SAND REPORT

SAND2003-2820
Unlimited Release
Printed August 2003

Laser Safety And Hazard Analysis For The Temperature Stabilized BSLT ARES Laser System

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Abstract

A laser safety and hazard analysis was performed for the temperature stabilized Big Sky Laser Technology (BSLT) laser central to the ARES 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*. As a result of temperature stabilization of the BSLT laser the operating parameters of the laser had changed requiring a hazard analysis based on the new operating conditions. 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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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.

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).

Point and Stare

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

Initial Operation

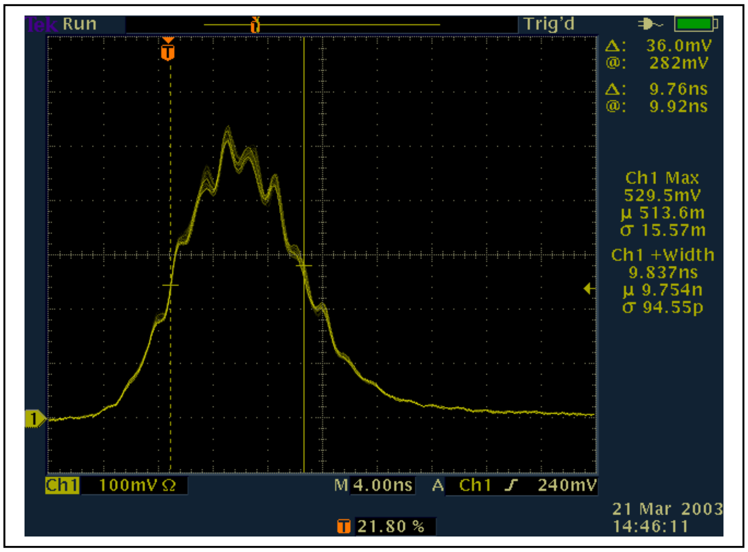
The initial operation of the ARES system was described in a SAND report[4]. Initially the ARES’ BSLT laser was operated with a maximum output of 20 mJ in a 13-nanosecond pulse delivered at a pulse repetition frequency (PRF) of 50 hertz.

Change In Operation Parameters:

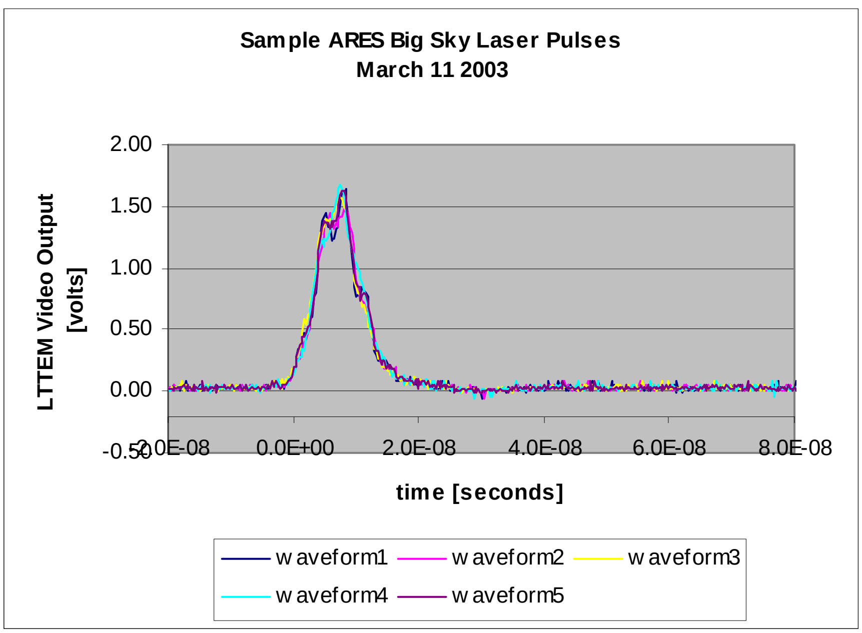
It was found that operating the BSLT laser at a PRF of 30 hertz, temperature stabilized, the maximum radiant output was increased to 50 mJ. Although the BSLT can produce 50 mJ per pulse at 30 hertz the ARES system is typically operated with a radiant output of 40 mJ in a 9-nanosecond pulse delivered at a PRF of 30 hertz.

Pulse Width

There are two BSLT laser heads, which are used at various times in the ARES systems. These two laser heads have slightly different pulse widths. An average pulse width of 9 nanoseconds was selected as the most conservative value for the pulse width (t) to use in the subsequent hazard analysis.



Pulse width for BSLT laser head 1



Pulse width for BSLT laser head 2

II. Laser Parameters (Temperature Stabilized)

Big Sky Laser

	Laser	Telescope
Model Number:	CFR-200	
Wavelength:	355 nm	
Radiant Output:		
Maximum	50 mJ	
Typical Operational	40 mJ	
Alignment (high)	6 mJ	
Alignment (low)	1 mJ	
Pulse Duration:	9×10^{-9} seconds	
Pulse Repetition Frequency:	30 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		15 degrees / second

III. Laser Safety and Hazard Analysis Terms

Outdoor Operations

Although general laser safety is addressed in the laser ANSI standard[1], outdoor operations are addressed in a separate ANSI standard[2] specific to laser safety outdoors. All laser operations outdoors, involving lasers exceeding the Class 3a Accessible 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 Accessible 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 the value 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 (pulse width and accumulated 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 effected or "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 a 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 a hazardous 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. Z136.1–2000 (8.2.3.1)].

IV. Laser Hazard Analysis

Maximum Permissible Exposure Determination

The following MPE determination is based on a 30,000 second exposure to a 30-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 (t) is given as 9 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.}
For: 1 ns t < 10 sec

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

$$\mathbf{MPE_{s.p.} = 5.45 \times 10^{-3}\ J/cm^2}$$

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

$$n = PRF \bullet T$$

$$= (30\ sec^{-1})\ (30 \times 10^3\ sec)$$

$$\mathbf{n = 900 \times 10^3\ \ pulses}$$

$$MPE_{/pulse} = \frac{MPE_{CW}}{n}$$

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

$$MPE_{/pulse} = \frac{1 \; {}^{J}\!/_{cm^2}}{900 \times 10^3 \; pulses}$$

$$MPE_{/pulse} = 1.11 \times 10^{-6} \; {}^{J}\!/_{cm^2}$$

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 x 10^4 seconds

$$MPE_{M.P.} = C_p \; MPE_{S.P.-thermal}$$

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

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

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

$$= [900 \times 10^3]^{-0.25}$$

$$C_p = 0.0325$$

$$MPE_{M.P.} = (0.0325)\ (5.45 \times 10^{-3}\ J/cm^2)$$

$$MPE_{M.P.} = 177 \times 10^{-6}\ J/cm^2$$

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

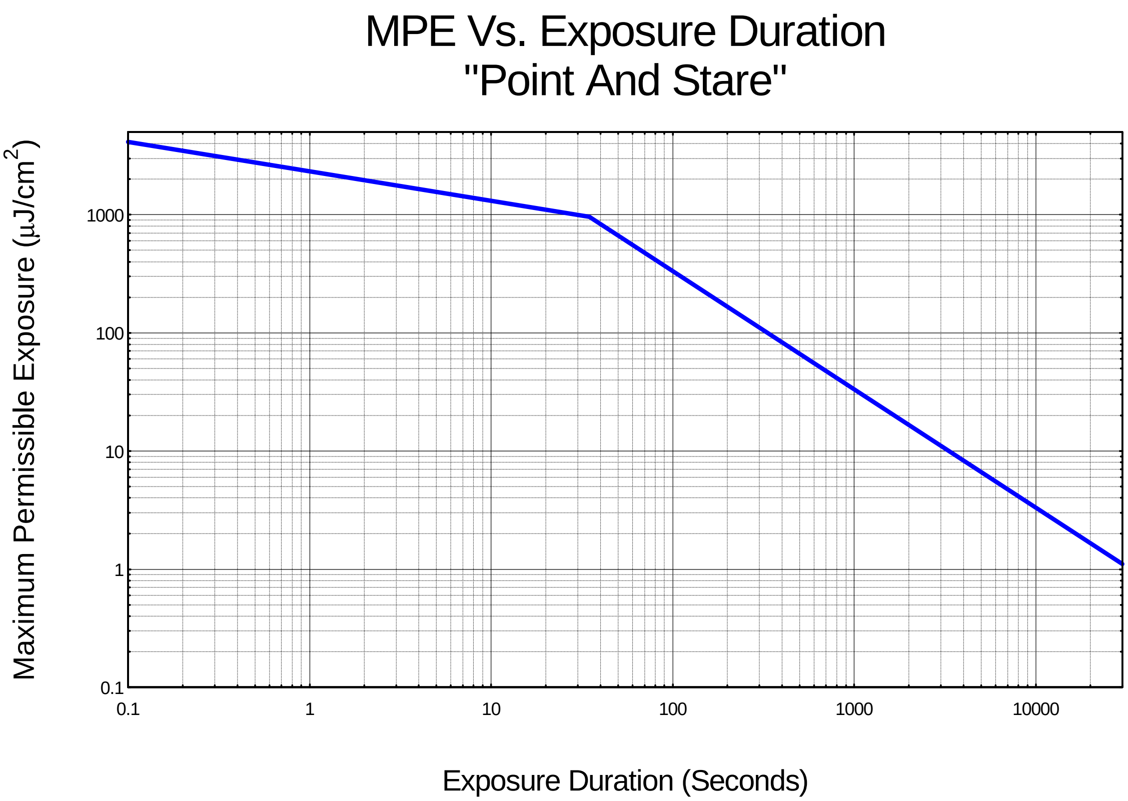
Appropriate MPE: Initial Exposure

λ = 355 nm - 30,000 Seconds @ 30 Hz

ANSI Rule	MPE (J/cm^2)	Comment
1	5.45×10^{-3}	
2	$\mathbf{1.11 \times 10^{-6}}$	**Appropriate MPE**
3	177×10^{-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 (first day) exposure MPE as a function of the accumulative exposure is plotted below for 30-Hz PRF for the “point and stare” condition.



Note that the slope of MPE curve change at a duration of approximately 34.7 seconds. This 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 can be 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:

$$MPE_{rule3} = MPE_{rule2}$$

$$C_p MPE_{thermal} = \frac{MPE_{CW}}{n}$$

For $n = n_x$:

$$n_x^{-0.25} MPE_{thermal} = \frac{MPE_{CW}}{n_x}$$

$$n_x^{0.75} = \frac{MPE_{CW}}{MPE_{thermal}}$$

$$n_x = \left[\frac{MPE_{CW}}{MPE_{thermal}} \right]^{4/3}$$

For a laser pulse-width (t) of 9-nanoseconds at wavelength of 355 nm, the MPE from ANSI Std. Z136.1–2000, Table 5a for T 10 seconds (CW) is listed as 1 J/cm^2.

$$n_x = \left[\frac{1 \ {}^{J}\!/_{cm^2}}{0.56 t^{0.25} \ {}^{J}\!/_{cm^2}} \right]^{4/3}$$

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

$$n_x = 1042 \ \ pulses$$

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

$$T_x = \frac{n_x}{PRF}$$

$$= \frac{1042}{30 \ \sec^{-1}}$$

$$T_x = 34.7 \ \sec$$

Table 2

Exposure Crossover Point

Number of Pulses	Time at 30 Hz
1042	34.7 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)].

$$MPE_{2^{nd}\,day} = \frac{MPE}{2.5}$$

$$= \frac{1.11 \times 10^{-6}\ {}^{J}\!/_{cm^2}}{2.5}$$

$$MPE_{2^{nd}\,day} = 444\ \times\ 10^{-9}\ J/cm^2$$

<u>**Accessible Emission/Exposure Limit**</u>

The Accessible 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 (First Day Exposure)

The AEL for the initial or first day exposure is simply the product of the MPE and the area of the limiting aperture listed in ANSI Std. Z136.1–2000 (Table 8).

$$AEL = MPE \cdot A_{\lim}$$

$$= \left(1.11 \times 10^{-6}\right) \frac{\pi \left(0.35\ cm\right)^2}{4}$$

$$AEL = 107\ \times\ 10^{-9}\ \ J$$

AEL 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.

$$AEL_{2^{nd}\ day} = MPE_{2^{nd}\ day} \cdot A_{\lim}$$

$$= \left(444 \times 10^{-9}\ {}^{J}\!/\!_{cm^2}\right) \frac{\pi \left(0.35\ cm\right)^2}{4}$$

$$AEL_{2^{nd}\ day} =\ 42.7 \times 10^{-9}\ \ J$$

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:

$$OD_{\min} = \log_{10}\left(\frac{Q_o}{AEL}\right)$$

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.

OD_{min} Successive Day Exposure

For the radiant output of 40 mJ at a PRF of 30–Hz at a wavelength of 355 nm, for "second day" exposure the minimum OD required is calculated as follows.

$$OD_{\min} = \log_{10}\left(\frac{Q_0}{AEL_{2^{nd}\ day}}\right)$$

$$= \log_{10}\left(\frac{40\times10^{-3}\ J}{42.7\times10^{-9}\ J}\right)$$

$$= \log_{10}\left(937\times10^{3}\right)$$

$$OD_{\min} = 5.97$$

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 5.97. A "barrier" with an OD of this value or greater is also sufficient to offer adequate protection as well.

Similarly for an output of 50 mJ at 30 hertz yields:

$$OD_{\min} = \log_{10}\left(\frac{50\times10^{-3}\,J}{42.7\times10^{-9}\,J}\right)$$

$$= \log_{10}\left(1.17\times10^{6}\right)$$

$$OD_{\min} = 6.07$$

Table 3

ARES Laser Area

(Successive Days)

Wavelength (nm)	**Output (Qo)**	**PRF (Hz)**	**Time (Seconds)**	**MPE (J/cm^2)**	**AEL (J)**	**OD_{min}**
355	40 mJ	30 Hz	30,000	1.11×10^{-6}	42.7×10^{-9}	5.97
355	50 mJ	30 Hz	30,000	1.11×10^{-6}	42.7×10^{-9}	**6.07**

The minimum Optical Density of 6.07 for laser safety eyewear will provide adequate protection for 30 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 PRF. The number of pulses distributed in the scan (n_s) is a function of the scan rate.

$$n_s = \left[\frac{scan\ \ angle}{scan\ \ rate} \right] PRF$$

$$n_s = \left[\frac{90^0}{scan\ \ rate} \right] PRF$$

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)	n_s
5	540
4	675
3	900
2	1350
1	2700

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

$$\beta = \frac{\left(\frac{\pi}{2} \right)}{n_s}$$

$$\beta = \frac{(\pi)}{2n_s}$$

Table 5

Angular Separation For Various Scan Rates At Select PRFs

Scan Rate (degrees / second)	n_s	β (radians)
5	540	2.91×10^{-3}
4	675	2.33×10^{-3}
3	900	1.75×10^{-3}
2	1350	1.16×10^{-3}
1	2700	582×10^{-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)[3] and not necessarily the limiting aperture (D_f) listed in ANSI Std. Z136.1–2000, *Table 4a* (1 & 3 –mm in the UV, used as a normalization factor for AEL determinations at various wavelength ranges).

$$Tan(\beta) = \frac{d_{eye}}{R_{\min}}$$

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

$$\beta \approx \frac{d_{eye}}{R_{\min}}$$

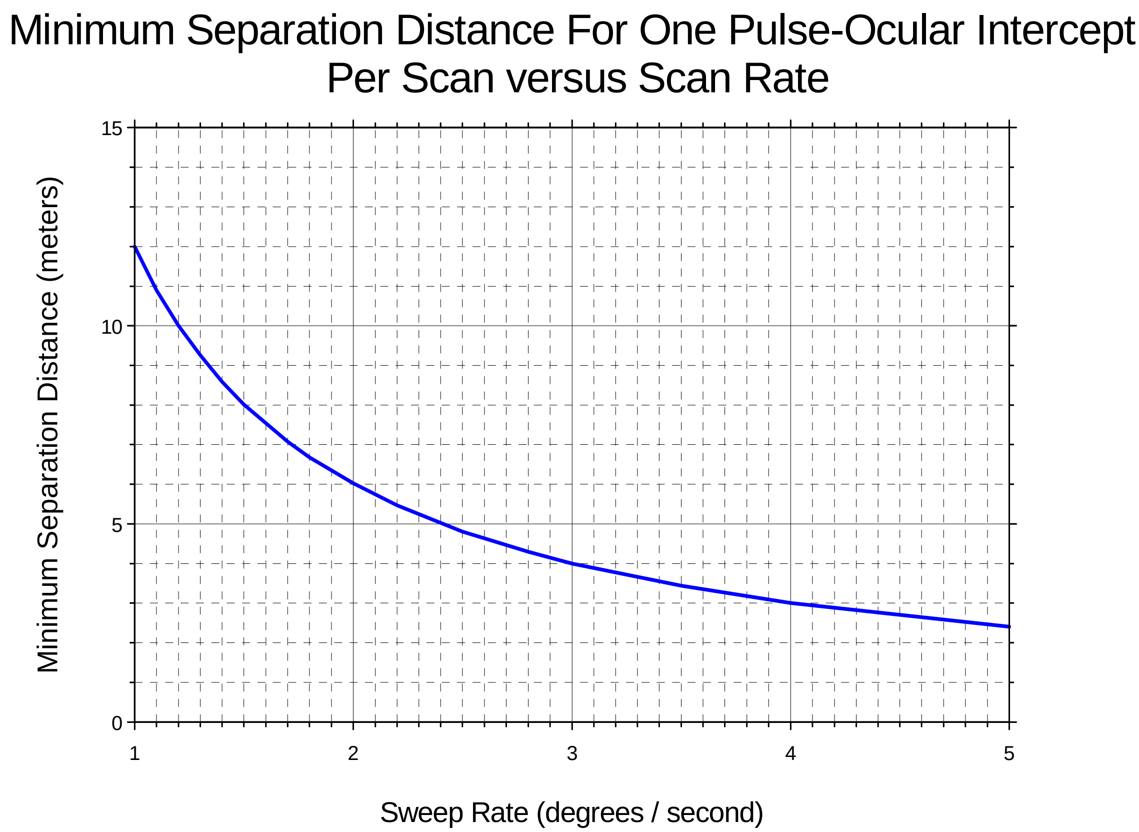
$$R_{\min} \approx \frac{d_{eye}}{\beta}$$

$$R_{\min} \approx \frac{0.7 \ \ cm}{\beta}$$

<u>Table 6</u>

Minimum Separation Distances For Various Scan Rates At Select PRFs

Scan Rate (degrees / second)	R_{min} (meters)
5	2.41
4	3.00
3	4.00
2	6.03
1	12.0

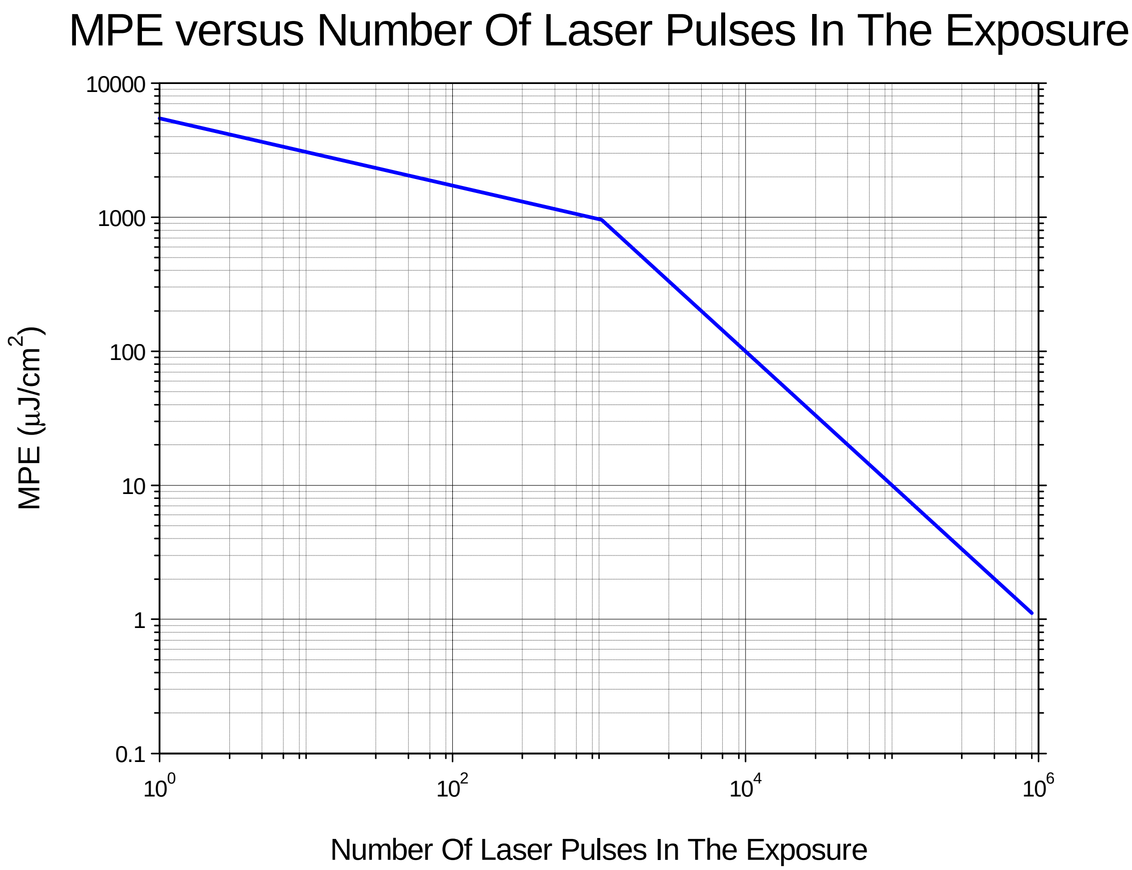


The angular separation varies from 2.91 milli-radians for a scan rate of 5 degrees per second to 582 micro-radians for a scan rate of 1 degree per second. This yields minimum separation distance which range from 2.41 meters for a 5 degrees per second scan rate to 12 meters for a scan rate of 1 degree per second.

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 1042 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 by entering into the NHZ.

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

$$NOHD = \frac{1}{\theta}\sqrt{\frac{4Q_o}{\pi MPE} - d_{out}^2} \quad cm$$

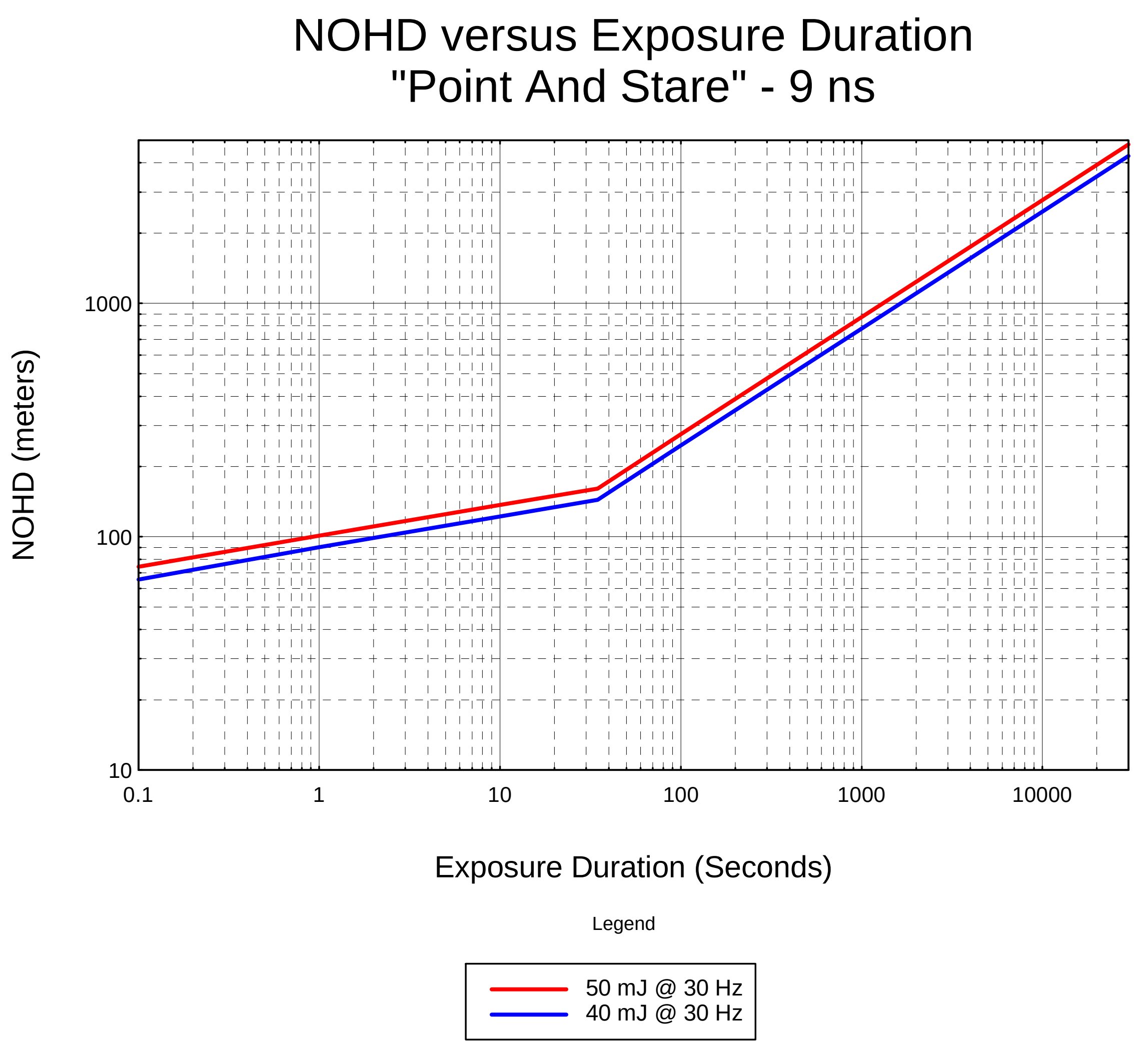
<u>Where</u>;

NOHD: Nominal Ocular Hazard Distance, in centimeters.
θ: Beam divergence, in radians.
Q_o: Output radiant energy, in joules.
MPE: Maximum Permissible Exposure, in Joules/cm^2.
d_{out}: Output beam diameter of the laser, in centimeters.

NOHD for "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 40 mJ and 50 mJ radiance outputs at a PRF of 30 hertz.

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.



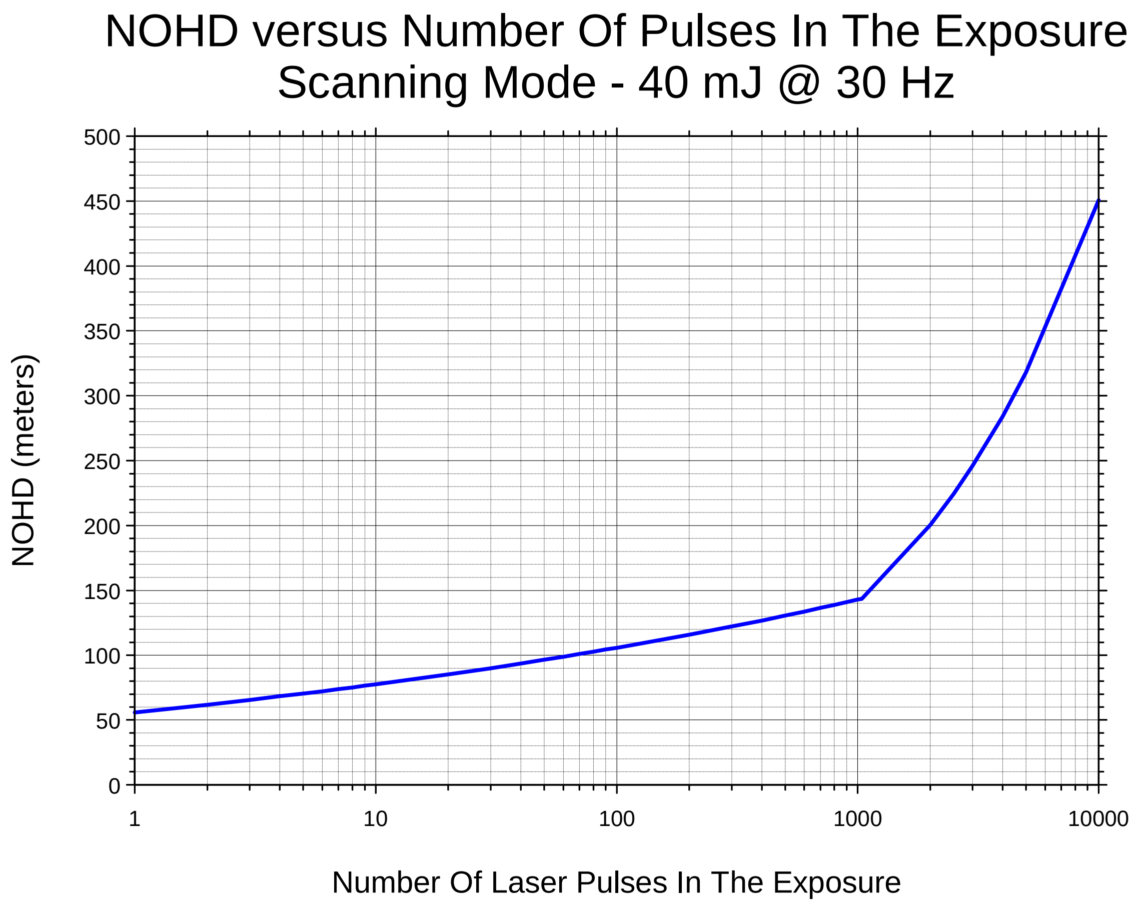
Note that the atmospheric transmission factors are not generally taken into consideration for transmissions under 1 Km. The "point and stare" mode exposure at any one point is expected to be on the order of 10 seconds with an accompanying NOHD on the order of 100 meters; therefore atmospheric transmission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

Worst case NOHD (50 mJ @ 30 Hz for 30,000 seconds) is 4,790 meters.

Note that the probability of a 30,000 second exposure is highly unlikely because it is not reasonable or likely that the ARES laser would be operated for 30,000 seconds in a single 24-hour period, targeted to a single location point in space, or that an unauthorized individual would be physically intrabeam to the ARES laser for 30,000 seconds without detection and removal.

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.



Eye-Safe Exposure Times

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

“Point And Stare” Mode – Unaided Viewing

The maximum eye-safe exposure 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.

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.

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

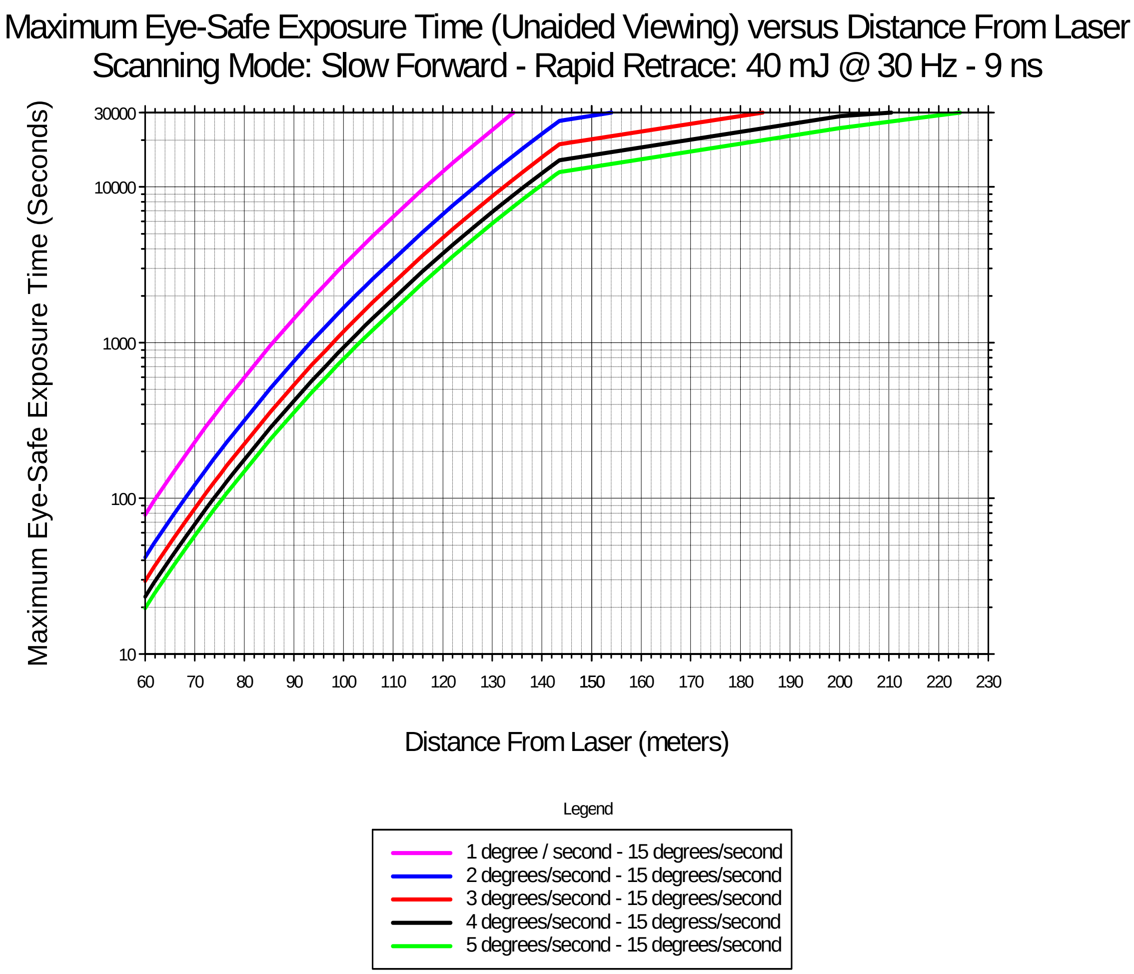
<u>Table 7</u>

Cycle Duration versus Scan Rates

Worst Case: 2 Laser Pulses Per Cycle

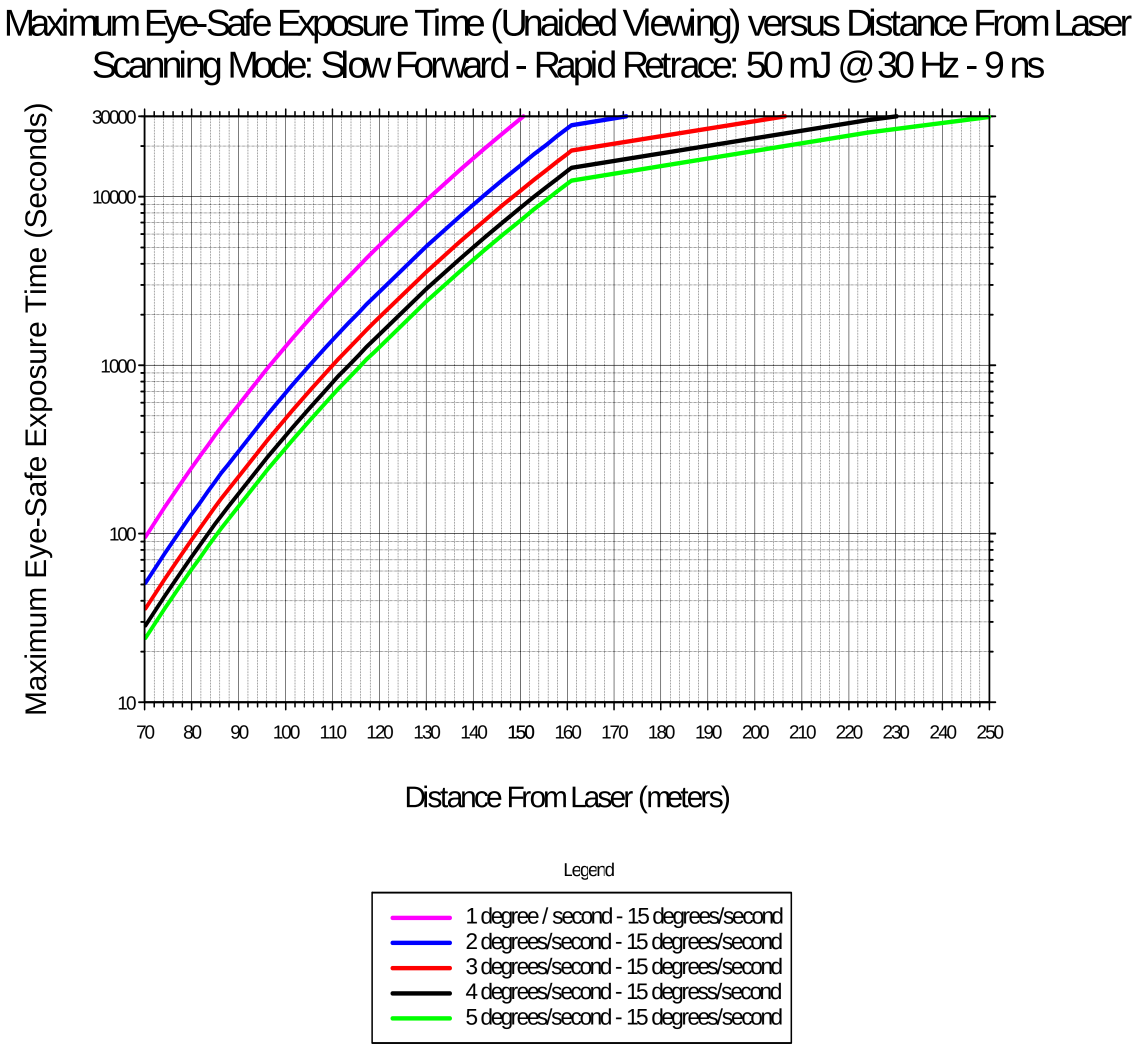
Forward Scan Rate (degrees/second)	Duration of Forward Scan (seconds)	Duration of Retrace (seconds)	Duration of Cycle (seconds)
5	18	6	24
4	22.5	6	28.5
3	30	6	36
2	45	6	51
1	90	6	96

The maximum "eye-safe" dwell time or exposure for unaided intrabeam viewing at various distances for a radiant output of 40 mJ at a PRF of 30 hertz can be attained from the following plot.



Should the BSLT laser be operated at maximum radiant output the eye-safe exposure times as a function of line-of-sight distance from the laser can be estimated from the charts that follow.

The maximum “eye-safe” dwell time or exposure for unaided intrabeam viewing at various distances for a radiant output of 50 mJ at a PRF of 30 hertz can be attained from the following plot.



Aided Viewing

The use of optical aides such as a pair of 7 X 50 binoculars for intrabeam viewing will increase the viewing hazard by as much as the square of the magnifying power (optical gain) of the optical system [ANSI Std. Z136.1–2000 (B6.4.3)].

Increased Hazard

The MPE is the quantification of the laser ocular hazard (H) for unaided intrabeam viewing presented by the laser since it is the threshold into the ocular hazard regime. The increased hazard as a result of aided intrabeam viewing can be expressed as a function of the MPE and the magnifying power of the aid:

$$H_{\max} = \frac{MPE}{P^2}$$

Where;
- H_{max}: Maximum increased hazard
- MPE: Maximum Permissible Exposure
- P: Magnifying Power

Optical Gain

The optical gain factor (G) represents the maximum increase in the optical hazard from the laser beam. In general for a 7 x 50 binocular for wavelengths in the retinal hazard region (400 nm $\leq$ λ < 1.40 μm) with an assumed 100% optical transmission and the exit pupil is approximately equal to the limiting aperture ($D_{f(visible)}$ = 7 mm) the optical gain (G) can be expressed as:

$$G = \left[\frac{D_o}{D_e}\right]^2 = P^2 \qquad \text{(ANSI Std. Z136.1 Eq B55)}$$

Where;
- G: Optical Gain
- P: Magnifying Power
- D_o: Diameter of Objective optic
- D_e: Diameter of exit pupil

Maximum Gain

For a pair of (**7** x 50) binoculars in the retinal hazard region the maximum gain is:

$$G_{\max} = (7)^2 = 49$$

Actual Gain

The actual gain of the optical system considers the transmission factor to the optical system.

$$G = \tau_{\lambda}\left[\frac{D_o}{D_e}\right]^2 = \tau_{\lambda}P^2$$

Where;

G: Optical Gain
P: Magnifying Power
D_o: Diameter of Objective optic
D_e: Diameter of exit pupil
τ_{λ}: Transmission factor of the optical system

Effective Gain

The effective optical gain is usually used when considering intrabeam aided viewing of laser sources at closer distances, where the collecting aperture is not necessarily the same as the diameter of the objective optic, generally in the retinal hazard region; however, "the effective gain is useful for calculating the hazards for lasers with wavelengths outside the retinal hazard region (302 nm $\lambda_{UV} < 400$ nm and 1.4 μm $\lambda < 2.8$ μm) [ANSI Std. Z136.1–2000 (B6.4.3.2)]. The limiting diameters in these wavelength regions are 3.5 mm and 1 mm respectively.

For wavelengths in these regions (302 nm $\lambda_{UV} < 400$ nm and 1.4 μm $\lambda_{IR} < 2.8$ μm) the hazard is to the cornea of the eye instead of to the retina.

The effective gain (G_{eff}) can be expressed as:

$$G_{eff} = \tau_{\lambda}\frac{\min\left(D_c^2, D_L^2\right)}{D_f^2} \qquad \text{(ANSI Std. Z136.1 Eq B57)}$$

Where;

G_{eff}: Effective Optical Gain
D_c: Diameter of collecting aperture
D_L: Diameter of laser beam at the viewing range from the laser
D_f: Diameter of limiting aperture (ANSI Std. Z136.1–Table 8)
τ_{λ}: Transmission factor of the optical system

Collecting Aperture

The diameter of the collecting aperture (D_c) can be determined from:

$$D_c = \min(D_o, P \cdot D_f) \quad \text{(ANSI Std. Z136.1 Eq B56)}$$

<u>Where</u>;

P: Magnifying power of the optical system
D_c: Diameter of collecting aperture
D_o: Diameter of the objective optic
D_f: Diameter of limiting aperture (ANSI Std. Z136.1–Table 8)

The following evaluation is for the case of intrabeam aided viewing of the ARES output with a pair of (7 x 50) binoculars.

The wavelength of the ARES laser falls with the UV corneal hazard region.

Evaluation for 7x50 Binoculars

For 302 nm $\lambda_{355\ nm} < 400$ nm:

<u>Given</u>:

P: 7 (**7** x 50) binoculars
D_o: 50 mm (7 x **50**) binoculars
D_f: 3.5 mm (for T 10 seconds – ANSI Z136.1 Table 8)

$$D_c = \min(D_o, P \cdot D_f)$$

$$= \min(50 \text{ mm}, 7 \times 3.5 \text{ mm})$$

$$= \min(50 \text{ mm}, 24.5 \text{ mm})$$

$$D_c = 24.5\ mm$$

The effective optical gain for intrabeam aided viewing of the ARES laser using a pair of 7 x 50 binoculars can be determined as follows:

$$G_{eff} = \tau_{\lambda} \frac{\min\left(D_c^2, D_L^2\right)}{D_f^2}$$

D_c: 24.5 mm (calculated above)
D_f: 3.5 mm (ANSI Std. Z136.1–Table 8)
τ_{λ}: 0.7 (ANSI Std. Z136.1–Table 9)

The diameter of the ARES laser beam (D_L) is a function of the distance from the laser.

$$D_L = d_o + \theta R$$

Where;
D_L: Diameter of the laser beam at range, R.
d_o: Exit diameter of the laser beam
θ: Beam divergence
R: Distance from the laser

The range at which the diameter of the laser beam is equaled to the diameter of the collecting aperture can be determined as follows:

$$D_L = D_c = d_{out} + \theta R$$

$$R = \frac{\left(D_c - d_{out}\right)}{\theta}$$

$$= \frac{\left(24.5\ mm - 12.5\ mm\right)}{0.5\ mR}$$

$$= \frac{12\ mm}{0.5\ mR}$$

$$R = 24\ meters$$

For aided viewing distances from 2 meters (minimum aided viewing distance) to 24 meters the actual diameter of the ARES beam should be used to determine the effective gain of the optical system. For viewing distances greater than 24 meters the diameter of the collecting aperture is the appropriate value for evaluating the effective gain of the pair of 7 x 50 binoculars. It is unlikely that aided viewing will take place inside of 24 meters.

Evaluation of the Effective Gain

For intrabeam aided viewing of the ARES laser at distances greater than 24 meters the effective optical gain can be calculated.

$$G_{eff} = \tau_\lambda \frac{D_c^2}{D_f^2} \qquad \text{for: } R > 24 \text{ meters}$$

<u>Given</u>:

D_c: 24.5 mm (calculated above)
D_f: 3.5 mm (ANSI Std. Z136.1–Table 8)
τ_λ: 0.7 (ANSI Std. Z136.1–Table 9)

$$G_{eff} = (0.7)\frac{(24.5\ mm)^2}{(3.5\ mm)^2}$$

$$G_{eff} = 34.3$$

Evaluation of Increased Hazard

The increase in the ocular hazard for intrabeam aided viewing of the ARES laser using a pair of (7 x 50) binoculars at greater than 24 meters, viewing longer than 10 seconds over similar unaided interviewing is as follows.

$$H_{7\times 50} = \frac{MPE}{34.3}$$

Extended Ocular Hazard Distance

In general, the use of optical viewing aids is not expected down range from the laser during laser operation.

The Extended Ocular Hazard Distance (EOHD) can be determined from the increased hazard as a result of the optical gain of the optical system.

The formula for calculating the EOHD is derived from the formula for the NOHD given in the Appendix of the ANSI Std. Z136.1–2000 as follows, where MPE is replaced by the increased hazard term (H):

Recall

$$NOHD = \frac{1}{\theta}\sqrt{\frac{4Q_o}{\pi MPE} - d_{out}^2} \quad cm$$

Where;

NOHD:	Nominal Ocular Hazard Distance, in centimeters.
θ:	Beam divergence, in radians.
Q_o:	Output radiant energy, in joules.
MPE:	Maximum Permissible Exposure, in Joules/cm^2.
d_{out}:	Output beam diameter of the laser, in centimeters.

$$EOHD = \frac{1}{\theta}\sqrt{\frac{4Q_o}{\pi H} - d_{out}^2} \quad cm$$

Where;

EOHD:	Extended Ocular Hazard Distance, in centimeters.
θ:	Beam divergence, in radians.
Q_o:	Output radiant energy, in joules.
H:	Increased hazard, in Joules/cm^2.
d_{out}:	Output beam diameter of the laser, in centimeters.

Where;

$$H = \frac{MPE}{G_{eff}}$$

$$EOHD = \frac{1}{\theta}\sqrt{\frac{4Q_o}{\pi \frac{MPE}{G_{eff}}} - d_{out}^2} \quad cm$$

Simplified as;

$$EOHD = \frac{1}{\theta}\sqrt{\frac{4G_{eff}Q_o}{\pi MPE} - d_{out}^2} \quad cm$$

As applied to the intrabeam viewing of the ARES laser with a pair of 7 x 50 binoculars at a distance greater than 24 meters for viewing times greater than 10 seconds.

Evaluation of the EOHD for a radiant output of 40 mJ

Given:

- θ: 500 x 10^{-6} radians
- Q_o: **40 x 10^{-3} Joules**
- d_{out}: 1.25 cm
- G_{eff}: 34.3

$$EOHD_{40mJ} = \frac{1}{\theta}\sqrt{\frac{(4)(34.3)(40\times10^{-3})}{\pi MPE} - (1.25)^2} \quad cm$$

$$EOHD_{40mJ} = 20\sqrt{\frac{1.747}{MPE} - 1.56} \quad meters$$

Evaluation of EOHD for radiant output of 50 mJ

Likewise for the following given parameters:

θ: 500×10^{-6} radians
Q_o: **50 x 10^{-3} Joules**
d_{out}: 1.25 cm
G_{eff}: 34.3

$$EOHD_{50mJ} = \frac{1}{\theta}\sqrt{\frac{(4)(34.3)\left(50 \times 10^{-3}\right)}{\pi MPE} - (1.25)^2} \quad cm$$

$$EOHD_{50mJ} = 20\sqrt{\frac{2.184}{MPE} - 1.56} \quad meters$$

Approximation Method

In this particular case where the single pulse MPE is 5.45 mJ/cm^2, and the output radiance is 40 mJ, the laser exit diameter term can be dropped with less than 0.5% error.

$$\frac{1.747}{MPE} = \frac{1.747}{5.45 \times 10^{-3}} = 320.5$$

$$320.5 >> 1.56$$

Similarly the laser exit diameter term can be dropped for an output radiance of 50 mJ (error < 0.4%).

$$\frac{2.184}{MPE} = \frac{2.184}{5.45 \times 10^{-3}} = 400.7$$

$$400.7 >> 1.56$$

The EOHD can be approximated from the NOHD multiplied by a scale factor (square root of the effective optical gain).

$$\text{EOHD} \approx \sqrt{G_{eff}} \bullet \text{NOHD}$$

Where;

EOHD: Extended Ocular Hazard Distance

NOHD: Nominal Ocular Hazard Distance

G_{eff}: Effective Gain of the Optical System

Alternatively;

$$EOHD \approx \sqrt{\tau_\lambda} \left[\frac{D_c}{D_f} \right] NOHD$$

Where;

D_c: Diameter of the collecting aperture
D_f: Limiting diameter (ANSI Std. Z136.1–Table 8)
τ_λ: Transmission factor (ANSI Std. Z136.1–Table 9)

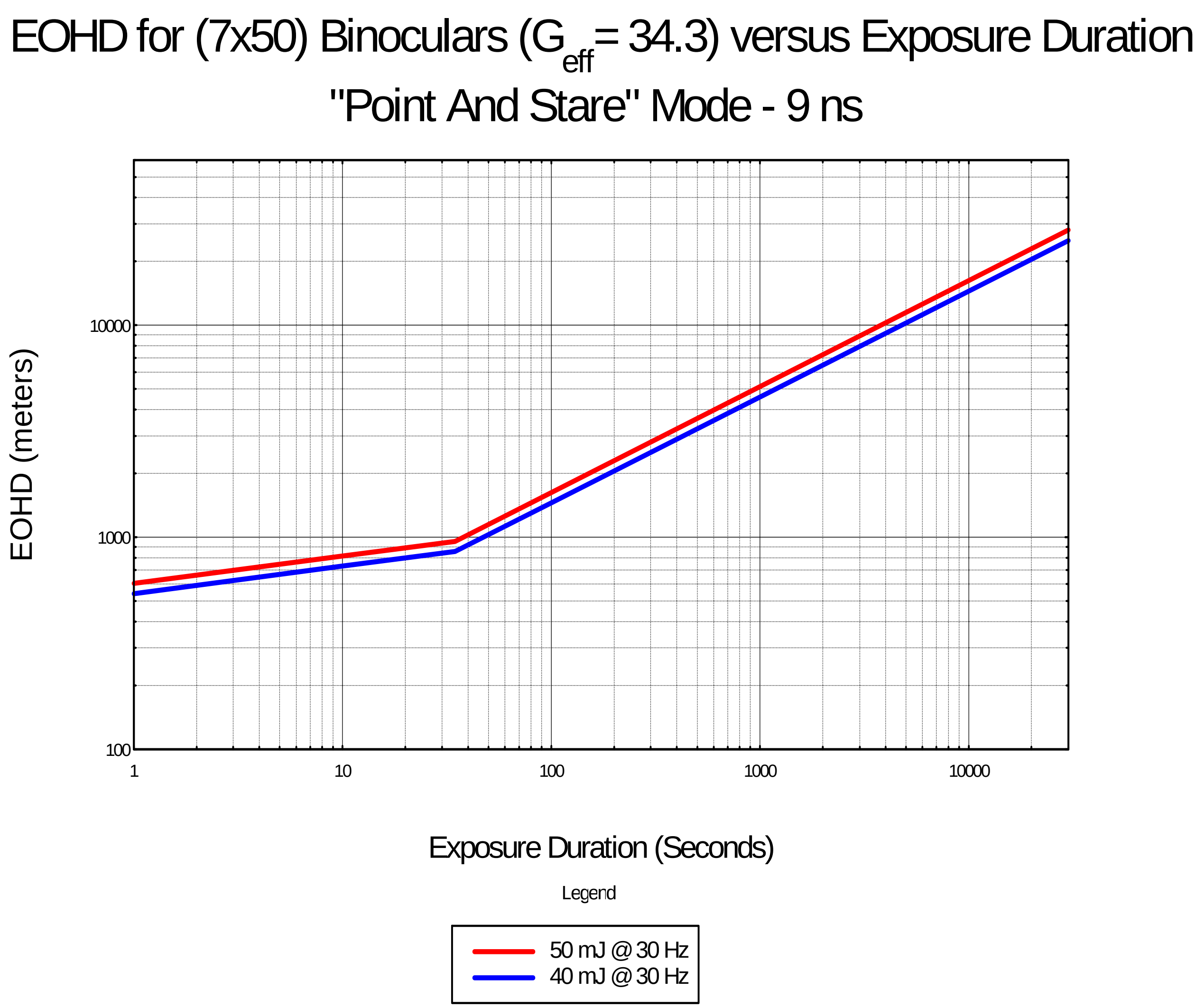
The approximation method is useful when used with a laser hazard computer program such as RLI® family of LAZAN© laser safety programs, which can readily be used to calculate the NOHD but not the EOHD.

The following series of plots were generated using the exact calculated values and not the approximation method.

Point and Stare Mode - Aided Viewing

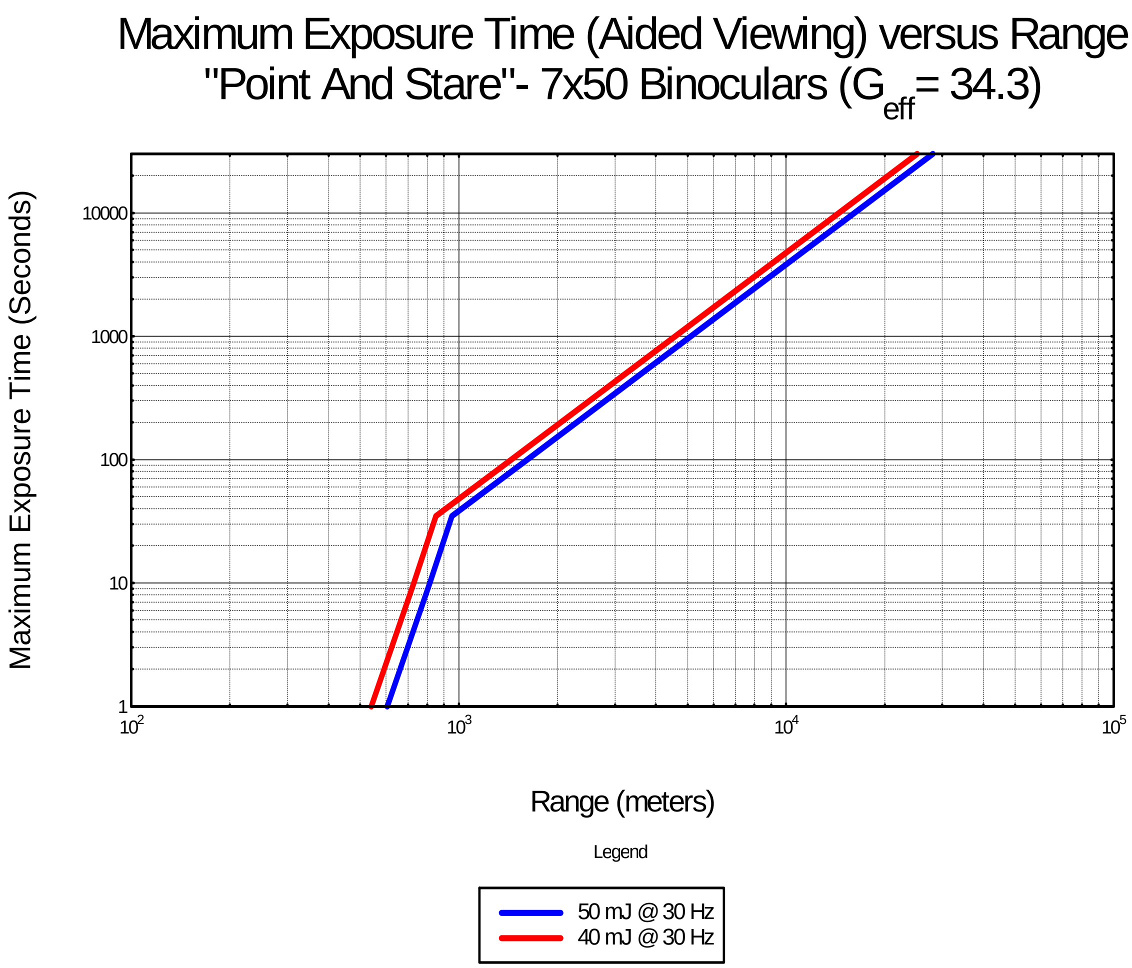
The "eye-safe" distances for aided intrabeam viewing for various laser run or exposure times can be acquired from the following plots.

EOHD versus Time - Point and Stare



Eye-Safe Exposure Time vs. Distance – Point and Stare

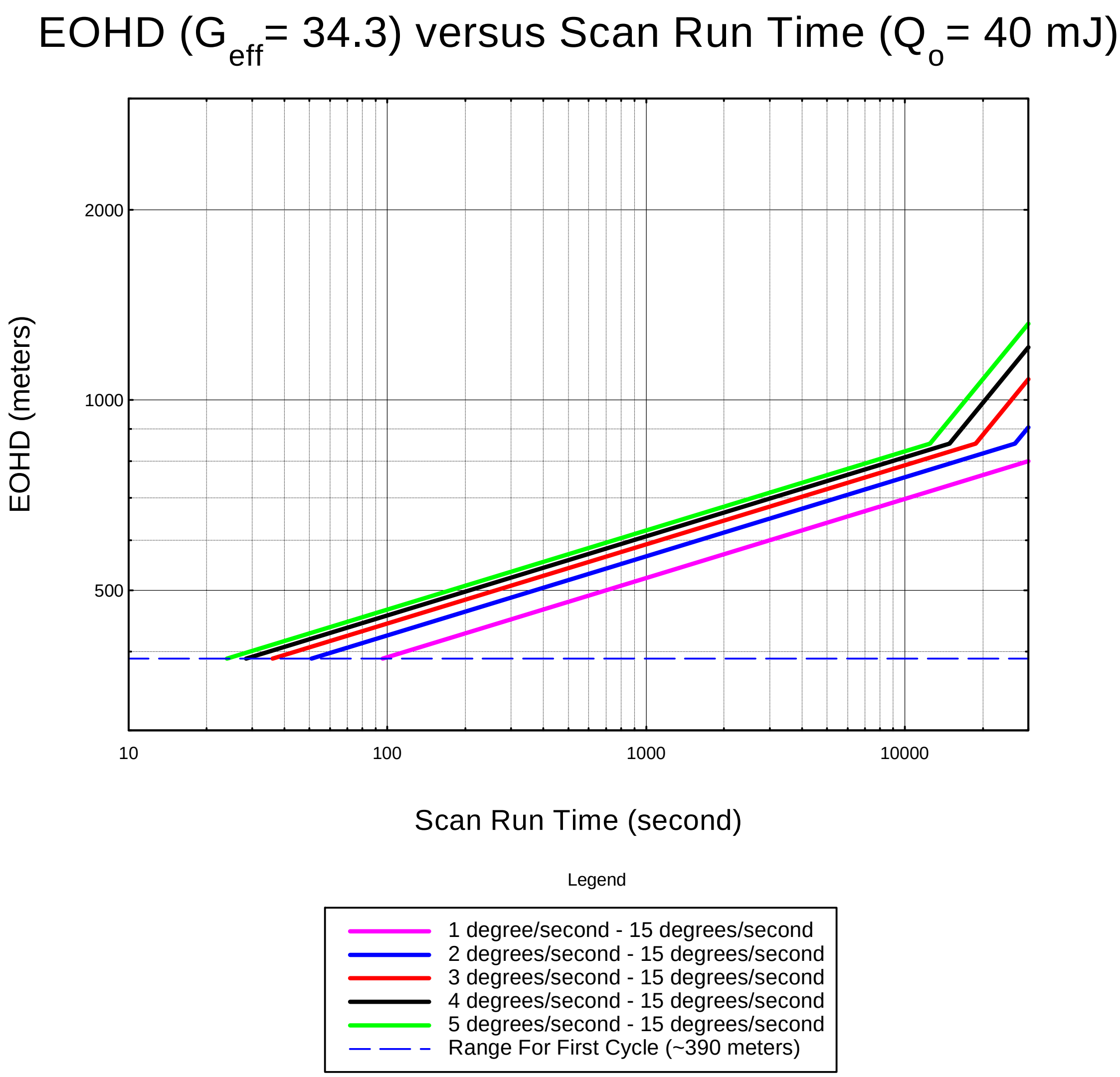
The maximum "eye-safe" dwell time or exposure for aided intrabeam viewing at various distances for a radiant output of 40 mJ and 50 mJ at a PRF of 30 hertz can be attained from the following plot.



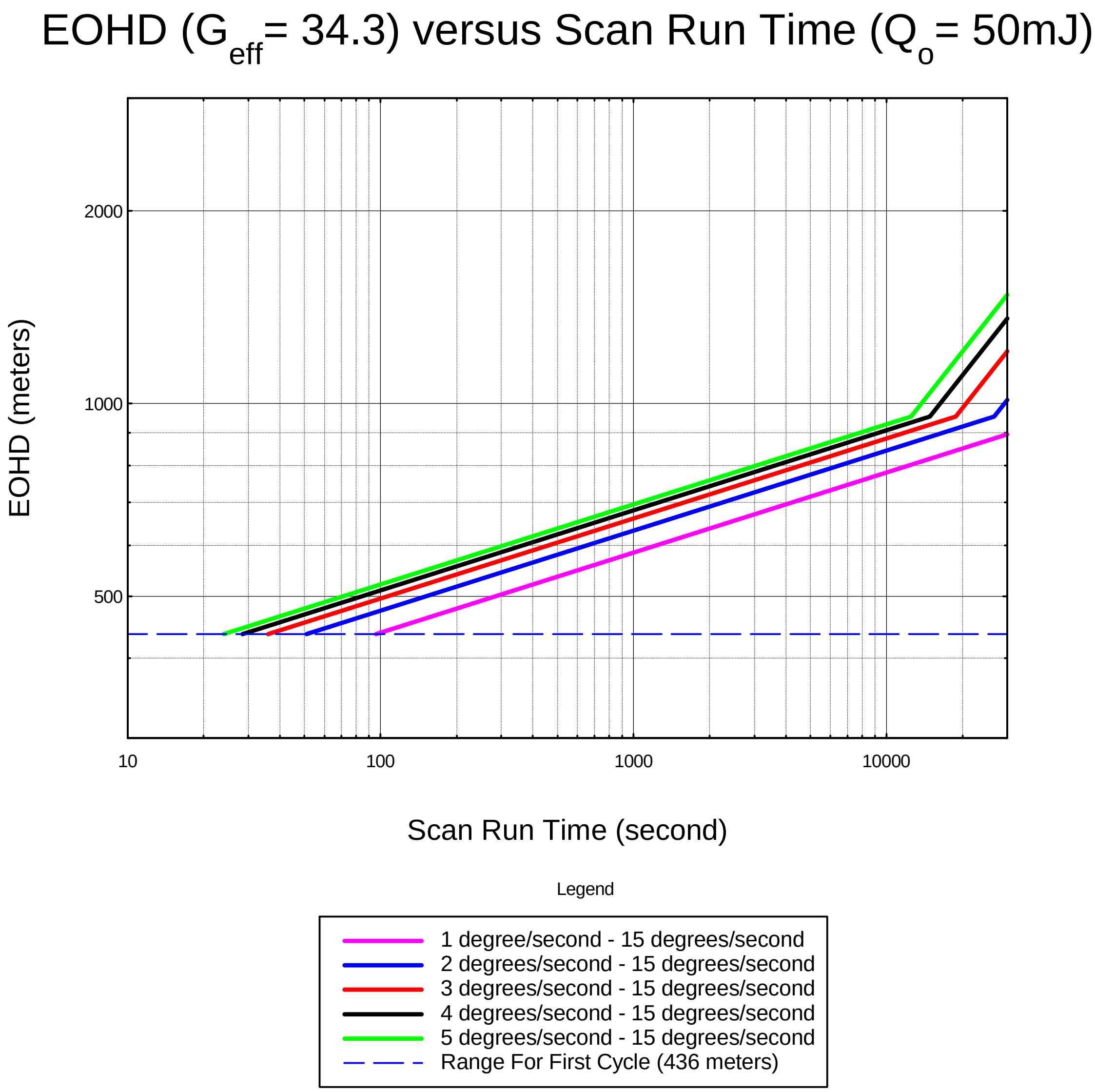
Scanning Mode (Aided Viewing)

EOHD in Scanning Mode

The “eye-safe” distances for aided intrabeam viewing for a radiant output of 40 mJ at a PRF of 30 hertz for various scan rates and laser operation times can be acquired for the following plot.

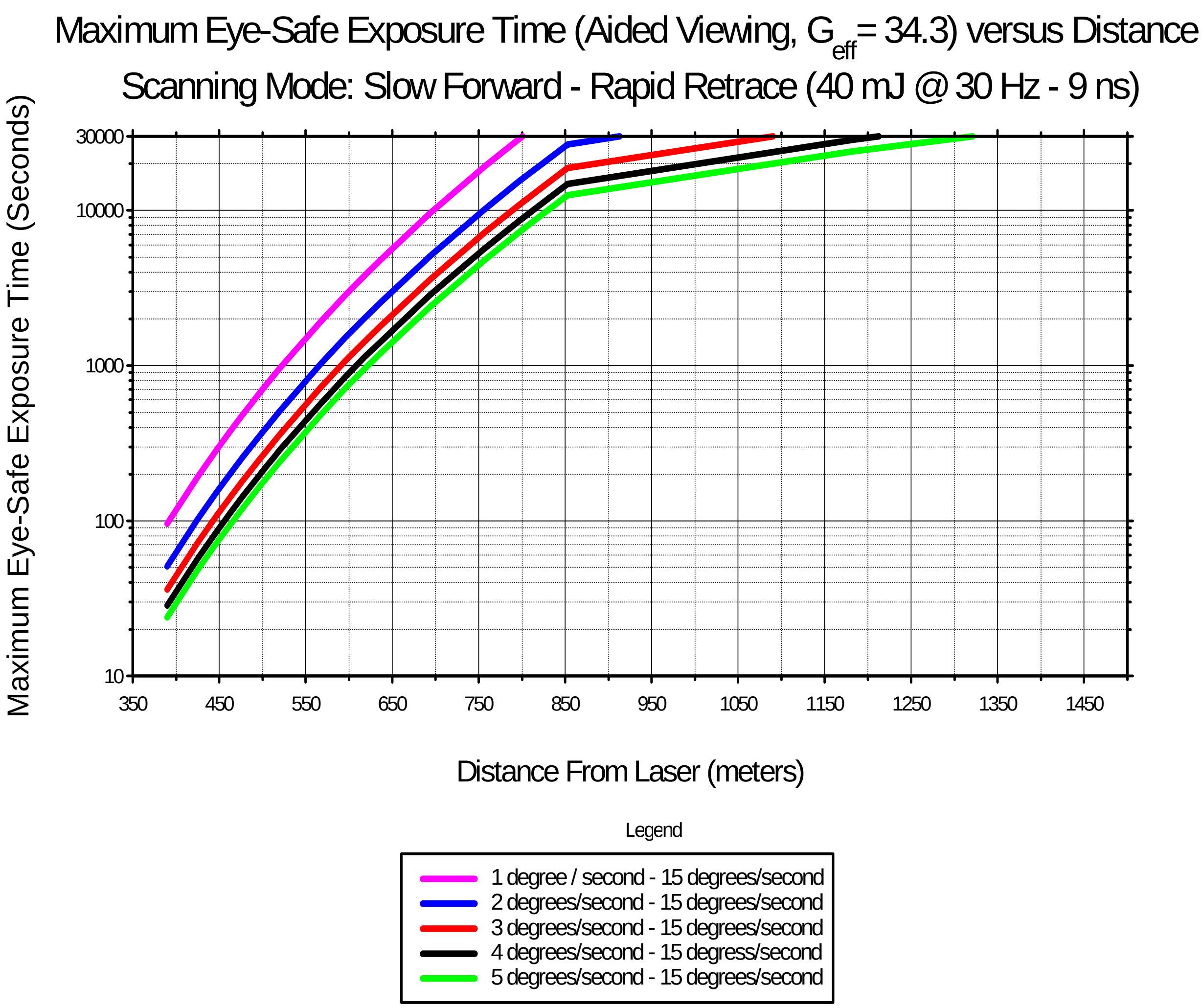


The “eye-safe” distances for aided intrabeam viewing for a radiant output of 50 mJ at a PRF of 30 hertz for various scan rates and laser operation times can be acquired for the following plot.



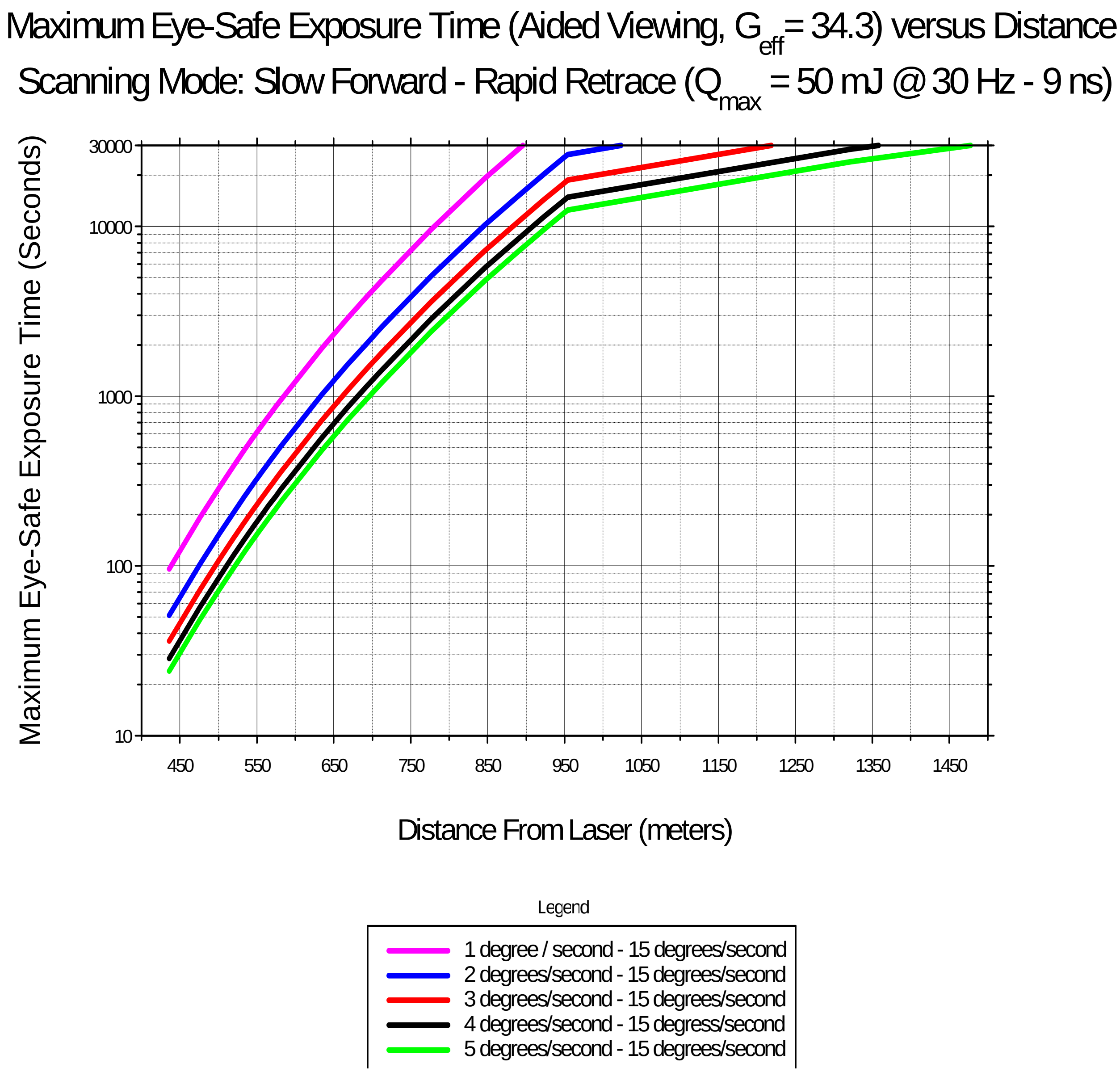
Eye-Safe Exposure Time versus Distance – Scanning Mode

The maximum eye-safe exposure times for "aided viewing" can be estimated from the plot that follows.



Should the BSLT laser be operated at maximum output the maximum eye-safe exposure times as a function of line-of-sight distance from the laser can be estimated from the charts that follow.

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



V. Summary

Eye-Safe Exposure Distances For Typical Operation (40 mJ @ 30 Hz)

Table 8

Summary of NOHD and EOHD – Point and Stare

	Point-N-Stare Mode	
Exposure (second)	NOHD (meters)	EOHD (meters)
1	90.1	547
10	122	731
60	190	903
100	246	1,448
600	605	3,543
30,000	4,284	25,090

Table 9

Summary of NOHD and EOHD – Typical Scanning Mode

		Scanning Mode	5^o/sec
Run Time	Exposure (second)	NOHD (meters)	EOHD (meters)
1 min	60	70.4	437
2 min	120	77.6	477
10 min	600	96.5	583
30 min	1,800	112	669
1 hr	3,600	122	730
2 hr	7,200	134	796
4 hr	14,400	154	915
8 hr	28,800	220	1,295

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 2003–0050, January 2003, Laser Safety And Hazardous Analysis for the ARES (Big Sky) Laser System, Arnold L. Augustoni

VII. Symbols and Abbreviations

AEL	Accessible Emission Limit or Allowable 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.
cm	Centimeter.
C_p	Multiple pulse correction-factor.
CW	Continuous wave.
D_c	Diameter of collecting aperture of an optical system.
D_e	Diameter of exit pupil of an optical system.
d_{eye}	Entrance (pupil) diameter of the eye.
D_f	Diameter of limiting aperture.
D_L	Laser beam diameter at some range from the laser.
d_{out}	Output beam diameter.
D_o	Diameter of the objective optic of an optical system.
E	Irradiance, in J/cm^2.
E_o	Output Irradiance, in J/cm^2.
EOHD	Extended Ocular Hazard Distance.
G	Optical Gain.
G_{eff}	Effective Optical Gain.
H	Increased Hazard (in J/cm^2).
H_{7x50}	Increased Hazard for a 7x50 binocular (in J/cm^2).
H_{max}	Maximum Increased Hazard (in J/cm^2).
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.
$MPE_{s.p.\text{-}thermal}$	Single Pulse MPE based on the thermal limit.
n	Number of pulses.
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.
P	Magnifying power.
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	Exposure duration, pulse duration or pulse width.
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.
β	Angular separation between laser pulses – scanning mode.
θ	Beam divergence.
τ_λ	Transmission factor (wavelength dependent).
λ	Wavelength.

VIII. Distribution List

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