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Laser Safety And Hazardous Analysis For The ARES (Big Sky) Laser System

Arnold L. Augustoni

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Laser Safety And Hazardous Analysis For The ARES (Big Sky) Laser System

Arnold L. Augustoni
Lasers, Optics & Remote Sensing Department
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-1423

Abstract

A laser safety and hazard analysis was performed for the ARES laser system based on the 2000 version of the American National Standards Institute's (ANSI) Standard Z136.1, *for Safe Use of Lasers* and the 2000 version of the ANSI Standard Z136.6, *for Safe Use of Lasers Outdoors*. The ARES laser system is a Van/Truck based mobile platform, which is used to perform *laser interaction* experiments and tests at various national test sites.

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Figure 1

ARES Van

I. Introduction

The ARES laser system is a portable LIDAR system utilizing a Class 4 tripled-YAG laser to perform various interaction tests and experiments at varying distances from the laser. The laser is mounted in a van but can be configured to other platforms. The laser has two basic modes of operations: scanning mode and a "point and stare" mode.

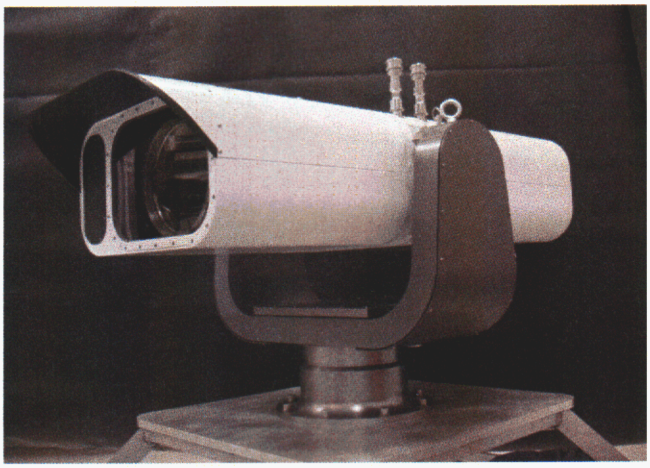


Figure 2

ARES LIDAR

Modes of Operations

Scanning Mode

The scanning mode sweeps the laser beam through a 90-degree arc along the horizontal axis at varying sweep rates (0 to 5 degrees per second).

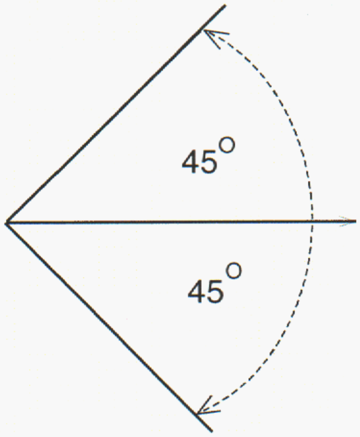


Figure 3

Angular scan range.

Point and Stare

The "point and stare" mode directs the laser beam to a fixed point in space for varying exposure durations.

II. Laser Parameters

Big Sky Laser

	Laser	Telescope
Model Number:	CFR-200	
Wavelength:	355 nm	
Radiant Output:		
Maximum	20 mJ	
Typical Operational	15 mJ	
Alignment (high)	6 mJ	
Alignment (low)	1 mJ	
Pulse Duration:	13 x 10^{-9} seconds	
Pulse Repetition Frequency:	30-50 Hz	
Exit Diameter:	0.63 centimeters	1.25 centimeters
Beam Divergence:	~ 1 milliradians	500 microradians
Gimbal Scanner:		
Angular Range (max)		± 45 degrees
Elevation Range (max)		± 20 degrees
Rate of Scan		0 to 5 degrees / second
Retrace Rate		20 degrees / second

III. Laser Safety and Hazard Analysis

Outdoor Operations

All laser operations outdoors, involving lasers exceeding the Class 3a Allowable Emission Limit (AEL) must have a laser hazard analysis performed [ANSI Std. Z136.6-2000 (3.3.1)]. Central to a laser hazard analysis is the determination of the appropriate Maximum Permissible Exposure, the Allowable Emission Limit and the "limiting aperture". All of which, to varying degrees, are wavelength dependent.

Maximum Permissible Exposure

The appropriate Maximum Permissible Exposure (MPE) for repetitively pulsed lasers is always the **smallest** of the MPE values derived from ANSI Rules 1 through 3 [ANSI Std. Z136.1-2000 (8.2.3)]. Rule 1 pertains to a single pulse exposure. Rule 2 pertains to the average power for thermal or photochemical hazards per pulse and Rule-3 pertains to the multiple-pulse, thermal hazard [ANSI Std. Z136.1-2000 (8.2.3)].

Ocular versus Skin Exposures

Throughout the ultraviolet region of the spectrum the ocular MPE is always less than or equal to the MPE for skin (*Table 5a* versus *Table 5b* of the ANSI standard). The consequence of an ocular exposure, with a resulting possible blindness, is far more severe than the consequence for a skin exposure ("skin burn"), which is more readily recoverable. Consequently, the following analysis will pertain to the MPE for ocular exposure. Keeping in mind; however, that personnel within the NHZ should always protect their skin through the use of adequate clothing and the application of sunscreen products on their exposed skin.

Unauthorized exposure of personnel who enter the NHZ will likely involve an over-exposure of both unprotected skin as well as to the eyes. The consequence of this over exposure will be far more severe for the eyes than for the skin. Over exposure to the skin will generally produce a burn (1^{st} or 2^{nd} degree and in extreme cases possibly a 3^{rd} degree burn) and possibly some long-term skin cancers. Generally, over exposure to the skin (burns) are recoverable. Whereas over exposure to the eye, generally, entail permanent damage, up to and including the loss of sight. As a result of these consequences it is far more important that the emphasis be placed on "eye-safety".

Persons, from the general public, entering the NHZ, unauthorized, will more likely than not have more skin protection than eye protection.

Ultraviolet Region (180 nm < λ < 400 nm)

The ultraviolet (UV) wavelength region from 180 nm to 400 nm is a "dual limit" region. The dual limits are comprised of the "**photochemical limit**" (the *left-hand* formula in *Table 5a* of the ANSI standard) and the "**thermal limit**" (the *right-hand* formula (notes) of *Table 5a* of the ANSI standard). The appropriate MPE is determined from the smallest of these dual limits [ANSI Std. Z136.1 (*Table 5a*)(notes)].

UV Region (315 nm < λ < 400 nm)

The appropriate MPE formula present in *Table 5a* of the ANSI Std. Z136.1 for laser emission wavelengths from 315 nm to 400 nm is the same for both the photochemical and thermal limits. The MPE for UV laser emission wavelengths longer than 280 nm is de-rated by a factor of 2.5 if laser exposures are expected on successive days [ANSI Std. Z136.1-2000 (8.2.3.1)]. The photochemical limit is equal to the thermal limit in this wavelength region for exposure times of 1 nanosecond to 10 seconds; however, for exposures of from 10 seconds to 30,000 seconds the only MPE form listed is for the photochemical limit and is given as: 1 J/cm^2 [ANSI Std. Z136.1-2000 (*Table 5a*)].

Expected Exposure Durations

The appropriate MPE for the UV region is strongly dependent upon the exposure duration. The appropriate exposure for the laser hazard analysis in this spectral region is the actual or expected exposure duration. For personnel who may happen to enter the "target" area the appropriate exposure is the duration of the particular lasing event. Actual exposure in the target area will also depend upon the mode of operation (scanning or the "point and stare" modes).

The typical "point and stare" mode exposure is on the order of 10 seconds (but could be as great as tens of minutes), before the laser beam is moved to the next target location within the scanning zone.

For personnel who are expected to be in the Nominal Hazard Zone (NHZ) "long term" the appropriate exposure is the accumulative exposures of each lasing event. The ANSI standard Z136.1-2000 (*Table 4a*) suggests 30,000 seconds for laser workers. The actual exposure for laser worker is expected to be much less than 30,000 seconds. The 30,000-second exposure; however, will be used to determine the appropriate MPE in order to ensure that the laser safety eyewear Optical Density (OD) is sufficiently adequate to provide the laser worker and other associated workers in the NHZ with full protection against ocular exposure. Additionally, the laser worker and associated ARES workers are expected to have successive day exposures, requiring the de-rating of the MPE by a factor of 2.5 [ANSI Std. 136.1-2000 (8.2.3.1)].

IV. <u>Laser Hazard Analysis</u>

Maximum Permissible Exposure Determination

The following MPE determination is based on a 30,000 second exposure to a 50-hertz laser (worst case). Following this analysis is presented a plot of the appropriate MPE versus exposure for durations of from 0.1 to 30,000 seconds.

Initial Exposure (Laser Worker- 8 hour exposure)

Rule 1: Single Pulse

The exposure to any pulse in a train of pulses shall not exceed the single pulse MPE [ANSI Std. Z136.1-2000 (8.2.3)(Rule 1)].

The appropriate MPE is derived from the smallest of the photochemical and thermal limits. For an exposure between 1 nanosecond and 10 seconds the photochemical limit is equal to the thermal limit. The laser pulse width is given as 13 nanoseconds.

$MPE_{s.p.}$ = min [photochemical limit, thermal limit] {Dual limit region}

= min [($0.56t^{0.25}$ J/cm^2), {$0.56t^{0.25}$ J/cm^2}] {*Table 5a* ANSI Std.}

= $0.56\ (13 \times 10^{-9})^{0.25}$ J/cm^2

$MPE_{s.p.} = 5.98 \times 10^{-3}$ J/cm^2

Rule 2: CW/Pulse

The MPE for a group of pulses delivered in time "T" shall not exceed the MPE for time "T". The MPE per pulse is the MPE for time "T" divided by the number of pulses delivered in time "T" [ANSI Std. Z136.1-2000 (8.2.3)(Rule 2)].

For the wavelength region 315 nm to 400 nm with exposures on the order of 10 to 30,000 seconds the photochemical limit MPE is defined as, "1 J/cm^2" and the **thermal limit does not apply** [ANSI Std. Z136.1-2000 (*Table 5a*)].

T = 30,000 seconds

n = PRF x T

= (50 sec^{-1}) (30 x 10^3 sec)

n = 1.5 x 10^6 pulses

$MPE_{/pulse} = MPE_{cw} / n$

MPE = 1 J/cm^2 10 sec < T < 3 x 10^4 sec {*Table 5a*}

$MPE_{/pulse}$ = [1 J/cm^2] / 1.5 x 10^6

$MPE_{/pulse} = 667 \times 10^{-9}$ J/cm^2

Rule 3: Multiple Pulses

Rule 3 protects against the sub-threshold pulse-cumulative thermal injury and pertains **only to the thermal limit** [ANSI Std. Z136.1-2000 (8.2.3)(Rule 3)].

The multiple-pulse MPE is the product of the single pulse (thermal limit) MPE and a multiple pulse correction factor (C_p). The multiple pulse correction C_p factor is a function of the number of pulses in the exposure and is presented as a formula in *Table 6* of the ANSI Z136.1 standard.

$T = 3 \times 10^4$ seconds

$MPE_{m.p.} = C_p \, MPE_{s.p.\text{-thermal}}$

$C_p = n^{-0.25}$ {*Table 6* ANSI Std.}

$= (PRF \times T)^{-0.25}$

$= [(50 \text{ sec}^{-1}) (30{,}000 \text{ sec})]^{-0.25}$

$= [1.5 \times 10^6]^{-0.25}$

$\mathbf{C_p = 0.0286}$

$MPE_{m.p.} = (0.0286) (5.98 \times 10^{-3} \text{ J/cm}^2)$

$\mathbf{MPE_{m.p.} = 171 \times 10^{-6} \text{ J/cm}^2}$

Appropriate MPE

The appropriate MPE for repetitively pulsed lasers is always the **smallest** of the MPE values derived from Rules 1 through 3 [ANSI Std. Z136.1-2000 (8.2.3)]. Rule 1 pertains to a single pulse exposure. Rule 2 pertains to the average power for thermal and photochemical hazards per pulse and Rule-3 pertains to the multiple-pulse, thermal hazard [ANSI Std. Z136.1-2000 (8.2.3)].

Table 1

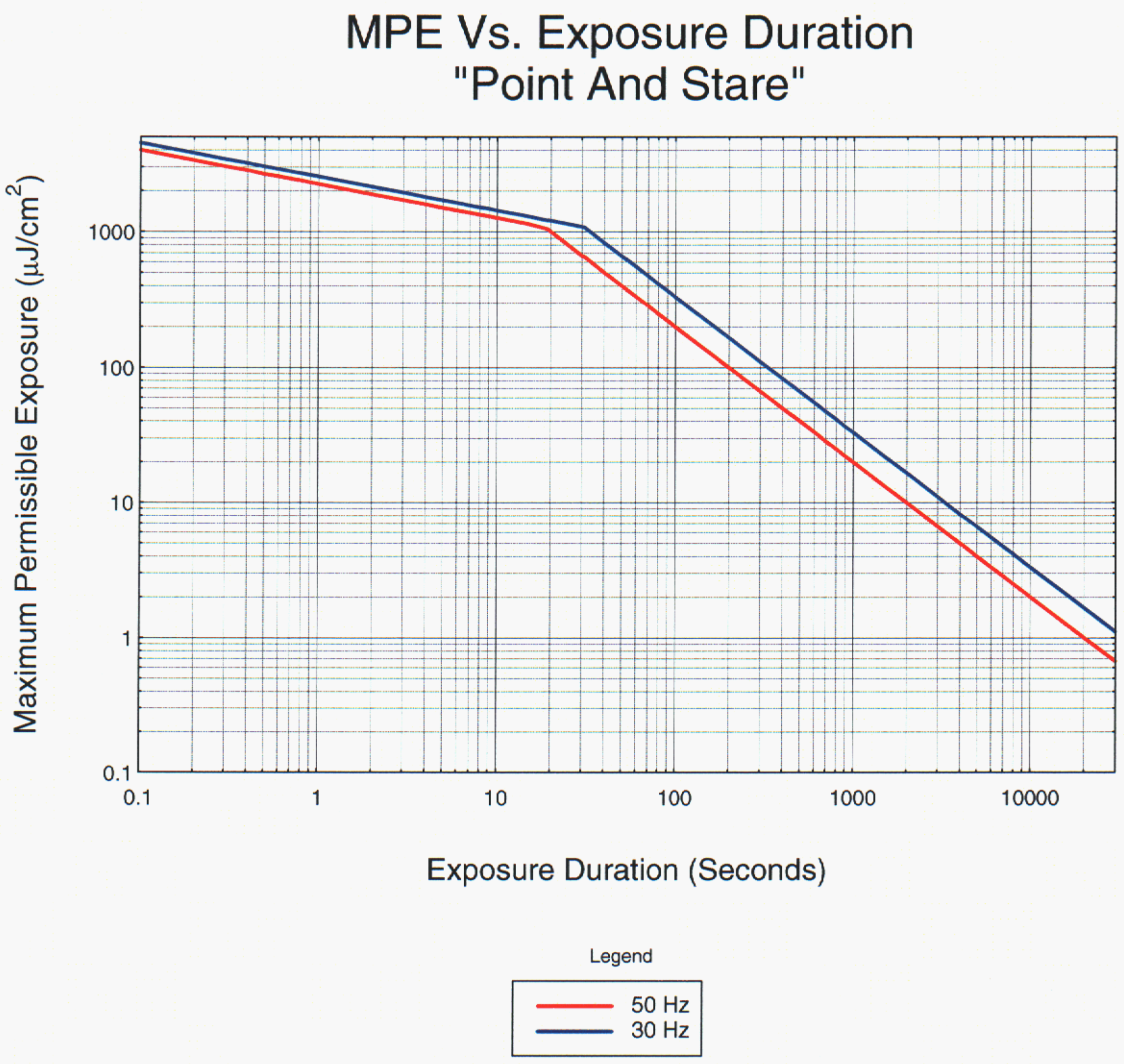
Appropriate MPE: Initial Exposure

λ = 355 nm - 30,000 Seconds @ 50 Hz

ANSI Rule	MPE **(J/cm^2)**	Comment
1	5.98×10^{-3}	
2	**667×10^{-9}**	**Appropriate MPE**
3	171×10^{-6}	

“Point And Stare” Mode of Operation

In the ultraviolet region of the spectrum the MPE is a function of the accumulative exposure time. The initial exposure MPE as a function of the accumulative exposure is plotted below for both (30 Hz and 50 Hz) Pulse Repetition Frequencies (PRF) for the “point and stare” condition.



Note that the slope of MPE curve for a PRF of 50 hertz changes at a duration of approximately 18 seconds; whereas, the slope for a PRF of 30 hertz changes at approximately 31 seconds. The change in the slope depicts the shift in the MPE from ANSI Rule 3 dominant to ANSI Rule 2 dominant.

ANSI Rule 2 – 3 Crossover Point

The MPE is always the smallest of the values derived from ANSI Rule 1 through ANSI Rule 3. For multiple pulse exposures to relatively uniform laser pulse trains the MPE will be the smallest value derived from ANSI Rule 2 and ANSI Rule 3. Initially ANSI Rule 3 will yield the smallest MPE value until a certain exposure where the MPE value derived from ANSI Rule 3 is equal to the value derived from ANSI Rule 2. This point of equality is referred to as the Rule 2-3 crossover point or simply the exposure "crossover point". For exposures greater than this crossover point exposure the MPE is derived from ANSI Rule 2.

Determination Of Crossover Point

The number of pulses (n_x) needed to reach the exposure crossover point can be found as follows:

$$MPE_{rule\ 3} = MPE_{rule\ 2}$$

$$C_p\ MPE_{thermal} = MPE_{cw} / n_x$$

$$n_x^{-0.25}\ MPE_{thermal} = MPE_{cw} / n_x$$

$$n_x^{0.75} = MPE_{cw} / MPE_{thermal}$$

$$\mathbf{n_x = [MPE_{cw} / MPE_{thermal}]^{4/3}}$$

For a laser pulsewidth (t_p) of 13 nanoseconds at wavelength of 355 nm:

$$n_x = [MPE_{cw} / MPE_{thermal}]^{4/3}$$

From ANSI Std. Z136.1-2000, Table 5a:

$$n_x = [(1\ J/cm^2) / (0.56\ t_p^{0.25}\ J/cm^2)]^{4/3}$$

$$n_x = [(1\ J/cm^2) / (0.56\{13 \times 10^{-9}\}^{0.25}\ J/cm^2)]^{4/3}$$

$$\mathbf{n_x = 921\ pulses}$$

The time to the exposure crossover point (T_x) can be determined as follows:

$$T_x = n_x / PRF$$

<u>Table 2</u>

Exposure Crossover Point

Pulses	@ 30 Hz	@ 50 Hz
921	30.7 seconds	18.4 seconds

Successive Day Exposures

It is assumed that only the authorized laser operators and associate workers shall have the potential for successive day exposures. Unauthorized exposures shall be assumed to have the potential for initial exposure only.

The MPE for successive day (second day) exposure to UV emissions with wavelengths longer than 280 nm require that the MPE to be de-rated by a factor of 2.5 [ANSI Std. Z136.1-2000 (8.2.3.1)].

$$MPE_{2nd\ day} = MPE / 2.5$$

$$= 667 \times 10^{-9}\ J/cm^2\ / 2.5$$

$$\mathbf{MPE_{2nd\ day} = 267 \times 10^{-9}\ J/cm^2}$$

Allowable Emission/Exposure Limit

The Allowable Emission Limit (AEL) is the largest output a laser may have and still be considered in a particular Laser Hazard Class. The AEL is the product of the appropriate MPE and the area of the limiting aperture [ANSI Std. Z136.1-2000 (3.2.3.4.1)(2)]. The values for the limiting aperture, as a function of laser wavelengths and exposure times, are presented in *Table 8* of the ANSI standard. The Class 1 AEL will henceforth be referred to simply as the "AEL". Relative to the exposed person this can also be considered an Allowable Exposure Limit for exposures to small beam lasers and will be referred to as the AEL as well.

Initial Exposure

$$AEL = (MPE)\ (A_{lim})$$

$$= (667 \times 10^{-9}\ J/cm^2)\ \pi\ (0.35\ cm)^2 / 4$$

$$\mathbf{AEL = 64.2 \times 10^{-9}\ J}$$

Successive Day Exposures

The appropriate $AEL_{2nd\text{-}day}$ for a laser with an output wavelength of 355 nm is the product of the de-rated MPE, for successive day exposures, and the limiting Area.

$$AEL_{2nd\text{-}day} = (MPE_{2nd\text{-}day})\ (A_{lim})$$

$$= (267 \times 10^{-9}\ J/cm^2)\ \pi\ (0.35\ cm)^2 / 4$$

$$\mathbf{AEL_{2nd\text{-}day} = 25.7 \times 10^{-9}\ J}$$

Minimum Optical Density

In general the minimum Optical Density (OD_{min}) of laser safety eyewear for a particular radiant output can be calculated as follows:

$$\mathbf{OD_{min} = \log_{10} (Q_o/AEL)}$$

Where;

OD_{min}	The minimum Optical Density for laser safety eyewear.
Q_o	Radiant Output Pulse Energy, in joules.
AEL	Allowable Emission/Exposure Limit (Class 1 for invisible lasers and Class 2 for visible lasers), in joules.

For the radiant output of 20 mJ at a PRF of 50 Hz at a wavelength of 355 nm, for "second day" exposure the minimum OD required is calculated as follows.

$$OD_{min} = \log_{10} (Q_o / AEL_{2nd\text{-}day})$$

$$= \log_{10} (20 \times 10^{-3}\ J / 25.7 \times 10^{-9}\ J)$$

$$= \log_{10} (779 \times 10^{3})$$

$$\mathbf{OD_{min} = 5.89}$$

The minimum optical density of laser safety eyewear used by the laser operators and others who may reasonably be expected to have long-term exposures (successive day exposures) is OD 5.89. A "barrier" with an OD of this value or greater is also sufficient to offer adequate protection as well.

Table 3

ARES Laser Area

(Successive Days)

Wavelength (nm)	Output (Qo)	PRF (Hz)	Time (Seconds)	MPE (J/cm^2)	AEL (J)	OD_{min}
355	20 mJ	30 Hz	30,000	444×10^{-9}	42.7×10^{-9}	5.67
355	20 mJ	50 Hz	30,000	267×10^{-9}	25.7×10^{-9}	**5.89**

The minimum Optical Density of 5.89 for laser safety eyewear will provide adequate protection for 30 Hz as well as 50 Hz. A ¼ inch thick (or greater) plexiglass © barrier will provide this level of protection as well.

Scanning Mode

In the scanning mode the laser beam is swept through a 90-degree ($\pi/2$ radians) arc at the selected PFR. The number of pulses distributed in the scan (n_s) is a function of the scan rate.

$$n_s = [\text{scan angle / scan rate}]\ \text{PRF}$$

$$n_s = [90^o / \text{scan rate}]\ \text{PRF}$$

The number of laser pulses emitted by the ARES LIDAR system per scan for various scan rates at the select PRF are presented in the table below.

Table 4

Laser Pulses Per Scan At Select Scan Rates

Scan Rate (degrees / second)	PRF (Hz)	n_s
5	30	540
5	50	900
4	30	675
4	50	1125
3	30	900
3	50	1500
2	30	1350
2	50	2250
1	30	2700
1	50	4500

The angular separation (B) between laser pulses can be determined as follows:

$$\mathbf{B = (\pi/2) / n_s}$$

Table 5

Angular Separation For Various Scan Rates At Select PRFs

Scan Rate (degrees / second)	B (radians) @ 30 Hz	B (radians) @ 50 Hz
5	2.91×10^{-3}	1.75×10^{-3}
4	2.33×10^{-3}	1.40×10^{-3}
3	1.75×10^{-3}	1.05×10^{-3}
2	1.16×10^{-3}	698×10^{-6}
1	582×10^{-6}	349×10^{-6}

There is some minimal distance (R_{min}) from the laser, such that the eye has the potential to receive only one laser pulse per scan cycle. This distance can be calculated by placing the ocular aperture (d_{eye}) at a distance such that the acceptance angle is equal to the angular separation between laser pulses. Note that the ocular aperture is the physical entrance (pupil) diameter of the eye (~7-mm) and not necessarily the limiting aperture listed in ANSI Std. Z136.1-2000, *Table 4a* (1 & 3.5-mm in the UV, used as a normalization factor for AEL determinations at various wavelength ranges).

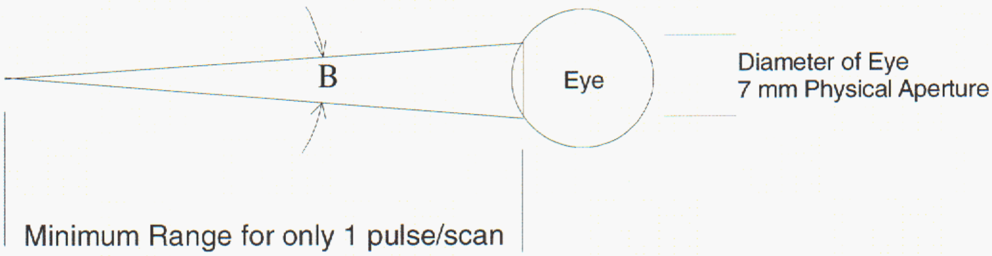


Figure 2

$$\tan B = d_{eye} / R_{min}$$

For angles less than 5 degrees the small angle approximation applies.

$$B \sim d_{eye} / R_{min}$$

$$R_{min} \sim d_{eye} / B$$

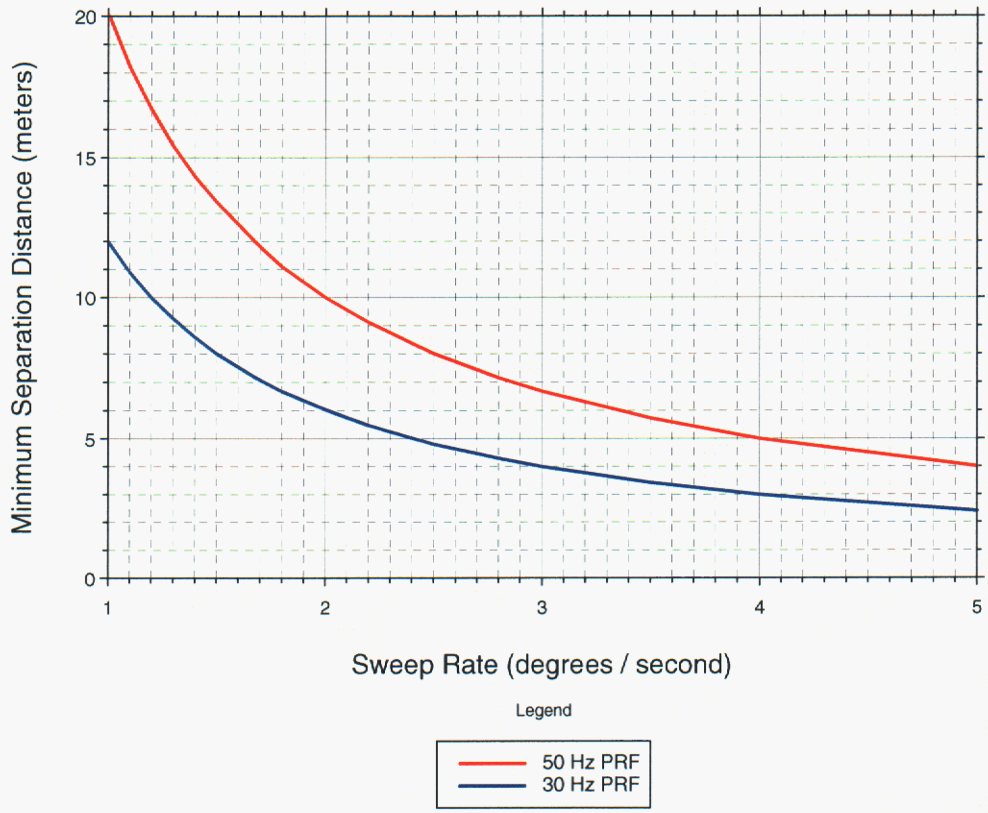
$$\mathbf{R_{min} \sim 0.7\ cm / B}$$

Table 6

Minimum Separation Distances For Various Scan Rates At Select PRFs

Scan Rate (degrees / second)	PRF (Hz)	R_{min} (meters)
5	30	2.41
5	50	4.00
4	30	3.00
4	50	5.00
3	30	4.00
3	50	6.67
2	30	6.03
2	50	10.0
1	30	12.0
1	50	20.1

Minimum Separation Distance For One Pulse-Ocular Intercept Per Scan versus Scan Rate

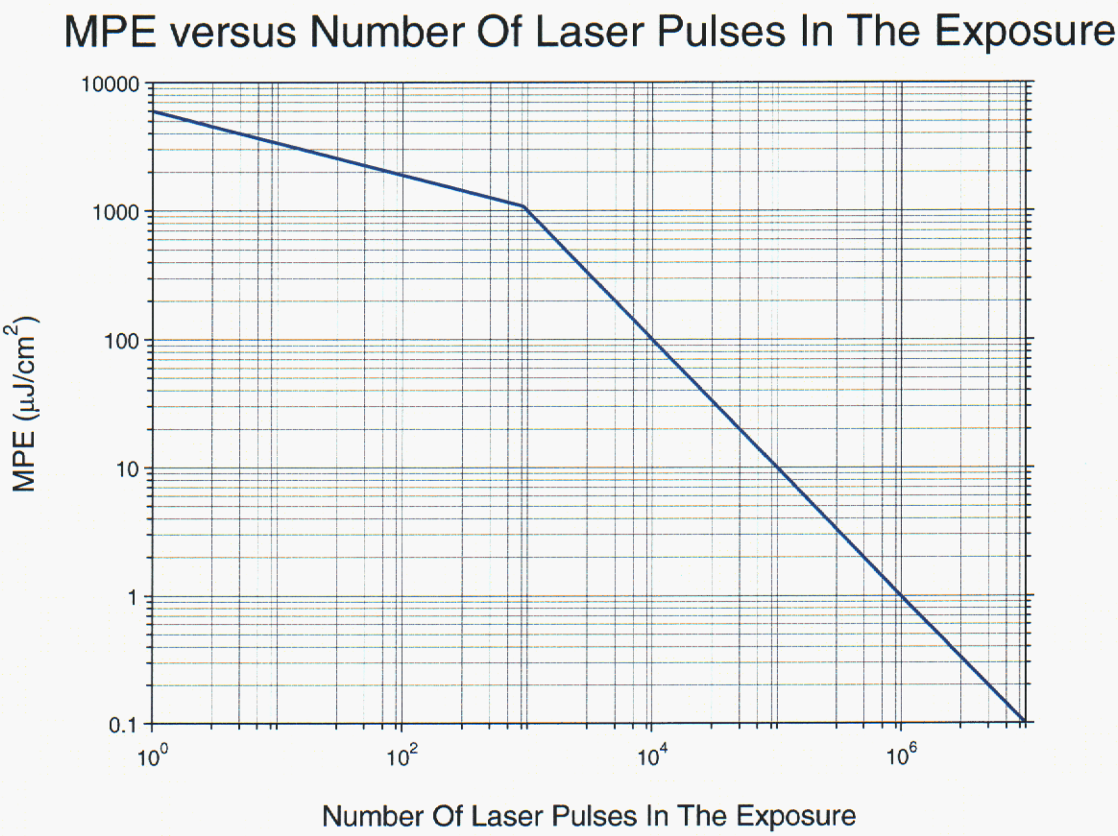


The angular separation varies from 2.91 milliradians for a scan rate of 5 degrees per second at a PRF of 30 hertz to 349 microradians for a scan rate of 1 degree per second at a PRF of 50 hertz. This yields minimum separation distance which range from 2.41 meters for a 5 degrees per second scan rate at 30 hertz to 20.1 meters for a scan rate of 1 degree per second at a PRF of 50 hertz.

Minimum separation distances for various scan rates (1 through 5 degrees per second) can be estimated from the curves above. As long as the exposure takes place at or beyond the minimum separation distance at most only one pulse will enter the eye per scan.

MPE versus Number of Pulses

The appropriate MPE for UV wavelengths is a function of the total number of laser pulses directly involved in the entire exposure over a 24-hour accumulation period. The MPE as a function of the number of laser pulses in the exposure is presented in the plot below.



Note that the exposure crossover (from ANSI Rule 3 dominant to ANSI Rule 2 dominant) occurs at approximately 921 pulses.

Nominal Ocular Hazard Distance

The Nominal Ocular Hazard Distance (NOHD) is the unaided eye-safe viewing distance. The NOHD can be the boundary of the Nominal Hazard Zone (NHZ) unless other engineering controls are installed to reduce the NHZ by terminating the laser beam at a shorter distance from the laser.

Authorized vs. Unauthorized Exposures

Authorized personnel working inside the NHZ are required to wear appropriate laser safety eyewear selected to provide full protection to the laser threat (laser hazard) present. In general the NHZ is inclusive to the laser control area. Access to the control area should be restricted to only personnel authorized to be in the NHZ [ANSI Std. Z136.6-2000 (4.5.4.1)].

The NOHD pertains to the unprotected and unintended exposure of an unauthorized person in the laser hazard zone to the incident laser beam or to specular reflections of the laser beam. Unauthorized personnel are unexpected in the laser control area and could lead to an unintended, unprotected ocular exposure. Generally, the unauthorized person has violated the boundaries of the laser control area and entered into the NHZ.

The formula for calculating the NOHD is given in the Appendix of the ANSI Std. Z136.1-2000 as follows:

$$NOHD = \theta^{-1} \left[(4Q_p / \pi\, MPE) - (d_{out})^2\right]^{0.5} \text{ cm}$$

<u>Where</u>:

NOHD	is the Nominal Ocular Hazard Distance, in centimeters.
θ	is the beam divergence, in radians.
Q_p	is the laser output radiant energy, in joules.
MPE	is the appropriate per pulse Maximum Permissible Exposure, in Joules/cm^2.
d_{out}	is the output beam diameter of the laser, in centimeters.

NOHD: "Point And Stare" Mode

The NOHD for the "point and stare" mode as a function of the exposure time is presented in the plot below for both (30 and 50 Hz) PRFs. The "worst" case output radiance (20 mJ) is used to calculate conservative NOHDs.

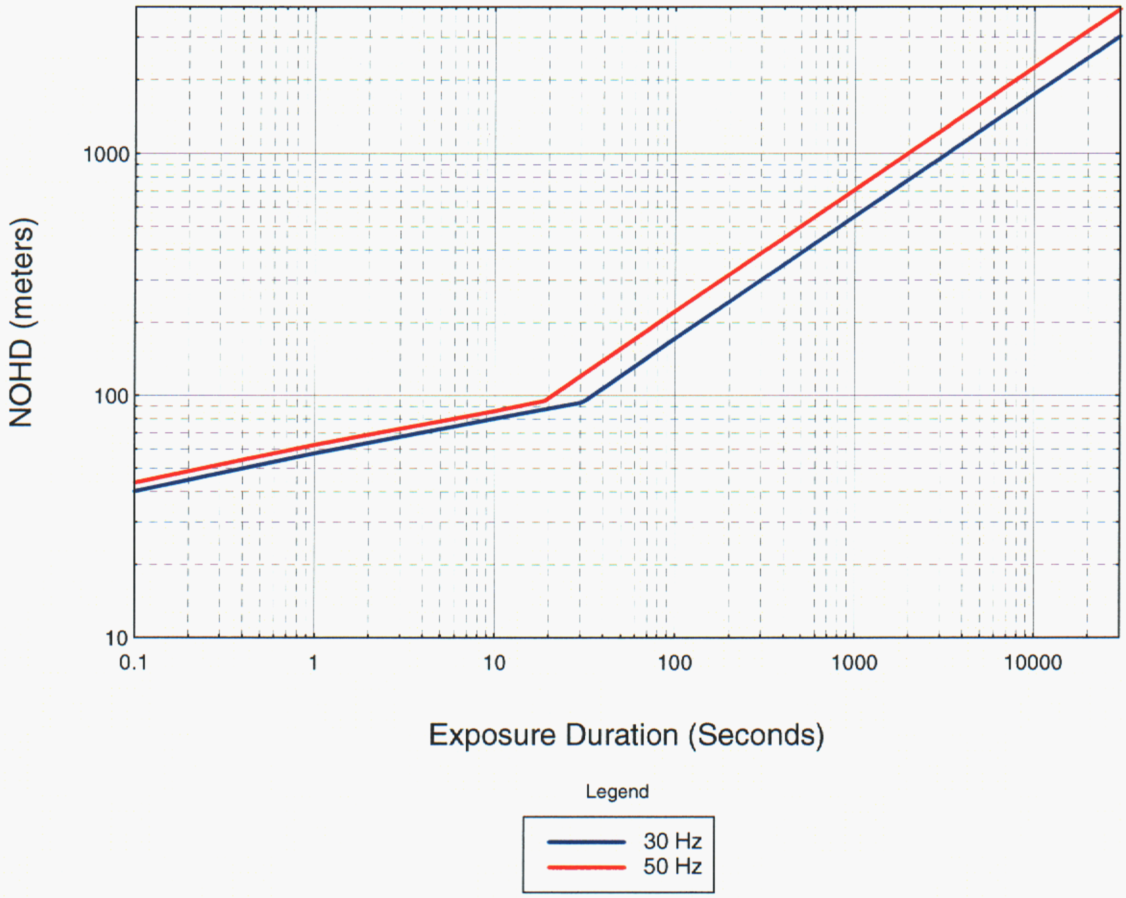
Note that the duration of the "point and stare" exposure at any one point is expected to be on the order of 10 seconds per exposure event, but this exposure could be longer. There may be several exposure events at the same point in any 24-hour period.

Extended Ocular Hazard Distance

In general, the use of optical viewing aids is not expected down range from the laser during laser operation. Should it become necessary to calculate Extended Ocular Hazard Distance (EOHD) refer to reference (4) for a quick estimate of this distance using the NOHD curves presented below and the "scale factor" (product of the square root of the transmission factor of the viewing aid and the ratio of the entrance diameter of the optical aid to the limiting aperture of the eye) derived by reference (4). An example, for 7 x 50 binocular is presented at the end of this section.

$$EOHD \sim (\tau_{aid})^{0.5} [d_{aid} / d_{lim}]\ NOHD$$

NOHD versus Exposure Duration
"Point And Stare"

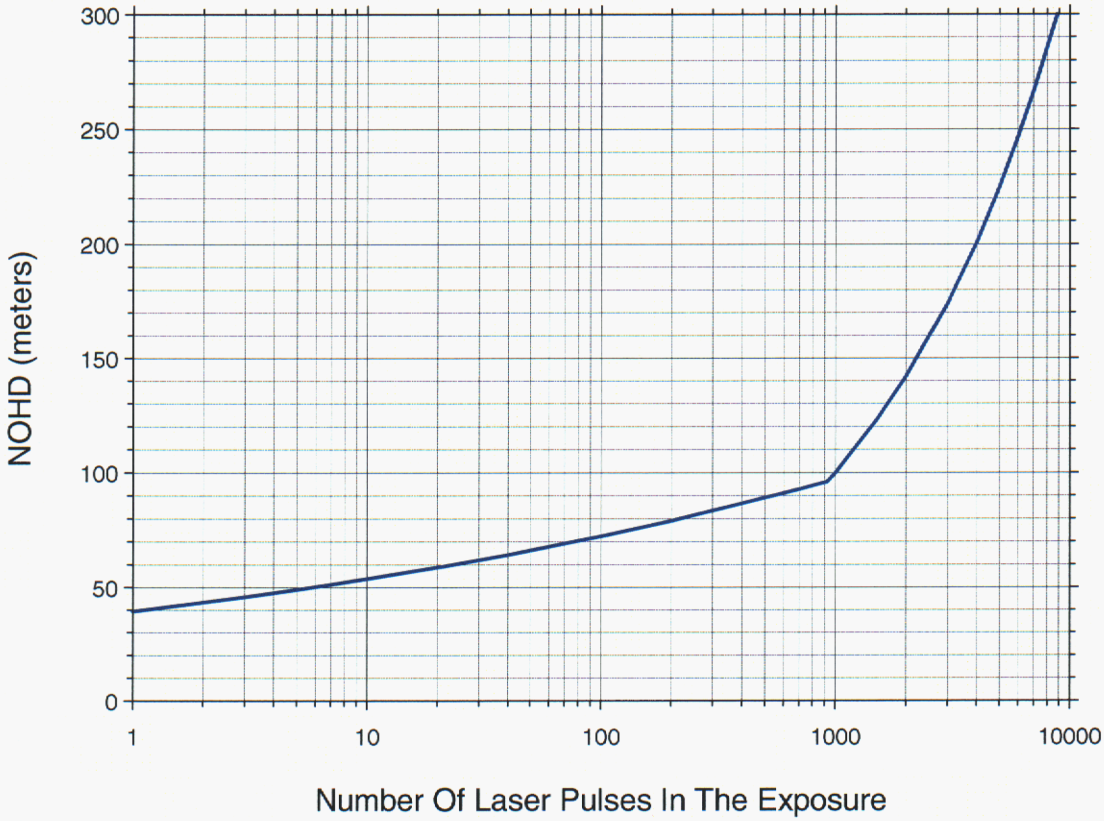


Note that the atmospheric transmission factors are not generally taken into consideration for transmissions under 1 Km. The "point and stare" mode exposure at any one point is expected to be on the order of 10 seconds with an accompanying NOHD less than 100 meters; therefore atmospheric transmission factors are not considered.

NOHD Scanning Mode

The NOHD for the scanning mode is a function of the total number of laser pulses intercepted at a particular point in the exposure duration.

NOHD versus Number Of Pulses In The Exposure Scanning Mode



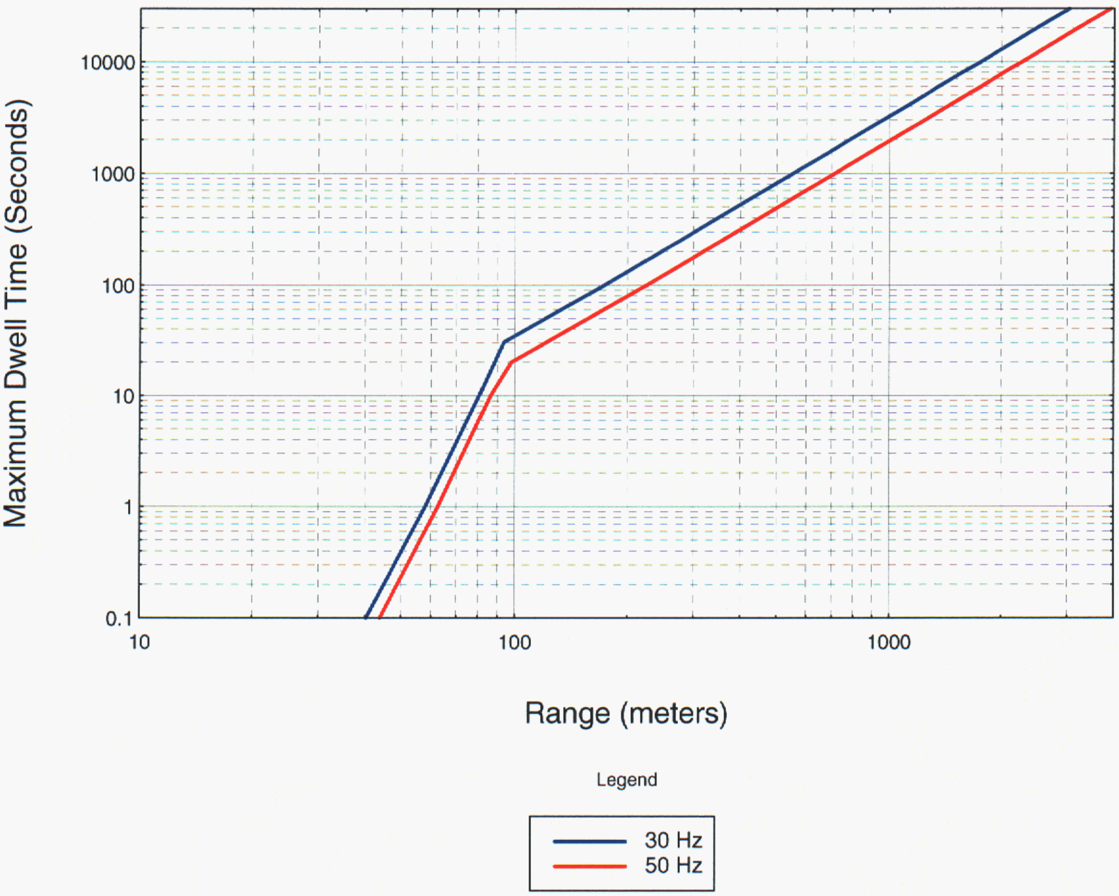
Eye-Safe Dwell Times

The eye-safe dwell time is the maximum exposure time at a particular location from the laser for which the exposure is less than the appropriate MPE for the laser conditions. The eye-safe dwell time is dependent on laser conditions, exposure conditions and distance from the laser.

"Point And Stare" Mode

The maximum eye-safe dwell time for the "point and stare" mode of operation is primarily dependent on the "line-of-sight" separation distance for the laser conditions as presented in the plot below.

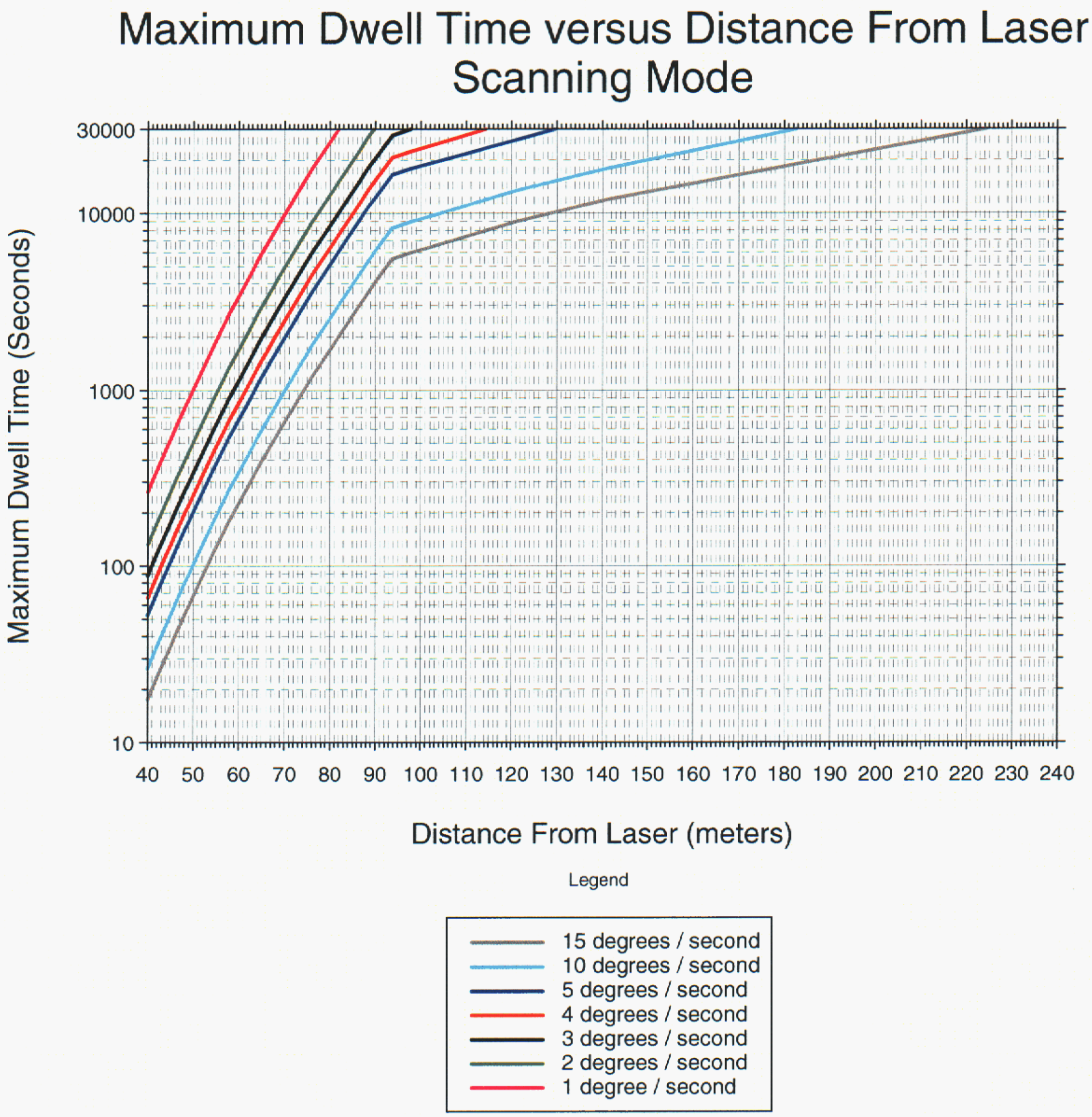
Maximum Dwell Time versus Range
"Point And Stare"



Scanning Mode

The maximum eye-safe dwell time is not only dependant on, the "line-of-sight" separation distance from the laser but is also a function of the scan rate and the number of pulses in the exposure.

The maximum eye-safe dwell times for various select scan rates at various line-of-sight distances are presented in the plot below.

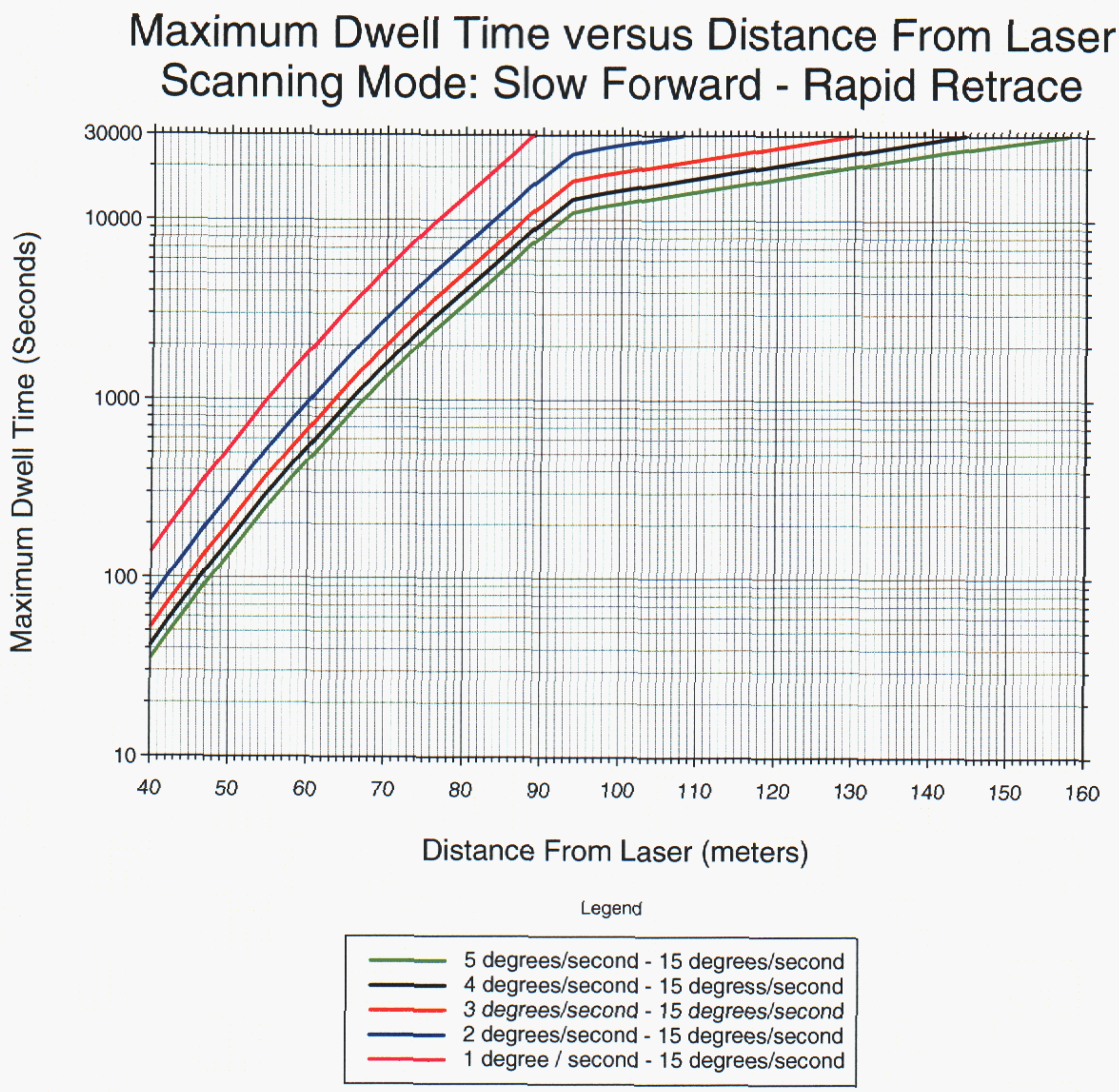


Some additional scanning modes of operations: slow forward scans (1 to 5 degrees per second) with a rapid retrace at 15 degrees per second. The worst-case ocular exposure is two laser pulses per cycle.

Table 7

Worst Case: 2 Laser Pulses Per Cycle

Forward Scan Rate (degrees/second)	Duration of Forward Scan (seconds)	Duration of Retrace (seconds)	Duration of Cycle (seconds)
5	18	6	24
4	22.5	6	28.5
3	30	6	36
2	45	6	51
1	90	6	96



Example Of Aided Viewing

The EOHD for 7 x 50 binocular viewing the above condition is estimated and presented as follows:

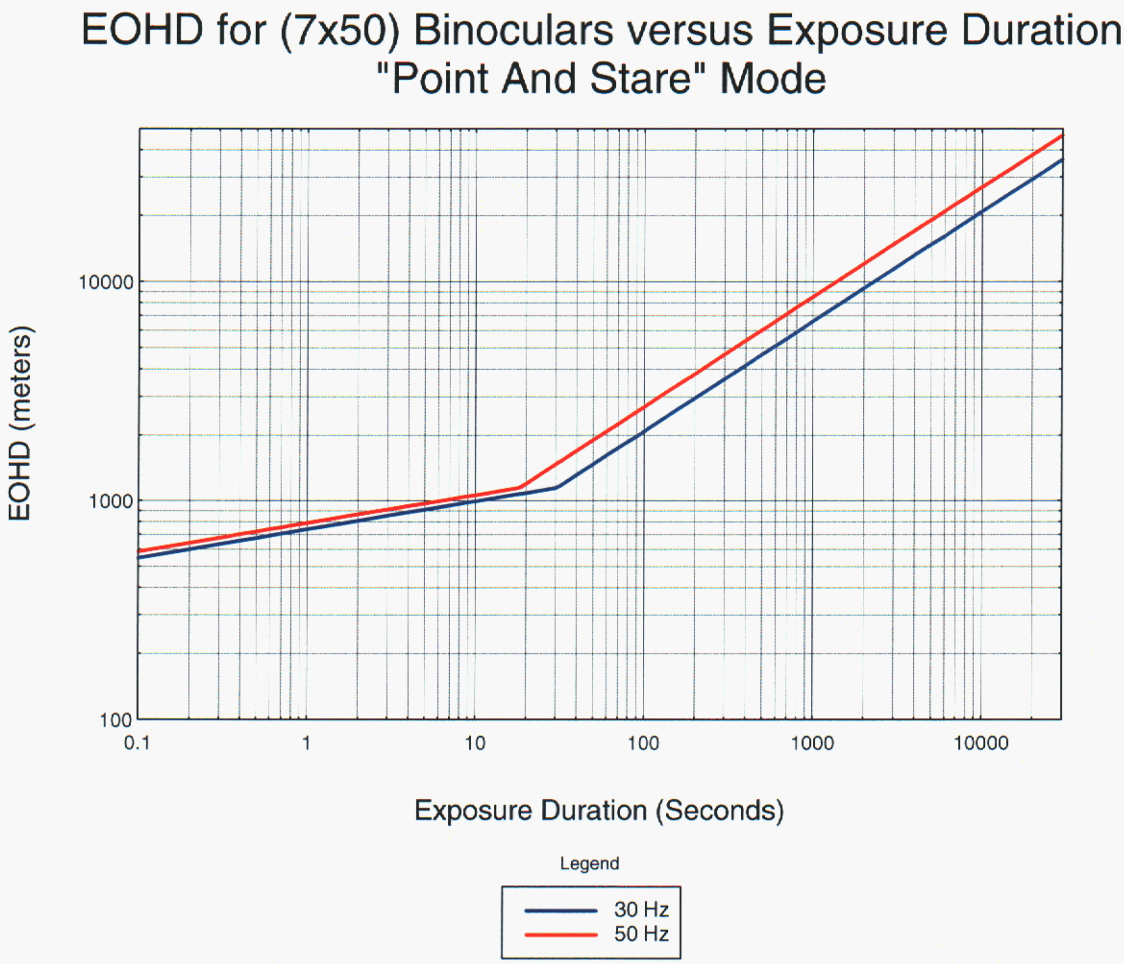
$$\mathbf{EOHD \sim (\tau_{aid})^{0.5}\ [d_{aid} / d_{lim}]\ NOHD}$$

Where,

τ_{aid}	Transmission of the aid	0.7	ANSI Std. Z136.1-2000 (*Table 9*)
d_{aid}	Entrance Diameter of aid	50 mm	
d_{lim}	Limiting Aperture	3.5 mm	ANSI Std. Z136.1-2000 (*Table 8*)

$$\mathbf{EOHD \sim\ (11.95)\ NOHD}$$

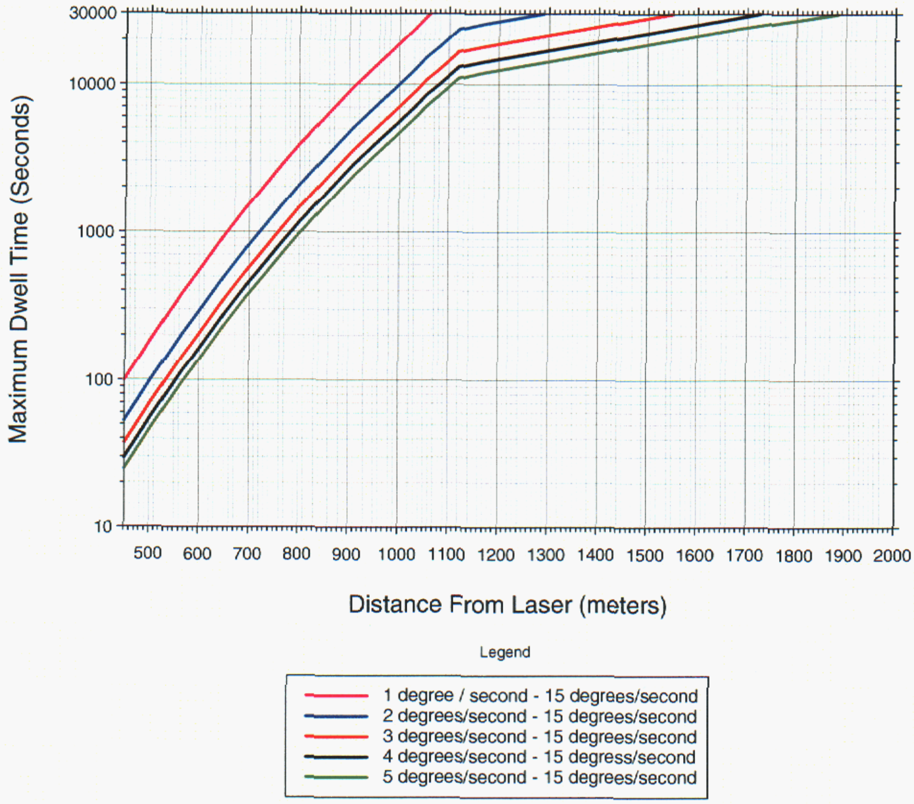
EOHD Point and Stare Mode



EOHD Scanning Mode

The "eye-safe" distance for aided viewing (7x50 binoculars), down range looking back towards the laser in the scanning mode is presented below.

Maximum Dwell Time For Aided Viewing versus Distance From Laser
Scanning Mode: Slow Forward - Rapid Retrace



V. Summary

Laser hazard analysis for UV lasers are always specific to the particular conditions presented and are subject to change due to changes in operating conditions or exposure durations. The laser hazard analysis presented here is valid for the conditions stated herein. Should these conditions change significantly the laser hazard analysis should be re-accomplished.

VI. References

1 ANSI Standard Z136.1-2000: for Safe Use of Lasers, Published by the Laser Institute of America.

2 ANSI Standard Z136.6-2000: for Safe Use of Lasers Outdoors, Published by the Laser Institute of America.

3 Safety with Lasers and Other Optical Sources – A Comprehensive Handbook, Sliney, David and Wolbarsht, Myron, Plenum Press, New York and London, 5th Printing, August 1985.

4 SAND 2002-1315, May 2002, Approximation Methods for Estimating the Eye-Safe Viewing Distances, with or without Atmospheric Transmission Factors Considered, For Aided and Unaided Viewing Conditions, A.L.Augustoni.

VII. Symbols and Abbreviations

AEL	Allowable Emission (Exposure) Limit
$AEL_{2nd\ day}$	AEL based on successive day exposure MPE (UV $\lambda > 280$ nm)
A_{lim}	Area of limiting aperture
ANSI	American National Standards Institute.
B	Angular separation between laser pulses – scanning mode.
cm	Centimeter
C_p	Multiple pulse correction factor.
CW	Continuous wave.
d_{aid}	Entrance diameter of the viewing aid.
d_{eye}	Entrance (pupil) diameter of the eye.
d_{lim}	Diameter of limiting aperture.
d_{out}	Output beam diameter.
E	Irradiance, in J/cm^{2}.
E_o	Output Irradiance, in J/cm^{2}.
EOHD	Extended Ocular Hazard Distance.
Hz	Hertz, cycle per second, sec^{-1}.
J	Joules, unit of energy.
Km	Kilometer (1,000 meters)
LIDAR	LIght Detection And Ranging
Min[a,b]	Minimum of value of a and b.
mJ	Millijoule, 10^{-3} Joules.
MPE	Maximum Permissible Exposure.
$MPE_{2nd\ day}$	Successive day MPE (MPE de-rated by 2.5).
MPE_{cw}	Continuous Wave Maximum Permissible Exposure.
$MPE_{photochemical}$	MPE based on the photochemical limit.
$MPE_{/pulse}$	Per Pulse Maximum Permissible Exposure.
$MPE_{m.p.}$	Multiple Pulse Maximum Permissible Exposure.
$MPE_{rule\ 2}$	MPE derived by ANSI Rule 2.
$MPE_{rule\ 3}$	MPE derived by ANSI Rule 3.
$MPE_{s.p}$	Single Pulse Maximum Permissible Exposure.
$MPE_{thermal}$	MPE based on the thermal limit.

NHZ	Nominal Hazard Zone.
nm	Nanometer, 10^{-9} meters.
NOHD	Nominal Ocular Hazard Distance.
ns	Nanosecond, 10^{-9} seconds.
n_s	Number of laser pulses in a scan cycle.
n_x	Number of pulses for MPE ANSI Rule 2 to equal MPE ANSI Rule 3
OD	Optical Density of the laser safety eye ware.
OD_{min}	Minimum Optical Density required of laser safety eye ware.
PRF	Pulse Repetition Frequency.
Q	Radiant Energy, in Joules.
Q_o	Output Radiant Energy, in Joules.
R_{min}	Minimum separation distance from a scanning laser for 1 pulse to the eye per scan cycle.
t_p	Exposure duration, pulse duration
T	Exposure duration, in seconds.
T_x	Time to exposure crossover ANSI Rule 2 = ANSI Rule 3
UV	Ultraviolet light
YAG	Yttrium aluminum garnet crystal
θ	Beam divergence.
λ	Wavelength

VIII. Distribution List

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