuation of the laser beam, the NODD can be adjusted as follows [33]:

Table 6. Typical Atmospheric Parameters

Description	Visibility (km)	Extinction Coefficient (km^{-1})
Very clear	30	0.1
Clear	15	0.2
Light haze	5	0.6
Haze	3	1.0

Table 7. Additional Parameters for the Example NODD Calculations

Parameter		Value	Units
Laser power	P	100	mW
Laser divergence	d	2	mrad
Visibility	V	15	km

$$R_{\text{NODD}\beta} = 0.5 \cdot R_{\text{NODD}} \cdot (1 + e^{-\beta \cdot R_{\text{NODD}}}), \qquad (22)$$

where β is the atmospheric extinction coefficient in km^{-1}. The extinction coefficient determines the overall attenuation of the incident light caused by the scattering and absorption of the atmosphere, and is specific to the scenario being modeled. While β does have wavelength dependence [34], for application to Eq. (22) it can be calculated from the simplified equation [35]

$$\beta = \frac{3}{V}, \qquad (23)$$

where V is the meteorological visibility (km). Typical values for V and β are given in Table 6, adapted from the International Visibility Code [34].

To provide some general guidance as to the minimum distance to detect a target in the presence of laser dazzle, Eq. (22) has been applied to the MDE values generated in Table 5 using the additional input parameters from Table 7. Table 8 shows the resulting calculated NODD values, including the effects of atmospheric attenuation. Where the MDE was found to be greater than the MPE, in this case the NODD would be shorter than the NOHD and should therefore be ignored.

From these calculations, it can be seen that the laser system being evaluated, representative of a moderately powered handheld laser pointer, can have a laser dazzle effect at significant ranges at nighttime ambient luminance levels. A 5° angle of obscuration

Table 8. Calculated NODD Values (km) for the Obscuration of a 1 Degree Target of 0.8 Contrast from a 40 Year Old with Brown Eyes, for Laser Power of 100 mW and a Divergence of 2 mrad, in an Atmosphere with 15 km Visibility

Obscuration Angle from Laser, θ (deg)	Laser Wavelength λ (nm)	Nominal Ocular Dazzle Distance (km)		
		Night (L_b) 0.01 cd $\cdot$ m^{-2}	Dawn/Dusk 10 cd $\cdot$ m^{-2}	Day 10,000 cd $\cdot$ m^{-2}
1	532	7.67	1.26	0.37
	635	4.45	0.67	0.19
5	532	1.73	0.20	0.05
	635	0.94	0.10	<NOHD
10	532	0.91	0.10	<NOHD
	635	0.47	0.05	<NOHD
20	532	0.49	0.05	<NOHD
	635	0.25	<NOHD	<NOHD

from the laser axis can be achieved at almost 2 km for a green laser and around 1 km for a red laser of the same 100 mW power level. Larger 20° angles of obscuration are possible out to around 0.5 km for green and 0.25 km for red. At dawn/dusk light levels, these effective ranges are approximately 10 times less, whereas at daytime light levels, even the smallest 1° obscuration can only be achieved at 0.37 km for green and 0.19 km for red. 5° (red only), and 10° and 20° (both red and green) obscuration extents are not achievable during the day without the laser being closer than the NOHD.

C. Angular Extent of Obscuration for a Given Laser

The angle of obscuration, θ, for a given laser that delivers an irradiance U to the target can be derived by equating L_v in Eqs. (5) and (18) and rearranging as follows:

$$f_{\text{eye}}(\theta)683V_\lambda U = \frac{L_b C_{\text{orig}}}{\Omega AF} - L_b,$$

$$\Rightarrow f_{\text{eye}}(\theta) = \frac{\left(\frac{L_b C_{\text{orig}}}{\Omega AF} - L_b\right)}{683V_\lambda U}. \quad (24)$$

Finding the angle of obscuration requires Eq. (24) to be solved by any of the following methods:

- A computer-based solving routine using a spreadsheet or mathematical software.
- Plotting a graph of $f(\theta)$ against θ and finding the angle at which the result matches the calculated value on the right side of the equation.
- Calculating $f(\theta)$ for a variety of θ values and then reading off the closest match to the desired value.

Table 9 shows the calculated obscuration angles for the example case defined by the input parameters in Tables 4 and 7, with an observer range, R, of 0.1 km. The 100 mW laser creates an extensive obscuration angle at the 0.1 km observation range for nighttime ambient luminance levels, exceeding 100° for a green laser and being around 75° for a red laser. These extents would completely obscure the vision of the observer and render the target detection task impossible. At dusk light levels, the obscuration half-angles are reduced to around 10° and 5° for green and red lasers, respectively, which represents a much more moderate level of obscuration.

Table 9. Calculated Angular Obscuration Extent (deg) for viewing at 0.1 km Range a 1 Degree Target of 0.8 Contrast by a 40 Year Old with Brown Eyes, for Laser Power of 100 mW and a Divergence of 2 mrad, in an Atmosphere with 15 km Visibility

Laser Wavelength λ (nm)	Obscuration Extent (deg)		
	Night (L_b) 0.01 cd·m⁻²	Dawn/Dusk 10 cd·m⁻²	Day 10,000 cd·m⁻²
532	>100	9.9	2.9
635	74.1	5.1	1.6

During the day, only angles of a few degrees can be obscured for this case.

5. Sensitivity Analysis

In order to understand the most important input parameters to the model, a sensitivity analysis of the NODD calculation has been performed. In Table 10, a set of "baseline" input parameters has been defined together with associated values that would cause less dazzle than the baseline case and therefore reduce the NODD, as well as values that would cause more dazzle and increase the NODD. For each parameter, the choice of upper and lower limits is set to represent possible uncertainties of estimated values, or possible spreads in the population of individuals being exposed to laser dazzle.

The NODD for the baseline case (1.73 km) was taken as the reference NODD, and then each parameter was individually varied to its extreme values to allow two further NODDs to be calculated. This was repeated for all parameters, with the outputs expressed in Table 11 as percentages greater (+) or less than (−) the baseline NODD. Finally, for each parameter the difference in kilometers between the lowest NODD and the highest NODD was calculated and the results table was sorted in order of the largest spread of calculated NODDs.

Table 10. The "Less Dazzle," "Baseline," and "More Dazzle" Input Parameters used in the Sensitivity Analysis

Parameter		Less	Baseline	More	Units
Age	A	30	40	50	Years
Eye pigmentation	p	0.0	0.5	1.2	—
Target size	α	2.0	1.0	0.5	deg
Target contrast	C_{orig}	1.0	0.8	0.6	—
Ambient luminance	L_b	0.100	0.010	0.001	cd·m⁻²
Obscuration extent	θ	7	5	3	deg
Laser wavelength	λ	512	532	552	nm
Laser power	P	50	100	200	mW
Laser divergence	d	4	2	1	mrad
Visibility	V	5	15	30	km

Table 11. Calculated NODD Spreads for the Sensitivity Analysis

Parameter	NODD Spread (km)	Less Dazzle	Baseline	More Dazzle
Ambient luminance	3.46	−59%		+141%
Laser divergence	2.05	−45%	↑	+73%
Obscuration extent	1.48	−27%		+59%
Laser power	1.01	−26%	1.73 km	+33%
Target size	0.89	−17%		+35%
Visibility	0.55	−22%	↓	+9%
Target contrast	0.44	−10%		+15%
Age	0.44	−9%		+16%
Laser wavelength	0.41	−19%		+5%
Eye pigmentation	0.07	−2%		+4%

The results highlight that, for this specific baseline condition, the most important input parameters to ensure an accurate NODD calculation are the ambient luminance, laser divergence, obscuration extent, laser power, and target size. For this case, it appears that the accuracies of the other parameters are less crucial, although it should be stressed that the importance of parameters will vary depending on the baseline case chosen.

Figure 4 highlights this fact by showing how the NODD changes when varying only a single parameter from the baseline inputs. The dashed vertical lines on the plots bound the extremes of the "less" and "more" dazzle cases, and it can be seen that these straddle regions of the graphs with a high rate of change of the NODD for the ambient luminance and laser power graphs presented. This means that a relatively small change in these input parameters can yield a relatively large change in the NODD for this particular test case. However, it can also be seen that the NODD calculation is not as sensitive to the observer's age and the laser wavelength as these parameters are in relatively flat regions of the NODD change for the given test case. If the age of the observer was (60 ± 10) years, or if the laser wavelength was (500 ± 20) nm, for example, then the accuracy of these parameters would have more significance for the given NODD calculations.

6. Discussion and Future Development

A simple model of laser eye dazzle effects has been presented to fill a gap in existing laser safety advice. The model permits a non-expert user to estimate laser eye dazzle effects in a range of scenarios using mathematics that can be computed on a basic pocket calculator. The Maximum Dazzle Exposure (MDE) has been introduced as quantifying the threshold laser irradiance below which a given target can be detected. The Nominal Ocular Dazzle Distance (NODD) has been introduced to calculate the minimum distance from a laser system for the visual detection of a target.

Example calculations have been presented to show the utility of the MDE and NODD concepts as complimentary parameters to existing MPE and NOHD calculations that quantify the risks of permanent eye damage. It is acknowledged that these new calculations are inherently more complex, requiring not only a few readily quantifiable laser source parameters, but also several inputs regarding the visual environment. Therefore, although the calculations are accessible to non-experts, it is important to provide users with careful guidance to ensure that they are applied correctly.

Calculated MDE values can be used to specify exposure limits to ensure that personnel can still perform their duties in the presence of laser dazzle, or, alternatively, they can drive the requirements of laser dazzle systems by indicating the irradiance needed to achieve a particular effect. Similarly, NODD calculations can be used to specify safety distances around laser systems for individuals to operate without laser dazzle affecting their performance, or, alternatively, they can indicate the effective range of a laser dazzle system.

The calculation of the angular extent of obscuration for a given laser system has also been presented and could find applications in understanding the severity of visual function deficit caused by laser dazzle systems.

The overall model represents a compromise between simplicity and accuracy, and accordingly, it leaves room for improvement in both areas. Regarding simplicity, there is scope to shield users from the more complicated MDE calculations [Eq. (19)] by presenting precalculated MDE tables for specific sets of input parameters. These would provide irradiance guidance while also allowing NODDs to be calculated for different laser systems using the more simple Eqs. (21) and (22). Such an approach presents challenges in establishing combinations of the seven input parameters to the MDE equation that can cover a suitably relevant range of scenarios.

Regarding accuracy, the authors are planning experiments to further validate the existing model and improve its precision. Human subject laser dazzle experiments are scheduled for 2014 and 2015 to provide additional data to improve the ambient luminance and laser wavelength dependencies within the model. The existing model has an ambient luminance correction factor based on the authors' previous work [20], but the aim is to provide additional data at a wide
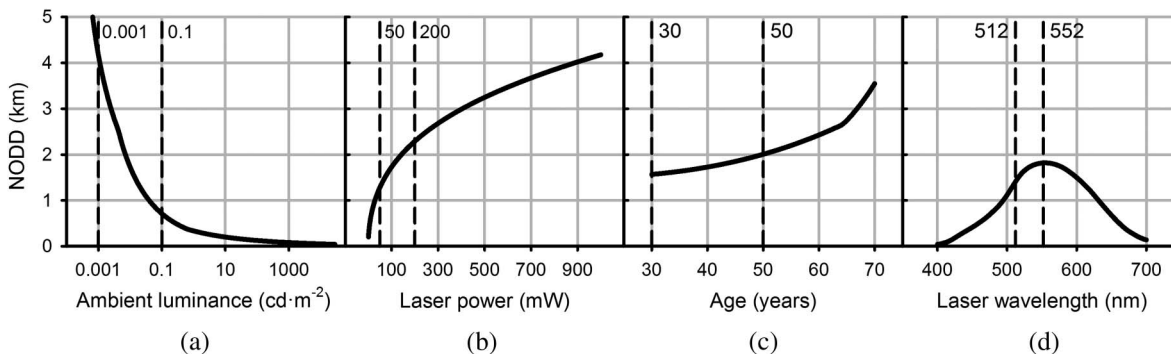

Fig. 4.   Graphs of NODD versus input parameters for the "baseline" case. (a) Ambient luminance, (b) laser power, (c) observer age, and (d) laser wavelength.

range of ambient luminance levels to further strengthen this factor. In terms of laser wavelength dependence, the authors' own experiences indicate that the photopic efficiency function used in this model is not a perfect method for accounting for the wavelength dependence of laser eye dazzle effects. Therefore, human exposures at a range of visible wavelengths will be used to derive a modified photopic efficiency function for this application.

Beyond these planned refinements is a desire to extend the relevance of the model in a number of ways. The current model has a static target detection paradigm, which could be extended to allow task complexity to be accounted for, perhaps incorporating more challenging tasks such as target identification or moving targets. Extraocular scattering sources (those external to the human eye) could also be included to account for other factors in the overall laser eye dazzle problem such as scatter from transparencies (e.g., car windshields or aircraft cockpit canopies), the atmosphere, and eyewear (e.g., spectacles or contact lenses). Including the effects of after-images would also be beneficial to determine the persistence of visual obscuration after the laser exposure has ceased.

The aforementioned simplifications, refinements, and extensions to the initial model are key to giving confidence in its accuracy and relevance. This is essential if the concepts of MDE and NODD presented herein are to be adopted more widely among the laser community.

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