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Safety and Hazard Analysis for the Coherent/Acculite Laser Based Sandia Remote Sensing System (Trailer B70)

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Abstract

A laser safety and hazard analysis is presented, for the Coherent® driven Acculite® laser central to the Sandia Remote Sensing System (SRSS). The analysis is 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 trailer (B70) based SRSS laser system is a mobile platform which is used to perform *laser interaction* experiments and tests at various national test sites. The trailer based SRSS laser system is generally operated on the United State Air Force Starfire Optical Range (SOR) at Kirtland Air Force Base (KAFB), New Mexico. The laser is used to perform *laser interaction* testing inside the laser trailer as well as outside the trailer at target sites located at various distances. In order to protect personnel who work inside the Nominal Hazard Zone (NHZ) from hazardous laser exposures, it was necessary to determine the Maximum Permissible Exposure (MPE) for each laser wavelength (wavelength bands) and calculate the appropriate minimum Optical Density (OD_{min}) necessary for the laser safety eyewear used by authorized personnel. Also, the Nominal Ocular Hazard Distance (NOHD) and The Extended Ocular Hazard Distance (EOHD) are calculated in order to protect unauthorized personnel who may have violated the boundaries of the control area and might enter into the laser's NHZ for testing outside the trailer.

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Summary

A summary of the values for the minimum Optical Density of the laser safety eyewear which are required to be worn by the personnel who work within the boundary of the Nominal Hazard Zone (both inside and outside the laser trailer) and the appropriate Safe Eye Exposure Distances also known as the Nominal Ocular Hazard Distance (outside the laser trailer) are presented in Table 1. Laser safety eyewear that is suitable for the NHZ inside the laser trailer will also be suitable for personnel in the NHZ outside the laser trailer. Having one set of laser safety eyewear, which protects against the greater ocular hazards inside the trailer will preclude the inadvertent use, by personnel inside the trailer, of inappropriate eyewear (OD too low to provide adequate protection) intended for use outside the trailer (down range).

Calculated values present within are displayed to two decimal places. An EXCEL spreadsheet calculator was developed to model this system and is presented in the APPENDIX. The values presented in the body of the report were determined by this EXCEL calculator.

Table 1

Laser Safety Eyewear Available

Manufacturer	Model	OD 180 – 315 nm	OD 180 – 315 nm	OD Green 532 nm	OD Red 633 nm	OD IR 1064 nm	OD IR 1550 nm
UVex*	**L268**	**8**	**8**	**0.2**	**1-2**	**8+**	**2+**
UVex	LOTG	9+	9+	-	-	7+	5+
Glendale	Argon	10	10	10	0.1	-	-

*UVex (L268) Eyewear meets minimum OD requirement for all wavelengths except for 532 nm.

Table 2

NOHD/EOHD (Day/Night)

Wavelength (nm)	Radiant Output	NOHD day (meters)	EOHD day (meters)	NOHD night (meters)	EOHD night (meters)
1550	10 mJ	**Eye Safe**	341	**Eye Safe**	341
1064	10 mJ	2,640	15,500	3,400	19,900
633	15 mw	27.4	182	35.2	234
315-400	20 mJ	**Eye Safe**	767	**Eye Safe**	767
355	35 mJ	**Eye Safe**	1,030	**Eye Safe**	1,030
180-302	10 mJ	1,740	1,720	1,740	1,720
266	20 mJ	2,460	2,440	2,460	2,440

*Shaded sections indicates "corneal hazard region", which is not affected by nighttime exposure.

Table 3

Laser Output Specifications / Characteristics / OD & NOHD

Wavelength (nm)	Output (mJ)	MPE (J/cm^2)	Time (sec)	OD_{min}	Suitable Laser Eyewear Available	NOHD/ NHZ (km)
		INSIDE	OF	THE	TRAILER	
1550	10	3.33×10^{-3}	10	**1.49**	**UVex L268** UVex LOTG	Room
1064	500	1.2×10^{-6}	10	**6.03**	**UVex L268** UVex LOTG	Room
633	15 mw	2.55×10^{-3} w/cm^2	0.25 *2	**1.19**	**UVex L268**	Room
532	250	297×10^{-9}	0.25 *2	**6.34**	**Glendale Argon**	Room
355	35	444×10^{-9} *3	30,000	**5.91**	**UVex L268** UVex LOTG	Room
266	20	3.33×10^{-9}	30,000	**7.79**	**UVex L268** UVex LOTG	Room
180-280	10	3.33×10^{-9}	30,000	**7.49**	**UVex L268** UVex LOTG	Room
280-302	10	1.33×10^{-9} *3	30,000	**7.89**	**UVex L268** UVex LOTG	Room
315-400	20	444×10^{-9} *3	30,000	**5.67**	**UVex L268** UVex LOTG	Room
		OUTSIDE	OF	THE	TRAILER	
1550	10	3.33×10^{-3}	10	**0 *4**	**UVex L268** **UVex LOTG**	**0*4**
1064	10	1.2×10^{-3}	10	**2.02**	**UVex L268** **UVex LOTG**	**2.05**
633	15 mw	10^{-3} w/cm^2	600 *1	**1.59**	**UVex L268**	**0.027 *2**
355	35	556×10^{-6}	60	**0 *4**	**UVex L268** **UVex LOTG**	**0 *4**
266	20	1.67×10^{-6}	60	**2.18**	**UVex L268** **UVex LOTG**	**2.46**
180-302	10	1.67×10^{-6}	60	**1.87**	**UVex L268** **UVex LOTG**	**1.74**
315-400	20	556×10^{-6}	60	**0 *4**	**UVex L268** **UVex LOTG**	**0 *4**

Bold Red Font: UVex (L268) Eyewear meets minimum OD requirement for all wavelengths **except** for **532 nm**.

*Notes:

1: Alignment exposure (600 seconds) – Class 1 Laser Hazard Protection
2: Aversion response exposure (0.25 seconds) – Class 2 Laser Hazard Protection
3: 2nd Day Exposure factor applied
4: Radiant Exposure at telescope output is less than the MPE
Shaded section indicates the laser parameters inside B70.

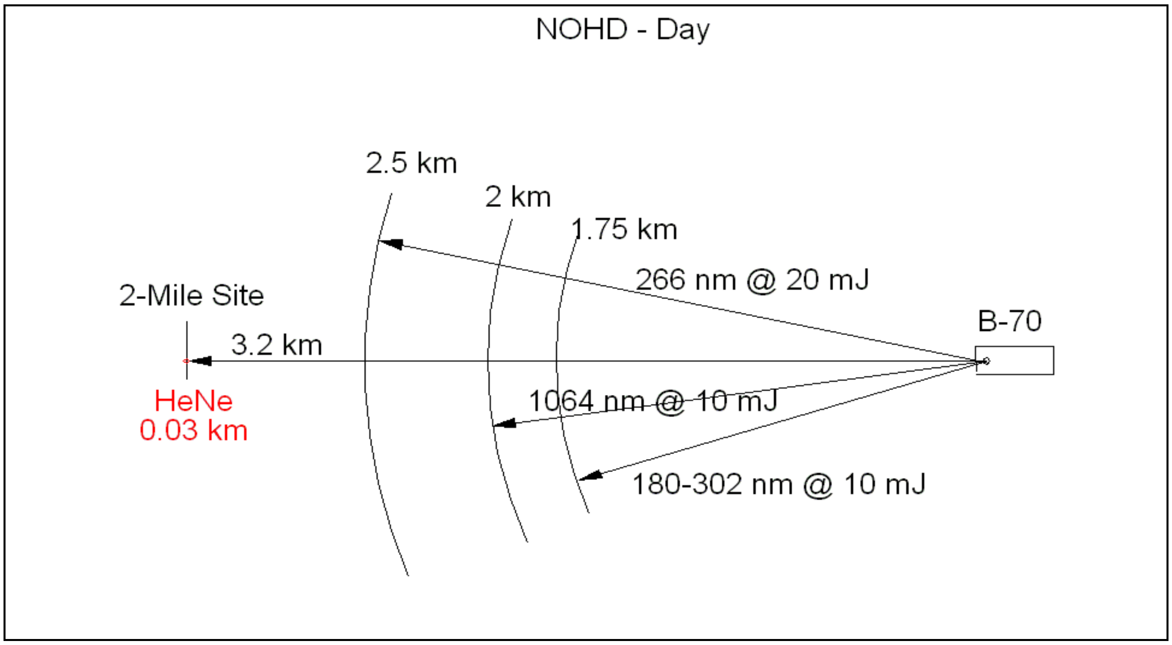

Figure 1

The Daytime Eye-Safe (NOHD) Ranges for a typical 60-second test at the various outputs from B70. Outputs at 315 nm to 400 nm and at 1550 nm are eye safe. The HeNe alignment laser NOHD is approximately 30 meters from the target area.

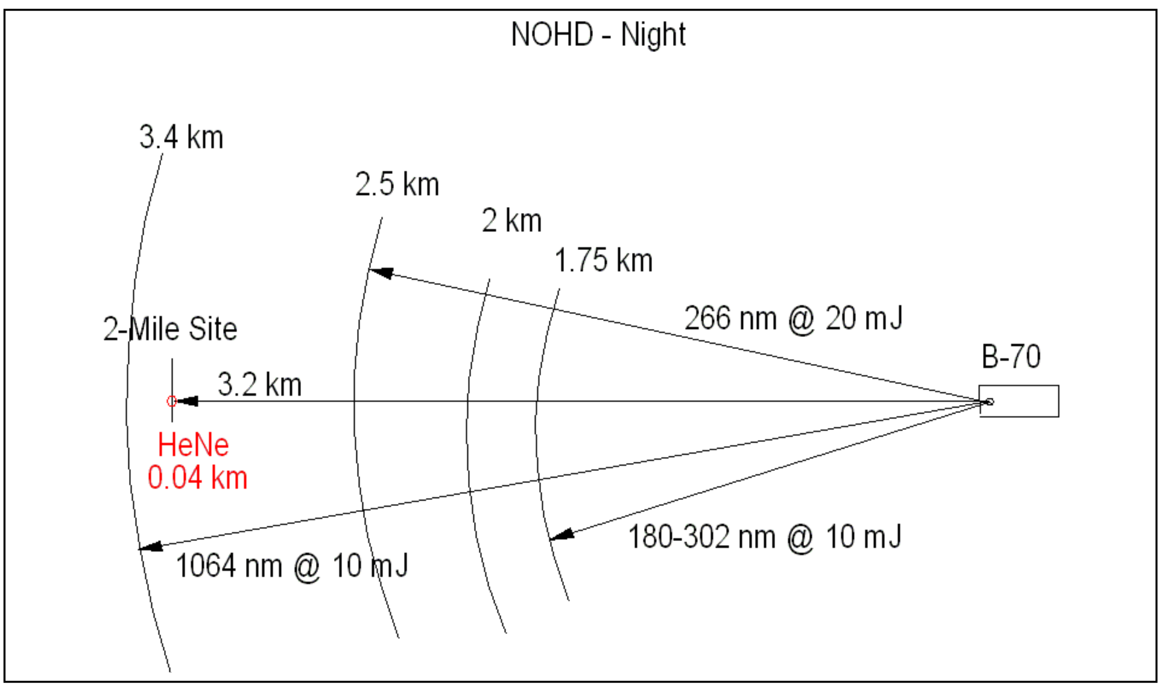

Figure 2

The Nighttime Eye-Safe (NOHD) Ranges for a typical 60-second test at the various outputs from B70. Outputs at 315 nm to 400 nm and at 1550 nm are eye safe. The HeNe alignment laser NOHD is approximately 40 meters from the target area.

I. Introduction

The trailer (B-70) based SRSS laser system contains a Class 4 Q-switched Nd:YAG laser, which serves as pump source to an Optical Parametric Oscillator (**OPO**), Optical Parametric Amplifier (**OPA**) and sum frequency generation (**SFG**). The SFG system can produce an output at ultraviolet (UV) wavelengths from 400 nm to 250 nm. It is mounted inside a mobile platform (trailer B-70). The output of the laser system can exit the trailer through a gimbaled telescope, which directs the beam to a distant location or test site to perform remote *interaction* tests. The gambol limits prevents the laser beam from entering into navigable air space. The SRSS laser can also be used to perform *laser interaction* tests and experiments inside the trailer as well as at remote test sites. The Class 3b Helium Neon (HeNe) laser is used as an alignment tool operated from the target location and directed back towards the SRSS trailer.

A. Laser Parameters

The Coherent® Nd:YAG laser can produce outputs at the fundamental, the second, third and fourth harmonics as indicated in Table 2 below. The Acculite ® OPO can produce outputs in the ultraviolet region and possible emissions in the IR region as indicated in Table 2 below. The diameter of the laser beam inside the trailer is 5 mm. The diameter of the beam exiting the telescope is 101 mm. The divergence of the laser beam outside the trailer is on the order of 500 micro-radians.

Table 4

Table of Laser Parameters
(t_{pulse} = 2 ns)

Type	Manufacturer	Model	Output	Wavelength (nm)
YAG	Coherent	Infinity	500 mJ @ 30 Hz	1064
Doubled YAG	"	"	250 mJ @ 30 Hz	532
Tripled YAG	"	"	35 mJ @ 30 Hz	355
Quadruple YAG	"	"	20 mJ @ 30 Hz	266
OPO	Acculite	Ultra source	10-20 mJ @ 30 Hz 1-10† mJ @ 30 Hz	250-400 1550
HeNe	Hughes*	3227H-C	15 mw	633

* Other HeNe lasers with outputs of 15 mw or less may be used instead or in addition to the one listed.
† Maximum output (requires system modification to achieve output at this wavelength).

B. Laser Safety (Terms and Definitions)

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, Standard Exposure Time and the "limiting aperture". All of which, to varying degrees, are wavelength dependent.

1. Maximum Permissible Exposure

The appropriate Maximum Permissible Exposure (**MPE**) for repetitively pulsed lasers is always the **smallest** of the MPE values derived from the application of ANSI Rule 1 through Rule 3 presented in the standard (*ANSI Std. Z136.**1**–2000 {8.2.3}*).

a. Ocular vs. Skin Exposure

Throughout the ultraviolet region of the spectrum the ocular MPE is always less than or equal to the MPE for skin (*Table 5a* vs. *Table 5b* of the *ANSI Std. Z136.**1***). 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 personnel within the Nominal Hazard Zone (**NHZ**) should always protect their exposed skin through the use of adequate clothing and "sunscreen" products on their exposed skin.

2. Allowable Emission Limit / Allowable 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 Class 1 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 Class 2 AEL (applicable to visible lasers only) uses the MPE calculated for the aversion response time of 0.25 seconds presented in *ANSI Std. Z136.**1**–2000 {Table 4a}*. The values for the limiting aperture, as a function of laser wavelengths and exposure times, are presented in *Table 8* of the ANSI Z136.**1** standard. Relative to the exposed person, for small source lasers, this can be considered an Allowable Exposure Limit and will hence be referred to also as the AEL. Additionally hereafter the term AEL will refer to the Class 1 AEL for "invisible lasers" ($\lambda < 400$ nm or $\lambda > 700$ nm) and to the Class 2 AEL for visible wavelength lasers (400 nm $\leq \lambda \leq$ 700 nm). Correction for the non-homogeneity of small source laser cross-section is not necessary since the laser output is averaged over the limiting aperture (*ANSI Std. Z136.**1**–2000 {9.2.2.1}*).

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

3. Minimum Optical Density For Laser Safety Eyewear

The minimum Optical Density (**OD_{min}**) necessary for determining the appropriate laser safety eyewear for a particular wavelength or band of wavelengths can be computed as the logarithm (base 10) of the ratio of the output Radiant Exposure (H_o) for pulsed lasers or the irradiance (E_o) for CW lasers to the appropriate MPE or alternately as the logarithm of the ratio of the Radiant Output to the AEL (for small beams) for the particular wavelength or wavelength band involved.

The OD for laser safety eyewear must be great enough to present, to the person wearing the eyewear, an ocular hazard no greater than Class 1 for exposure to an "invisible" laser or no greater than Class 2 for an exposure to "visible" lasers.

In general for small beam lasers, in terms of the Radiant Exposure at the eye (*ANSI Std. Z136.**1**–2000 {4.6.2.5.1}*) the minimum Optical Density can be expressed as:

$$OD_{\min} = \log_{10}\left[\frac{H_f}{MPE}\right] \qquad \textit{ANSI Std. Z136.1–2000 \{Equation B98\}}$$

Where;

$OD_{\min}$: The minimum Optical Density for laser safety eyewear.

H_f : The radiant exposure, beam energy average over the limiting aperture, in J/cm^2.

MPE : The appropriate MPE, in J/cm^2.

Or in terms of the output Radiance Output:

$$OD_{\min} = \log_{10}\left[\frac{Q_o}{AEL}\right] \qquad \textit{ANSI Std. Z136.6–2000 \{Equation B4\}}$$

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 large beam lasers ($d_o > D_f$), in terms of Radiant Exposure:

$$OD_{\min} = \log_{10}\left[\frac{H_p}{MPE}\right] \qquad \textit{ANSI Std. Z136.}\boldsymbol{1}\textit{–2000 \{Equation B99\}}$$

<u>Where;</u>

$OD_{\min}$: The minimum Optical Density for laser safety eyewear.

H_p: The radiant exposure, beam energy average over the beam area in J/cm^2.

MPE: The appropriate MPE, in J/cm^2.

4. <u>Nominal Ocular Hazard Distance</u>

The Nominal Ocular Hazard Distance (**NOHD**) is the unaided eye-safe intrabeam viewing distance from the laser. The NOHD is generally 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.

a. <u>Authorized vs. Unauthorized Exposures</u>

Authorized personnel working inside the NHZ are required to wear appropriate laser safety eyewear selected to provide full protection to the ocular threat (laser hazard) present. Typically, the NHZ is inclusive to the laser control area. Access to the control area is 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, to the incident laser beam or to specular reflections of the laser beam. Unauthorized personnel are not expected to be in the laser control area and their presence 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:

$$NOHD = \frac{1}{\theta} \cdot \sqrt{\frac{4 \cdot Q_o}{\pi \cdot MPE} - d_o^2} \qquad \textit{ANSI Std.Z136.}\boldsymbol{1}\ \textit{\{Figure B6\}}$$

Where;

$NOHD$:	Nominal Ocular Hazard Distance, in centimeters.
θ :	Beam divergence, in radians.
Q_o :	Laser radiant output energy, in joules.
MPE :	Appropriate per pulse Maximum Permissible Exposure, in J/cm^2.
d_o :	Output beam diameter of the laser, in centimeters.

b. Atmospheric Transmission Considerations

Atmospheric transmission conditions **are not** normally considered for transmissions of less than a kilometer. For laser transmissions of a kilometer or greater atmospheric transmission losses may be considered when calculating the "eye safe" distances.

When atmospheric transmission conditions are considered the NOHD can be approximated as follows:

$$NOHD_{atm} = \frac{1}{\theta} \cdot \sqrt{\frac{4 \cdot \tau_{atm} \cdot Q_o}{\pi \cdot MPE} - d_o^2}$$

$$NOHD_{atm} \sim \sqrt{\tau_{atm}} \cdot NOHD$$

Where;

$NOHD_{atm}$:	Nominal Ocular Hazard Distance for atmospheric transmission conditions considered.
$NOHD$:	Nominal Ocular Hazard Distance (determined to provide a range estimate).
τ_{atm} :	Atmospheric *transmission factor* estimate for the range estimated by NOHD.

There are several sources for values of atmospheric *transmission factors* as a function of the laser wavelength and the range or distance. One such source is *Appendix C* of *ANSI Std. Z136.**6** – 2000*, which provides a table for atmospherically corrected values of NOHD based on the NOHD in vacuum for select atmospheric conditions. Another source is in Safety with Lasers and Other Optical Sources, Sliney and Wolbarsht.

5. Extended Ocular Hazard Distance

The eye safe distance for aided intrabeam viewing is referred to as the Extended Ocular Hazard Distance (**EOHD**). Although the use of optical aides is not anticipated, the possible use of optical aides is usually considered in the hazard evaluation of outdoor laser operations (*ANSI Std. Z136.**6** – 2000 {3.2.5.2}*).

a. Aided Viewing

The use of optical aides such as a pair of 7x50mm (7x magnifying power, 50 mm-objective) 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}*).

$$EOHD = \frac{1}{\theta} \cdot \sqrt{\frac{4 \cdot Q_o}{\pi \cdot \left(\frac{MPE}{G}\right)} - (d_o)^2} \;\; cm$$

Where;
G: Optical gain

Increased Hazard

The MPE is the quantification of the laser ocular hazard (***HAZ***) 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 viewing aid:

$$HAZ_{\uparrow} = \frac{MPE}{P^2}$$

Where;
$HAZ_{\uparrow}$: Represents the increased in the ocular hazard
MPE: Maximum Permissible Exposure
P: Magnifying Power

Optical Gain

The optical gain factor (***G***) represents the maximum increase in the ocular hazard of intrabeam viewing of the laser. In general, for a 7x50mm binocular, for laser wavelengths in the retinal hazard region (400 nm $\leq \lambda <$ 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 can be expressed as:

$$G = \left[\frac{D_o}{D_e}\right]^2 = P^2$$ *ANSI Std. Z136.**1** {Equation B55}*

<u>Where;</u>

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

Maximum Gain

For example, a pair of (**7**x50mm) binoculars with a **7x** magnifying power (viewing in the retinal hazard region) the maximum gain is:

$$G_{\max} = (7)^2 = 49$$ *ANSI Std. Z136.**1**-2000 {Example 42}*

Actual Gain

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

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

<u>Where;</u>

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 $\leq \lambda_{UV} <$ 400 nm and 1.4 µm $\leq \lambda <$ 2.8 µm) (*ANSI Std. Z136.**1**–2000 {B6.4.3.2}*). The limiting aperture (diameter) in these wavelength regions are 3.5 mm for exposures of ten seconds or greater. For a single pulse (sub-microsecond) exposure in the UV region the limiting aperture is 1 mm (*ANSI Std. Z136.**1**–2000 {Table 8}*).

For laser wavelengths in these regions (302 nm $\leq \lambda_{UV} <$ 400 nm and 1.4 µm $\leq \lambda_{IR} <$ 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:

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

<u>Where;</u>

- 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 (*ANSI Std. Z136.**1**{Table 9}*)

Collecting Aperture

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

$$D_c = \min\left(D_o,\ P \cdot D_f\right)$$ *ANSI Std. Z136.**1** {Equation B56}*

<u>Where;</u>

- P: Magnifying power of the optical system.
- D_c: Diameter of the collecting aperture.
- D_o: Diameter of the objective optic.
- D_f: Diameter of the limiting aperture (*ANSI Std. Z136.**1**-2000 {Table 8}*).

EOHD (Retinal Hazard Region):

$$EOHD = \frac{1}{\theta} \cdot \sqrt{\frac{4 \cdot G \cdot Q_o}{\pi \cdot MPE} - (d_o)^2} \ \ cm \qquad (400\ \ nm \le \lambda \le 1.4\ \ \mu m)$$

EOHD (Corneal Hazard Region):

$$EOHD = \frac{1}{\theta} \cdot \sqrt{\frac{4 \cdot G_{eff} \cdot Q_o}{\pi \cdot MPE} - (d_o)^2} \ \ cm \qquad \text{For } (302\ \ nm \le \lambda < 400\ \ nm)$$

$$\& \ (1.4\ \ \mu m < \lambda \le 2.8\ \ \mu m)$$

EOHD Approximation Method:

$$EOHD \sim \sqrt{G_{aid}(\lambda)} \cdot (NOHD) \qquad (d_o < d_f)$$

Where:

$EOHD$: Extended Ocular Hazard Distance associated with intrabeam aided viewing of the laser.

$G_{aid}(\lambda)$: Optical gain of the viewing aid as a function of wavelength regions of the spectrum.

$NOHD$: Nominal Ocular Hazard Distance associated with intrabeam viewing of the laser.

EOHD Approximation With Atmospheric Transmission Considered:

The EOHD with atmospheric transmission conditions considered can be approximated as follows:

$$EOHD_{atm}(\lambda) = \sqrt{\tau_{atm}(\lambda)} \cdot EOHD$$

Where;

$EOHD_{atm}(\lambda)$: Extended Ocular Hazard Distance for atmospheric transmission conditions considered as a function of radiant wavelength.

$\tau_{atm}(\lambda)$: Atmospheric transmission as a function of the radiant wavelength.

$EOHD$: Extended Ocular Hazard Distance.

6. Nighttime Laser Hazard

The SRSS can be operated at night as well as in the day and may present an enhanced ocular hazard to the retina (from the visible or possible NIR output of the YAG pump).

(a) Retinal Hazard Region

Nighttime ocular exposures to visible-near infrared laser light, presents an **enhanced retinal hazard,** due to the increase in the pupil size. As a consequence of this larger pupil size there is an increased energy transmitted to the retina. The increased pupil size is a biophysical response to the reduced ambient light levels. This Nighttime Enhanced Ocular Hazard (**NEOH**) may be applicable for laser wavelengths in the retinal hazard region, $0.4\mu m \le \lambda \le 1.4\mu m$ (*ANSI Std.Z136.**6**–2000 {3.2.6}*). Within this retinal hazard region, the applicable limiting values in *ANSI Std. Z136.**1**–2000 {Table 5a}*, the diameter of the pupil is standardized to 7 mm, which is almost the largest pupil size for typical ambient illuminations (*ANSI Std.Z136.**6**–2000 {3.2.5}*). However, if the laser is used under total darkness conditions the Nighttime Enhanced Ocular Hazard (NEOH) factor may need to be evaluated (Safety with Lasers and Other Optical Sources, Sliney & Wolbarsht). This NEOH factor is applicable to the visible and NIR (633 nm and possible 532 nm & 1064 nm) output of the SRSS. The standard ANSI analysis, based on the daylight MPE values, can be adjusted for nighttime exposure by the use of the *NEOH* factor.

Pupil Size and the Limiting Aperture

The typical pupil size for a normal human is on the order of 3 mm (in a 70 year old person) to 5 mm (in a 20 year old person) in indoor/daylight and >3 mm (in a 70 year old person) to 9 mm (in a 20 year old person) at night depending upon the age of the individual and the ambient light conditions. The *limiting aperture* for the *retinal hazard region* listed in *ANSI Std.Z136.**1**–2000 {Table 8}* is **standardized at 7 mm** and may **not be the actual physical** pupil **size**.

Worst Case NEOH

The worst case (most conservative) would involve an increase in pupil size from 7 mm to 9 mm. The increase in the nighttime ocular exposure hazard level or the *NEOH* factor can be estimated by the ratio of the pupil areas (nighttime at total darkness to the limiting aperture presented in *ANSI Std. Z136.**1**–2000 {Table 8}*.

$$NEOH = \frac{A_{night-pupil}}{A_{day-pupil}}$$

$$NEOH = \frac{(d_{night-pupil})^2}{(d_{day-pupil})^2}$$

$$NEOH = \frac{(9 \ \ mm)^2}{(7 \ \ mm)^2}$$

$$NEOH = 1.65$$

The worst-case nighttime enhanced ocular hazard factor is: **1.65**.

Increased Night Hazard

$$MPE_{night} = \frac{MPE}{NEOH}$$

$$MPE_{night} = \frac{MPE}{1.65}$$

C. Modes of Operations

The SRSS laser system can present several modes of operations. The indoor mode involves system alignment and adjustments or performing interaction tests or experiments inside the trailer. The outdoor mode involves laser interaction tests and experiments outside the trailer (including alignment to the target).

1. Indoor Mode: System Alignment

   The process to align the pump laser source (Nd:YAG laser) to the various system elements, in the OPO/A, generally involves significantly greater exposure durations than are anticipated for the routine or typical laser interaction tests or experiments.

2. Indoor Testing Mode

   Laser interaction tests can be conducted inside the SRSS laser trailer (B-70). These laser interaction tests are expected to be on the order of 60 seconds in duration. There may be up to 12 outdoor laser runs in a test day. The appropriate exposure for workers in the immediate area of the laser operations, suggested by *ANSI Std. Z136.**1**–2000 {Table 4a}*, is 30,000 seconds. Consequently indoor laser interaction testing can be considerably longer in duration than outside laser interaction testing.

3. Outdoor Alignment Mode

   The alignment of the test target to the SRSS laser output beam is accomplished using a Class 3b visible laser (HeNe) operated from the target location and directed back to the SRSS trailer light collecting telescope. The duration of the alignment process could be as long as 600 seconds (10 minutes). The appropriate exposure to use for this analysis is 600 seconds.

4. Outdoor Testing Mode

   The typical expected duration for outdoor laser interaction testing is on the order of 60 seconds per test with an accumulative exposure of 720 seconds for a test day.

D. Appropriate Exposures

The appropriate exposures, which are used in performing a laser safety and hazard evaluation; generally involve the "time of intended use" if known (*ANSI Std. Z136.**1**–2000 {4.6.2.5.2}*) or the exposure times suggested in *Table 4a* of the *ANSI Z136.**1**–2000* standard if the expected exposure is not known.

Table 5

Appropriate Exposures

Wavelength (nm)	NHZ Location	Time (Seconds)	Comments
1064	Inside	10	ANSI Std. Z136.1 *Table 4a*
532	Inside	0.25	ANSI Std. Z136.1 *Table 4a*
355	Inside	30,000	ANSI Std. Z136.1 *Table 4a*
266	Inside	30,000	ANSI Std. Z136.1 *Table 4a*
250-400	Inside	30,000	ANSI Std. Z136.1 *Table 4a*
633	Inside	0.25	ANSI Std. Z136.1 *Table 4a*
250-400	Outside	60	Intended (Single Test) Exposure
250-400	Outside	600	Intended Accumulative Exposure
633	Outside	600	Expected Event Duration

II. Laser Hazard Analysis (Small Beam) **Inside** Trailer

Personnel who work in the NHZ of the SRSS laser inside the trailer can be exposed to several laser wavelengths at possibly hazardous levels. The wavelengths presented inside the SRSS laser trailer ranges from the UV, doubled YAG (green) in the visible and as well as the infrared (**IR**). Since eyewear to protect against all possible wavelengths at all times would be opaque, except during alignment, unused beams are blocked. The appropriate laser safety eyewear must at a minimum protect against all the invisible wavelengths at all times. Laser safety eyewear must protect personnel from the green, as well as the invisible wavelengths when the doubled YAG is present.

A. UV Region (180 nm $\leq \lambda < 400$ nm)

The 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 Z136.1* standard) and the “**thermal limit**” (the *right-hand* formula (notes) of *Table 5a*). The appropriate MPE is determined from the smallest of these dual limits (*ANSI Std. Z136.1* {*Table 5a*} {*notes*}).

The UV outputs of the SRSS laser fall into the **two** major **bands** in the UV region as presented in *Table 5a* of the *ANSI Std. Z136.1–2000*. These bands are from 180 nm to 302 nm, which is referred to hereafter as UV-1 and the band from 315 nm to 400 nm is referred to as UV-2.

1. <u>UV-1 Region</u> (**180 nm ≤ λ < 302 nm**)

The appropriate MPE formula present in *Table 5a* of the *ANSI Std. Z136.**1*** is the same for laser emission wavelengths from 180 nm to 302 nm for the first day or "initial exposure". The MPE for UV laser 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}*).

a. <u>Appropriate MPE Determination</u>

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 only (*ANSI Std. Z136.**1**–2000 {8.2.3}*).

The MPE (for each of the three rules) is dependent on the expected exposure duration. For personnel working inside the NHZ of the SRSS trailer the suggested exposure is 30,000 seconds (*ANSI Std. Z136.**1**–2000* {*Table 4a*}).

(1) <u>Rule 1 MPE</u> (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 single pulse MPE is the minimum of the MPE values for the photochemical and the thermal limits.

$$MPE_{rule1} = \min\left[photochemical\ \ \lim,\ \ thermal\ \ \lim\right] \qquad \text{\{Dual limit region\}}$$

$$= \min\left[3\times10^{-3}\ {}^{J}\!/_{cm^2},\ 0.56\cdot t^{0.25}\ {}^{J}\!/_{cm^2}\right] \quad (\textit{ANSI Std. Z136.1 Table 5a})$$

$$= \min\left[3\times10^{-3}\ {}^{J}\!/_{cm^2},\ 0.56\cdot\left(2\times10^{-9}\right)^{0.25}\ {}^{J}\!/_{cm^2}\right]$$

$$= \min\left[3\times10^{-3}\ {}^{J}\!/_{cm^2},\ 3.74\times10^{-3}\ {}^{J}\!/_{cm^2}\right]$$

$$MPE_{rule1} = 3\times10^{-3}\ {}^{J}\!/_{cm^2}$$

(180 nm ≤ λ < 302 nm)

(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}*).

$$MPE_{rule2} = \frac{MPE(T)}{n(T)}$$

The appropriate MPE for time "T" is the smallest of the MPE values derived from the photochemical and the thermal limits.

$$MPE_{rule2} = \frac{\min\left[MPE_{photochemical},\ MPE_{thermal}\right]}{n} \qquad \text{\{Dual limit region\}}$$

$$n = PRF \cdot T$$

$$= \left(30\ \sec^{-1}\right)\cdot\left(30{,}000\ \sec\right)$$

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

$$MPE_{rule2} = \frac{\min\left[3 \times 10^{-3}\ J/cm^{2},\ 0.56 \cdot \left(30 \times 10^{3}\right)^{0.25}\right]}{900 \times 10^{3}}$$

$$= \frac{\min\left[3 \times 10^{-3}\ J/cm^{2},\ 7.37\ J/cm^{2}\right]}{900 \times 10^{3}}$$

$$MPE_{rule2} = 3.33 \times 10^{-9}\ J/cm^{2}$$

(180 nm $\leq \lambda <$ 302 nm)

(3) <u>Rule 3 (Multiple-Pulse):</u>

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.

$$MPE_{rule3} = C_p \cdot MPE_{thermal}$$

$$= n^{-0.25} \cdot 0.56 \cdot t^{0.25} \qquad \textit{ANSI Std.Z136.1–2000 \{Table 6\}}$$

$$= \left(30 \ \sec^{-1} \cdot 30 \times 10^3 \sec\right)^{-0.25} \cdot 0.56 \cdot \left(2 \times 10^{-9}\right)^{0.25}$$

$$= \left(900 \times 10^3\right)^{-0.25} \cdot \left(3.74 \times 10^{-3}\ {}^{J}\!/_{cm^2}\right)$$

$$MPE_{rule3} = 122 \times 10^{-6}\ {}^{J}\!/_{cm^2}$$

(4) <u>Appropriate MPE</u>:

The appropriate MPE for the initial (first day) exposure is the smallest of the MPE values derived from ANSI Rules 1 through Rule 3 for laser emissions from 180 nm to 302 nm as presented in Table 4 below.

Table 6

Appropriate MPE (UV-1: Initial Exposure)

($180 \text{ nm} \le \lambda < 302 \text{ nm}$) - 30,000 Seconds

ANSI Rule	MPE (J/cm^2)	Comment
1	3×10^{-3}	
2	$\mathbf{3.33 \times 10^{-9}}$	**Appropriate MPE**
3	122×10^{-6}	

MPE for Successive Day Exposure

The MPE for successive day (second day) exposure to UV emission wavelengths longer than 280 nm requires that the MPE to be de-rated by a factor of 2.5 (*ANSI Std. Z136****.1****–2000 {8.2.3.1}*).

$$MPE_{2^{nd}\,Day} = \frac{MPE_{280-302}}{2.5}$$

$$= \frac{3.33 \times 10^{-9}\ {}^{J}\!/\!{}_{cm^2}}{2.5}$$

$$MPE_{2^{nd}\,Day} = 1.33 \times 10^{-9}\ {}^{J}\!/\!{}_{cm^2}$$

Table 7

Appropriate MPE (UV-1: Successive Day Exposure)

($280\ nm \le \lambda \le 302\ nm$) - 30,000 Seconds

ANSI Rule	1st Day MPE (J/cm^2)	2nd Day MPE (J/cm^2)	Comment
1	3×10^{-3}	1.2×10^{-3}	
2	**3.33×10^{-9}**	**1.33×10^{-9}**	**Appropriate MPE 2nd Day**
3	122×10^{-6}	48.4×10^{-6}	

b. Appropriate AEL Determination

The appropriate Class 1AEL is the product of the appropriate MPE and the area associated with the limiting aperture in *ANSI Std. Z136.1–2000* (*Table 8*).

(1) AEL (**$180\ nm \le \lambda \le 302\ nm$**)

$$AEL = MPE \cdot A_{\lim} \qquad \textit{ANSI Std.Z136.1–2000 \{3.2.3.4.1 (2)\}}$$

$$= MPE \cdot \frac{\pi}{4} \cdot (D_f)^2 \qquad \textit{ANSI Std.Z136.1–2000 \{Equation B23\}}$$

$$D_f = 0.35\ cm \qquad \textit{ANSI Std.Z136.1–2000 \{Table 8\}}$$

$$= \left(3.33 \times 10^{-9}\ J/cm^2\right)\frac{\pi}{4} \cdot (0.35\ cm)^2$$

$$AEL = 321 \times 10^{-12}\ J$$

(2) **AEL** (280 nm ≤ λ ≤302 nm {**2nd Day**})

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

$$= \left(.33 \times 10^{-9}\, {}^{J}\!/_{cm^2}\right)\frac{\pi}{4} \cdot \left(0.35\ \ cm\right)^2$$

$$AEL_{2^{nd}\,Day} = 128 \times 10^{-12}\, J$$

c. <u>Minimum OD Calculation</u>

(1) For the Range: **180 nm ≤ λ ≤ 280 nm**
(Use the AEL for <u>initial</u> exposure)

$$OD_{\min} = \log_{10}\left[\frac{Q_o}{AEL}\right]$$ *ANSI Std.Z136.**6**–2000 (Equation B4}*

$$= \log_{10}\left[\frac{10 \times 10^{-3}\, J}{321 \times 10^{-12}\, J}\right]$$

$$OD_{\min} = 7.49$$

(2) For the Range: **280 nm ≤ λ ≤ 302 nm**
(Use AEL for <u>successive day</u> exposure)

$$OD_{\min} = \log_{10}\left[\frac{Q_o}{AEL_{2^{nd}\,Day}}\right]$$

$$= \log_{10}\left[\frac{10 \times 10^{-3}\, J}{128 \times 10^{-12}\, J}\right]$$

$$OD_{\min} = 7.89$$

d. Summary

Laser workers and other personnel who work inside the SRSS trailer (B-70) NHZ (laser room) are expected to be exposed to the ocular hazards tabulated below and are required to wear laser safety eyewear with minimum OD(s) in the wavelength ranges indicated in the table below whenever the laser system is activated for the duration of their stay in the NHZ. It is assumed that authorized workers shall be a subjected to successive day exposures.

Table 8

SRSS Laser Room (UV-1 Exposures)

($180 \text{ nm} \leq \lambda \leq 302 \text{ nm}$)

Wavelength (nm)	**Output**	**Time (seconds)**	**MPE (J/cm^2)**	**AEL (J)**	**OD_{min}**
$180 \leq \lambda \leq 280$	10 mJ @ 30 Hz	30,000	3.33×10^{-9}	321×10^{-12}	7.49
$280 < \lambda \leq 302$	10 mJ @ 30 Hz	30,000	1.33×10^{-9}	128×10^{-12}	7.89
266	20 mJ @ 30 Hz	30,000	3.33×10^{-9}	321×10^{-12}	7.79

2. UV-2 Region (**$315 \text{ nm} \leq \lambda < 400 \text{ nm}$**)

The appropriate MPE formula, present in *Table 5a* of the *ANSI Std. Z136.1*–2000 for laser wavelengths from 315 nm to 400 nm, is identical for both the photochemical and thermal limits. The MPE for UV laser 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, but for exposures of 10 to 30,000 seconds the photochemical limit MPE is 1 J/cm^2 (*ANSI Std. Z136.1–2000 {Table 5a}*).

a. Appropriate MPE Determination

The appropriate MPE is always the smallest value derived from the application of ANSI Rules 1-3 to *Table 5a*.

(315 nm $\leq \lambda <$ 400 nm)

(1) MPE Rule 1 (Single Pulse):

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 2 nanoseconds.

$$MPE_{rule1} = \min\left[\textit{photochemical}\ \lim,\ \textit{thermal}\ \lim\right] \qquad \text{\{Dual limit region\}}$$

$$= \min\left[0.56 \cdot t^{0.25}\ {}^{J}\!/_{cm^2},\ 0.56 \cdot t^{0.25}\ {}^{J}\!/_{cm^2}\right] \qquad \textit{ANSI Std. Z136.1 \{Table 5a\}}$$

$$= 0.56 \cdot \left(2 \times 10^{-9}\right)^{0.25}\ {}^{J}\!/_{cm^2}$$

$$MPE_{rule1} = 3.74 \times 10^{-3}\ {}^{J}\!/_{cm^2}$$

(2) Rule 2 (CW/pulse):

For the wavelength region from 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". The **thermal limit does not apply** for exposures greater than 10 seconds (*ANSI Std. Z136.1–2000* {*Table 5a*} {right-hand note}).

T = 30,000 seconds

$$\begin{aligned} n &= PRF \cdot T \\ &= \left(30\ \sec^{-1}\right)\cdot\left(30{,}000\ \sec\right) \\ n &= 900 \times 10^3 \end{aligned}$$

$$MPE_{rule2} = \frac{MPE(T)}{n(T)}$$

ANSI Std.Z136.1–2000 {Table 5a}

$$MPE = 1\ {}^{J}\!/_{cm^2} \qquad 10\ \sec < T \leq 30 \times 10^3 \sec$$

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

$$MPE_{rule2} = 1.11 \times 10^{-6}\ {}^{J}\!/_{cm^2}$$

(315 nm $\leq$ λ < 400 nm)

(3) <u>MPE Rule 3</u> (Multiple-pulse):

Rule 3 applies **only** to the **thermal limit** (*ANSI Std. Z136.1–2000 {8.2.3.1}*).

T = 30,000 seconds

$$MPE_{rule3} = C_p \cdot MPE_{thermal}$$

$$= n^{-0.25} \cdot 0.56 \cdot t^{0.25} \qquad \text{ANSI Std.Z136.1–2000 \{Table 6\}}$$

$$= \left(30 \ \sec^{-1} \cdot 30 \times 10^3\right)^{-0.25} \cdot 0.56 \cdot \left(2 \times 10^{-9}\right)^{0.25}$$

$$= \left(900 \times 10^3\right)^{-0.25} \cdot \left(3.74 \times 10^{-3}\ J/cm^2\right)$$

$$MPE_{rule3} = 122 \times 10^{-6}\ J/cm^2$$

(4) <u>Summary MPE Table</u>:

<u>Table 9</u>

Appropriate MPE (UV-2: Initial Exposure)

(315 nm $\leq$ λ < 400 nm) - 30,000 Seconds

ANSI Rule	MPE (J/cm^2)	Comment
1	3.74×10^{-3}	
2	$\mathbf{1.11 \times 10^{-6}}$	**Appropriate MPE**
3	122×10^{-6}	

MPE for Successive Day Exposure

The MPE for successive day or second day exposure to UV emissions longer than 280 nm requires that the MPE to be de-rated by a factor of 2.5 (*ANSI Std. Z136.**1**–2000 {8.2.3.1}*).

$$MPE_{2^{nd}\ Day} = \frac{MPE_{315-400}}{2.5}$$

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

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

b. Appropriate AEL Determination

The appropriate AEL for the wavelength-range: 315 nm to 400 nm is the product of the de-rated MPE, for successive day exposures, and the limiting Area.

$$AEL = MPE_{2^{nd}\ Day} \cdot A_{\lim}$$
$$= \left(444 \times 10^{-9}\ J/cm^2\right)\frac{\pi}{4} \cdot (0.35\ \ cm)^2$$

$$AEL = 42.8 \times 10^{-9}\ J$$

c. Minimum Optical Density Calculation

(1) For the radiant OPO/A output of **20 mJ** @ 30 Hz in the wavelength range: **315 nm** $\leq$ **λ < 400 nm** the minimum OD required is as follows.

$$OD_{\min} = \log_{10}\left[\frac{Q_o}{AEL}\right] \qquad \textit{ANSI Std. Z136.6–2000 \{Equation B4\}}$$
$$= \log\left[\frac{20 \times 10^{-3}\ J}{42.8 \times 10^{-9}\ J}\right]$$

$$OD_{\min} = 5.67$$

(2) For a radiant output of **35 mJ** @ 30 Hz from the Tripled YAG (**355 nm**) the minimum OD required is:

$$OD_{\min} = \log_{10}\left[\frac{Q_0}{AEL}\right]$$ *ANSI Std. Z136.6–2000 {Equation B4}*

$$= \log\left[\frac{35\times10^{-3}\,J}{42.8\times10^{-9}\,J}\right]$$

$$OD_{\min} = 5.91$$

d. Summary

Laser workers and other personnel who work inside the SRSS trailer NHZ (laser room) are expected to be exposed to the ocular hazard tabulated below and are required to wear laser safety eyewear with the minimum OD(s) in the wavelength ranges indicated in the table below whenever the laser system is activated for the duration of their stay in the NHZ. It is assumed that authorized laser workers shall be subjected to successive day exposures.

Table 10

SRSS B-70 Laser (UV-2 Exposures)

(315 nm $\leq \lambda <$ 400 nm)

Wavelength (nm)	Output	Time (Seconds)	MPE (J/cm²)	AEL (J)	OD_{min}
$315 \leq \lambda < 400$	20 mJ @ 30 Hz	30,000	444×10^{-9}	42.8×10^{-9}	5.67
355	35 mJ @ 30 Hz	30,000	444×10^{-9}	42.8×10^{-9}	5.91

B. Visible Region (**400 nm $\leq$ λ $\leq$ 700 nm**)

There are two possible sources of visible wavelengths in the laser room of the SRSS trailer (B-70): the doubled YAG (532 nm) output of the pump laser and possible a CW HeNe (633 nm) alignment laser.

1. **Doubled YAG (532 nm)**

Aversion Response MPE (T = 0.25 seconds)

The aversion response protects up to a Class 2 laser hazard.

a. MPE Rule 1 (Single Pulse):

The single pulse MPE is a constant value throughout the visible region of the spectrum, for exposures of 1 nanosecond to 18 microseconds.

ANSI Std. Z136.1–2000 {Table 5a}

$$MPE_{rule1} = 5\times10^{-7}\ J/cm^2 \qquad (400\ nm \leq \lambda \leq 700\ nm)$$

$$(10^{-9}\sec \leq t \leq 18\times10^{-6}\sec)$$

b. MPE Rule 2 (CW/pulse):

$$MPE_{rule2} = \frac{MPE(T)}{n(T)}$$

For, T = 0.25 seconds;

$$\begin{aligned} n &= PRF \cdot T \\ &= (30\ \sec^{-1})\cdot(0.25\ \sec) \\ &= 7.5 \end{aligned}$$

The value of "n" is always an integer. Whenever the number of pulses in the exposure is fractional number; round this number up to the next whole number. Therefore the number of pulses in this exposure will be considered to be 8.

(400 nm ≤ λ ≤ 700 nm)

In the time range for the aversion response exposure (0.25 seconds) the MPE is given in *ANSI Std. Z136.1–2000* (*Table 5a*) to be of the form:

$$MPE = 1.8 \cdot t^{0.75} \times 10^{-3}\ {}^{J}\!/\!_{cm^2} \qquad (400\ nm \le \lambda \le 700\ nm)$$

$$(18 \times 10^{-6}\ \sec < t \le 10\ \sec)$$

$$MPE_{rule2} = \frac{1.8 \cdot (0.25)^{0.75} \times 10^{-3}\ {}^{J}\!/\!_{cm^2}}{8}$$

$$= \frac{636 \times 10^{-6}\ {}^{J}\!/\!_{cm^2}}{8}$$

$$MPE_{rule2} = 79.5 \times 10^{-6}\ {}^{J}\!/\!_{cm^2}$$

c. <u>Rule 3 (Multiple-Pulse)</u>:

The number of pulses in the aversion response exposure (0.25 seconds) has been determined to be 8 (from Rule 2 above).

$$MPE_{rule3} = C_p \cdot MPE_{thermal}$$

$$= n^{-0.25} \cdot MPE_{rule1}$$

$$= (8)^{-0.25} \cdot \left(5 \times 10^{-7}\ {}^{J}\!/\!_{cm^2}\right)$$

$$= (0.595) \cdot \left(5 \times 10^{-7}\ {}^{J}\!/\!_{cm^2}\right)$$

$$MPE_{rule3} = 297 \times 10^{-9}\ {}^{J}\!/\!_{cm^2}$$

d. Summary of MPE Table:

Table 11

Appropriate MPE (Doubled YAG)

532 nm, T = 0.25 Seconds

ANSI Rule	MPE (J/cm^2)	Comment
1	500×10^{-9}	
2	79.5×10^{-6}	
3	**297×10^{-9}**	**Appropriate MPE**

e. AEL Determination

The appropriate AEL is the product of the appropriate MPE and the area associated with the limiting aperture in *ANSI Std. Z136.1–2000* (*Table 8*). The diameter of the limiting aperture is given as: **7 mm**.

$$Claas\ \ 2\ \ AEL = MPE_{0.25\,\text{sec}} \cdot A_{\lim}$$

$$= \left(297 \times 10^{-9}\ {}^{J}\!/_{cm^2}\right) \frac{\pi}{4} \cdot \left(0.7\ \ cm\right)^2$$

$$Class\ \ 2\ \ AEL = 114 \times 10^{-9}\,J$$

f. Minimum Optical Density Calculation

The minimum OD necessary to protect against Doubled YAG to the Class 2 aversion response limit is as follows:

$$OD_{\min} = \log_{10}\left[\frac{Q_o}{Class\ \ 2\ \ AEL}\right]$$

$$= \log_{10}\left[\frac{0.250\ \ J}{114\times10^{-9}J}\right]$$

$$OD_{\min} = 6.34$$

2. **HeNe Alignment Laser**

Aversion Response MPE (T = 0.25 seconds)

The CW MPE for the aversion response can be expressed as follows;

MPE:

$$MPE = 1.8\cdot t^{0.75}\times10^{-3}\ {}^{J}\!/\!{}_{cm^2}$$

ANSI Std. Z136.1–2000 {Table 5a}

(18×10^{-6} sec < t < 10 sec)

$$MPE_T = \frac{MPE(T)}{T}$$

$$MPE_{0.25\sec} = \frac{1.8\cdot(0.25)^{0.75}\times10^{-3}\ {}^{J}\!/\!{}_{cm^2}}{0.25\sec}$$

$$= \frac{636\times10^{-6}\ {}^{J}\!/\!{}_{cm^2}}{0.25\sec}$$

$$MPE_{0.25\sec} = 2.55\times10^{-3}\ {}^{w}\!/\!{}_{cm^2}$$

$$Class\ \ 2\ \ AEL = MPE_{0.25\sec} \cdot A_{\lim}$$

$$= \left(2.55 \times 10^{-3}\ {}^{w}\!\!/_{cm^2}\right)\left(0.385\ \ cm^2\right)$$

$$Class\ \ 2\ \ AEL = 980 \times 10^{-6}\, w$$

<u>Minimum OD Calculation</u> (Φ = **15 mw** @ **633 nm**)

Protection for a 0.25-second exposure (Class 2 Laser Hazard)

$$OD_{\min} = \log_{10}\left(\frac{\Phi_o}{Class\ \ 2\ \ AEL}\right)$$

$$= \log_{10}\left(\frac{15 \times 10^{-3}\, w}{980 \times 10^{-6}\, w}\right)$$

$$= \log_{10}(15.3)$$

$$OD_{\min} = 1.19$$

3. <u>Summary of the Visible Region of the Spectrum</u>

Laser workers and other personnel who work inside the SRSS trailer NHZ (laser room) are expected to be exposed to the ocular hazard tabulated below and are required to wear laser safety eyewear with minimum OD(s) in the wavelength ranges indicated in the table below whenever the laser system or possibly the HeNe alignment laser is activated for the duration of their stay in the NHZ.

<u>Table 12</u>

SRSS B-70 Laser Room (Visible Region)

Output Wavelength Range: 400 nm ≤ λ ≤ 700 nm

Wavelength (nm)	Output (Q_o, Φ_o)	Time (Seconds)	MPE (J/cm²)	AEL (J)	OD_{min}
532	250 mJ @ 30 Hz	0.25	297 x 10^{-9}	114 x 10^{-9}	**6.34**
633	15 mw	0.25	2.55 x 10^{-3} watts/cm²	980 x 10^{-6} watts	**1.19**

C. Infrared Region (**1050 nm < λ ≤1400 nm**)

The fundament wavelength of the Nd:YAG pump laser is 1.064 μm (**1064 nm**). Although most of the IR pulse energy is dissipated in the conversion to the second (532 nm), the third (355 nm) and the fourth (266 nm) harmonics there is always some fundamental bleed through. For the purpose of this analysis the full amount of the fundament pulse energy will be considered to be available to the laser hazard, especially during system alignment when the alignment of the primary element could subject the laser worker to a possible exposure to the fundamental output of the YAG.

1. Full Protection (T = 10 seconds)

The standard IR laser (1064 nm) exposure is given by the *ANSI Std. Z136.**1**–2000* (*Table 4*) and (*8.2.2*) as 10 seconds. The appropriate MPE for a repetitively pulsed laser is always the smallest value derived by the application of ANSI Rules 1 through 3 to *ANSI Std. Z136.**1**-2000* (*Table 5a*).

a. MPE Rule 1 (Single Pulse):

The single pulse MPE form for a 2-nanosecond, 1064 nm laser pulse is given by *ANSI Std. Z136.**1**–2000 {Table 5a}* as:

$$MPE_{rule1} = 5 \cdot C_c \times 10^{-6}\ {}^{J}\!/_{cm^2}$$

(1050 nm < λ ≤ 1400 nm)

(10^{-9} sec ≤ t ≤ 50 x 10^{-6} sec)

*ANSI Std. Z136.**1**–2000 {Table 6}*

$C_c = 1.0$ (1050 nm ≤ λ ≤ 1150 nm)

$$MPE_{rule1} = 5 \times 10^{-6}\ {}^{J}\!/_{cm^2}$$

b. MPE Rule 2 (CW/pulse):

$$MPE_{rule2} = \frac{MPE(T)}{n(T)}$$

For a standard 10-second IR (**1050 nm to 1400 nm**) exposure the appropriate form of the MPE is given by *ANSI Std. Z136.1–2000 {Table 5a}* as:

$$MPE_{10\sec} = 9 \cdot C_c \cdot t^{0.75} \times 10^{-3}\ J/cm^2 \qquad (50 \times 10^{-6} \sec < t \leq 10 \sec)$$

The *ANSI Std. Z136.1–2000 {Table 6}* gives, C_c as equal to "1" for wavelengths greater than 1050 nm but less than 1150 nm.

$$MPE_{10\sec} = 9 \cdot (10)^{0.75} \times 10^{-3}\ J/cm^2$$

$$= 9 \cdot (5.62) \times 10^{-3}\ J/cm^2$$

$$MPE_{10\sec} = 50.6 \times 10^{-3}\ J/cm^2$$

The "per pulse" MPE for Rule 2 is this 10-second MPE form divided by the number of pulses delivered in 10 seconds.

$$MPE_{rule2} = \frac{MPE_{10\sec}}{n(T)}$$

$$n = PRF \cdot T$$

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

$$n = 300$$

$$MPE_{rule2} = \frac{50.6 \times 10^{-3}\ J/cm^2}{300}$$

$$MPE_{rule2} = 169 \times 10^{-6}\ J/cm^2$$

(1050 nm < λ ≤ 1400 nm)

c. <u>MPE Rule 3</u> (Multiple-Pulse):

T = 10 seconds
n = 300 pulses

$$MPE_{rule3} = C_p \cdot MPE_{thermal}$$

$$= n^{-0.25} \cdot MPE_{rule1}$$

$$= (300)^{-0.25} \cdot \left(5 \times 10^{-6}\ {}^{J}\!/\!_{cm^2}\right)$$

$$= (0.24) \cdot \left(5 \times 10^{-6}\ {}^{J}\!/\!_{cm^2}\right)$$

$$MPE_{rule3} = 1.2 \times 10^{-6}\ {}^{J}\!/\!_{cm^2}$$

d. <u>Summary MPE Table For The 1064 nm Output</u>:

Table 13

Appropriate MPE (YAG: Fundamental)

1064 nm, T = 10 Seconds

ANSI Rule	**MPE (J/cm^2)**	**Comment**
1	5.0×10^{-6}	
2	169×10^{-6}	
3	$\mathbf{1.2 \times 10^{-6}}$	**Appropriate MPE**

e. AEL Determination:

The AEL for a **1064 nm** pulsed laser source is the product of the appropriate MPE and the area of the 7-mm limiting aperture indicated in *Table 8* of the *ANSI Std. Z136.1–2000*.

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

$$= \left(1.2 \times 10^{-6}\ J/cm^2\right)\frac{\pi}{4} \cdot \left(0.7\ \ cm\right)^2$$

$$AEL = 462 \times 10^{-9}\, J$$

f. Minimum Optical Density Calculation:

$$OD_{\min} = \log_{10}\left[\frac{Q_o}{AEL}\right]$$ *ANSI Std. Z136.6–2000 {Equation B4}*

$$= \log_{10}\left[\frac{0.5\ \ J}{462 \times 10^{-9} J}\right]$$

$$= \log_{10}\left(541 \times 10^{3}\right)$$

$$OD_{\min} = 6.03$$

D. Infrared Region (**1500 nm < λ ≤ 1800 nm**)

MPE Determination (1500 nm < λ ≤ 1800 nm)

Rule 1 MPE (1500 nm < λ ≤ 1800 nm)

ANSI Std. Z136.1–2000 {Table 5a}
(1500 nm < λ ≤ 1800 nm)
(10^{-9} sec ≤ T ≤ 10 sec)

$$MPE_{rule1} = 1\ \ J/cm^2$$

Rule 2 MPE (**1500 nm < λ ≤1800 nm**)

$$MPE_{rule2} = \frac{MPE(T)}{n(T)}$$

$$T = 10 \text{ sec}$$

$$MPE_{rule2} = \frac{1 \ J/cm^2}{(30 \ \sec^{-1}) \cdot (10 \ \sec)}$$

$$MPE_{rule2} = 3.33 \times 10^{-3}$$

Rule 3 MPE (1500 nm < λ ≤1800 nm)

$$MPE_{rule3} = C_p MPE_{thermal}$$

For radiant wavelengths in the region from 1500 nm to 1800 nm the value of $t_{\min}$ is 10 seconds. $T_{\min}$ is the maximum duration for which the value of the MPE is the same as the MPE for a one nanosecond exposure. When laser pulses occur within the duration of $t_{\min}$ the MPE value for a $t_{\min}$ exposure is distributed equally among these pulse because it is assumed that the energy delivered, by the laser pulses, with $t_{\min}$ act as if the total was delivered in a single pulse (*ANSI Std. Z136.**1**–2000 {8.2.3 – Rule 3 (note)}*).

$$t_{\min} = 10 \ \sec$$
$$C_p = n^{-0.25} = (1)^{-0.25} = 1$$

$$MPE_{rule3}(t_{\min}) = \frac{1 \ J/cm^2}{(30 \ \sec) \cdot (10 \ \sec)}$$

$$MPE_{rule3} = 3.33 \times 10^{-3}$$

Table 14

Appropriate MPE (Acculite)

1550 nm, T = 10 Seconds

ANSI Rule	MPE (J/cm^2)	Comment
1	1	
2	3.33×10^{-3}	**Appropriate MPE**
3	3.33×10^{-3}	**Appropriate MPE**

AEL (**1500 nm < λ ≤ 1800 nm**)

T=10 second

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

$$D_f = 0.35 \ cm \qquad \textit{ANSI Std. Z136.1–2000 \{Table 8 - note\}}$$

$$AEL = \left(3.33 \times 10^{-3} \, {}^{J}\!/_{cm^2}\right)\frac{\pi}{4} \cdot (0.35 \ cm)^2$$

$$AEL = 321 \times 10^{-6} J$$

Minimum Optical Density (**1500 nm < λ ≤ 1800 nm**)

$$OD_{\min} = \log_{10}\left[\frac{Q_o}{AEL}\right] \qquad \textit{ANSI Std. Z136.6–2000 \{Equation B4\}}$$

$$= \log_{10}\left[\frac{10 \times 10^{-3} J}{321 \times 10^{-6} J}\right]$$

$$OD_{\min} = 1.49$$

1. Summary for Indoor Operation

The following table summarizes the ocular hazard mitigation for laser operations inside the laser room of the SRSS trailer (B-70).

Table 15

Operations Inside of the Laser Room (NHZ) of the SRSS Trailer

Wavelength (nm)	Output (mJ) @ 30 Hz	Time (sec)	MPE (J/cm^2)	AEL (J)	OD_{min}	OD Eyewear
1550	10	10	3.33×10^{-3}	321×10^{-6}	**1.49**	2+*3
1064	500	10	1.2×10^{-6}	462×10^{-9}	**6.03**	10*3
633	15 mw	0.25*2	2.55×10^{-3} w/cm²	980×10^{-6} w	**1.19**	1-2 *3
532	250	0.25*2	297×10^{-9}	114×10^{-9}	**6.34**	7
355	35	30,000	444×10^{-9}*	42.8×10^{-9}	**5.91**	20
266	20	30,000	3.33×10^{-9}	321×10^{-12}	**7.79**	~20
180-280	10	30,000	3.33×10^{-9}	321×10^{-12}	**7.49**	~20
280-302	10	30,000	1.33×10^{-9}*	128×10^{-12}	**7.89**	~20
315-400	20	30,000	444×10^{-9}*	42.8×10^{-9}	**5.67**	7 *3

Notes:
*: Successive day exposure value.
*2: Aversion Response (0.25 seconds)
*3: Uvex® (L268) Eyewear

III. <u>Outdoor Operation Of The Trailer Based SRSS Laser System</u>

The outdoor operation of the SRSS laser consists primarily of select wavelengths in the ultraviolet region of the spectrum, which are used to perform laser interaction tests and experiments on various “targets”. The duration of these individual tests varies but is generally on the order of 60 seconds. Accumulative exposure is expected to be on the order of 600 seconds per day, but may be greater. A visible alignment laser, HeNe-red, at 633 nm is used to align the particular test “target” to the SRSS UV source. The alignment process is expected to last for up to 600 seconds in duration. The HeNe laser is operated at the target location and is directed back to the SRSS trailer.

<u>Laser Hazard Analysis (Large Beam) **Outside** Trailer</u>

The laser beam exits the SRSS trailer by means of a gimbaled beam expanding telescope, which directs the laser beam to a remote “target”. The beam diameter, exiting the telescope, is 101 mm with a beam divergence on the order of 500 micro-radians.

A. <u>UV Region</u> (180 nm $\leq \lambda <$ 400 nm):

1. <u>UV-1 Region</u>: **180 nm $\leq \lambda <$ 302 nm**

As previously stated during the “indoor” hazard analysis, specific wavelengths in this UV band may be required in the performance of certain laser interaction tests or experiments. The region 180 nm to 302 nm of the optical spectrum is a dual limit region where the smallest value for the MPE form that is derived from the photochemical limit and the thermal limit is used. The MPE form is the same for the wavelengths in this region depending on the particular laser parameters (i.e.; Pulse width, Pulse Repetition Frequency and the Exposure).

a. <u>Appropriate MPE Determination For A Typical 60-Second Test</u>

Recall that the appropriate MPE for a multiple pulse laser is always the smallest of the values derived from *ANSI Std. Z136.1–2000, Rules* 1 through 3.

(1) <u>MPE Rule 1</u> (Single Pulse):

For a typical laser test lasting 60 seconds no single laser pulse in the pulse train may exceed the single pulse MPE. The single pulse MPE is the smallest of the MPE form values for the photochemical limit and the thermal limit.

For exposures in the range of: 10^{-9} sec < T $\leq 3 \times 10^4$ sec the Single Pulse MPE is:

$$MPE_{rule1} = \min\left[photochemical \;\lim,\; thermal \;\lim\right] \quad \text{(Dual Limit Region)}$$

$$= \min\left[3\times10^{-3}\,{}^{J}\!/_{cm^2},\; 0.56\cdot t^{0.25}\,{}^{J}\!/_{cm^2}\right] \quad \textit{ANSI Std.Z136.1 Table 5a}$$

$$= \min\left[3\times10^{-3}\,{}^{J}\!/_{cm^2},\; 0.56\cdot\left(2\times10^{-9}\right)^{0.25}\,{}^{J}\!/_{cm^2}\right]$$

$$= \min\left[3\times10^{-3}\,{}^{J}\!/_{cm^2},\; 3.74\times10^{-3}\,{}^{J}\!/_{cm^2}\right]$$

$$MPE_{rule1} = 3\times10^{-3}\,{}^{J}\!/_{cm^2}$$

(2) <u>Rule 2 (CW/pulse) For A 60-Second Exposure</u> (**180 nm $\leq \lambda <$ 302 nm**):

The MPE for a group of pulses delivered in 60 seconds, T, shall not exceed the MPE for a 60-second exposure time. The MPE per pulse is the MPE for 60-second exposure divided by the number of pulses delivered in the time of 60 seconds (*ANSI Std. Z136.1–2000 {8.2.3 – rule 2}*).

T = 60 seconds

$$\begin{aligned} n &= PRF\cdot T \\ &= \left(30\;\sec^{-1}\right)\cdot\left(60\;\sec\right) \\ n &= 1{,}800 \end{aligned}$$

The appropriate MPE for a 60-second exposure is always the smallest of the MPE values derived from the photochemical limit and the thermal limit in the dual limit region.

$$MPE_{Rule2} = \frac{MPE(T)}{n(T)}$$

$$MPE_{Rule2} = \frac{\min\left[MPE_{photochemical},\; MPE_{thermal}\right]}{n}$$

$$= \frac{\min\left[3\times10^{-3}\,{}^{J}\!/_{cm^2},\; 0.56\cdot t^{0.25}\,{}^{J}\!/_{cm^2}\right]}{n}$$

$$= \frac{\min\left[3\times10^{-3}\ J/cm^2,\ 0.56\cdot(60)^{0.25}\ J/cm^2\right]}{1800}$$

$$= \frac{\min\left[3\times10^{-3}\ J/cm^2,\ 1.56\ J/cm^2\right]}{1800}$$

$$= \frac{3\times10^{-3}\ J/cm^2}{1800}$$

$$MPE_{Rule2} = 1.67\times10^{-6}\ J/cm^2$$

(3) <u>Rule 3 (Multiple-pulse) For A 60-Second Exposure</u> **(180 nm $\leq \lambda <$ 302 nm)**:

Rule 3 applies to the **thermal limit only** (*ANSI Std. Z136.1–2000 {8.2.3.1}*).

$$MPE_{rule3} = C_p \cdot MPE_{thermal}$$

$$C_p = n^{-0.25} \qquad \textit{ANSI Std.Z136.1–2000 \{Table 6\}}$$

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

$$= \left\{(30\ \sec^{-1})\cdot(60\ \sec)\right\}^{-0.25}$$

$$= (1800)^{-0.25}$$

$$C_p = 0.154$$

$$MPE_{rule3} = (0.154)\cdot\left(3.74\times10^{-3}\ J/cm^2\right)$$

$$MPE_{rule3} = 575\times10^{-6}\ J/cm^2$$

(4) Summary MPE Table:

The MPE derived from Rule 2 provides the smallest value for a 60-second exposure to a wavelength in the range from 180 nm to 302 nm.

Table 16

Appropriate MPE (UV-1: Single Outdoor Test)

(180 nm $\leq \lambda <$ 302 nm), 60-Second Exposure

ANSI Rule	MPE (J/cm^2)	Comment
1	3×10^{-3}	
2	**1.67×10^{-6}**	**Appropriate MPE**
3	575×10^{-6}	

b. Radiant Exposure vs. MPE

The average **radiant exposure** (H_o) of the laser beam exiting the telescope is approximately the radiant pulse energy distributed over the beam cross-sectional area at the telescope.

$$H_o = \frac{Q_o}{A_{exit}}$$

$$= \frac{Q_o}{\frac{\pi}{4} \cdot (d_{exit})^2}$$

$$= \frac{Q_o}{\frac{\pi}{4} \cdot (10.1\ cm)^2}$$

$$H_o = \frac{Q_o}{80.1\ cm^2}$$

The radiant exposure for a 10 mJ radiant output and the large exit beam (10.1 cm diameter) can be calculated as follows:

$$H_o = \frac{10 \times 10^{-3} J}{80.1 \ cm^2}$$

$$H_o = 125 \times 10^{-6} \, {}^{J}\!/\!{}_{cm^2}$$

$$H_o > MPE$$

The radiant exposure at the exit of the telescope is greater than the MPE for a 60-second exposure and must be considered hazardous.

Extended Source Criteria

Extended source criteria **cannot** be applied to the large diameter UV beams produced by the trailer based SRSS laser system. The large beam at the exit could be considered an extended source if the viewing angle (α) is greater than some minimum angle (α_{min}); however, the extended source criteria can only be applied to wavelengths greater than 400 nm but less than 1.4 μm (*ANSI Std. Z136.**1**–2000 {Table 6 – note 1}*).

c. Minimum Optical Density Calculation

The minimum OD appropriate for laser eyewear for the outdoors operation in this wavelength band is calculated from the logarithm of the ratio of the laser beam radiant exposure to the appropriate MPE.

1. **180 nm to 302 nm**, **10 mJ** @ 30 Hz, T = 60 seconds;

$$OD_{\min} = \log_{10}\left[\frac{H_o}{MPE}\right] \qquad \textit{ANSI Std. Z136.1–2000 \{Equation B98\}}$$

$$= \log_{10}\left[\frac{125 \times 10^{-6} \, {}^{J}\!/\!{}_{cm^2}}{1.67 \times 10^{-6} \, {}^{J}\!/\!{}_{cm^2}}\right]$$

$$= \log_{10}(74.9)$$

$$OD_{\min} = 1.87$$

2. For quadrupled YAG: **266 nm**, **20 mJ** @ 30 Hz, T = 60 seconds;

$$OD_{\min} = \log_{10}\left[\frac{H_o}{MPE}\right] \qquad \textit{ANSI Std. Z136.1–2000 \{Equation B98\}}$$

$$= \log_{10}\left[\frac{Q_o / A_{exit}}{MPE}\right]$$

$$= \log_{10}\left[\frac{20\times10^{-3}\,J / 80.1\ cm^2}{1.67\times10^{-6}\,J / cm^2}\right]$$

$$= \log_{10}(150)$$

$$OD_{\min} = 2.18$$

d. <u>NOHD Calculation</u>

1. **180 nm to 302 nm**, **10 mJ** @ 30 Hz, T = 60 seconds;

$$NOHD = \frac{1}{\theta}\cdot\sqrt{\frac{4\cdot Q_0}{\pi\cdot MPE} - d_o^2} \qquad \textit{ANSI Std.Z136.1-2000 \{Equation B51\}}$$

$$= \frac{1}{500\times10^{-6}}\cdot\sqrt{\frac{4\cdot(10\times10^{-3}\,J)}{\pi\cdot(1.67\times10^{-6}\,J / cm^2)} - (10.1\ cm)^2}$$

$$= 174\times10^3\,cm$$

$$NOHD = 1.74\ km$$

2. For quadrupled YAG: **266 nm**, **20 mJ** @ 30 Hz, T = 60 seconds;

$$NOHD = \frac{1}{\theta} \cdot \sqrt{\frac{4 \cdot Q_0}{\pi \cdot MPE} - d_o^2} \qquad \textit{ANSI Std.Z136.1-2000 \{Equation B51\}}$$

$$= \frac{1}{500 \times 10^{-6}} \cdot \sqrt{\frac{4 \cdot \left(20 \times 10^{-3}\, J\right)}{\pi \cdot \left(1.67 \times 10^{-6}\, J/cm^2\right)} - \left(10.1\ cm\right)^2}$$

$$= 246 \times 10^3\, cm$$

$$NOHD = 2.46\ km$$

a. EOHD (180 nm $\leq \lambda \leq$ 302 nm)

It is assumed that any optical viewing aid that might be used would be a standard **7 x 50 mm** binocular (7x magnifying power and 50 mm entrance aperture). *ANSI Standard Z136.1–2000* (*Table 9*) gives the transmission factor through the optical aid as **less than 2%** for the **UV** region of the spectrum.

This wavelength range presents a hazard to the cornea. The effective gain of the optical is used for this wavelength range.

1. **180 nm** $\leq \lambda \leq$ **302 nm**, **10 mJ** @ 30 Hz, T = 60 seconds

Collecting Diameter (180 nm $\leq \lambda \leq$ 302 nm)

$$D_c = \min\left[D_0,\ P \times D_f\right] \qquad \textit{ANSI Std. Z136.1–2000 \{Eq. B56\}}$$

$$= \min\left[50\ mm,\ 7 \times 3.5\ mm\right]$$

$$= \min\left[50\ mm,\ 24.5\ mm\right]$$

$$D_c = 24.5\ mm$$

Effective Gain (180 nm $\leq \lambda \leq$ 302 nm)

$$G_{eff} = \tau_\lambda \times \frac{\min\left(D_c^2,\ D_L^2\right)}{D_f^2} \qquad \text{ANSI Std. Z136.1–2000 \{Equation B57\}}$$

$$\approx (0.02) \times \frac{\min\left[(24.5\ mm)^2, (50\ mm)^2\right]}{(3.5\ mm)^2} \qquad (\tau_\lambda < 0.02)$$

$$G_{eff} \approx 0.98\,*$$

*Because of the high absorption of the optical material in this wavelength region the use of binoculars offers more ocular protection than the intrabeam viewing with the naked eye.

<u>EOHD</u> (180 nm $\leq \lambda \leq$ 302 nm)

$$EOHD = \frac{1}{\theta} \cdot \sqrt{\frac{4 \cdot G_{eff} \cdot Q}{\pi \cdot MPE} - d_o^2}$$

$$= \frac{1}{500 \times 10^{-6}} \cdot \sqrt{\frac{4 \cdot (0.98) \cdot \left(10 \times 10^{-3}\ J\right)}{\pi \cdot \left(1.67 \times 10^{-6}\ J/cm^2\right)} - (10.1\ cm)^2}$$

$$EOHD = 172\ \times 10^3\, cm$$

$$EOHD = 1.72\ \ km$$

2. For quadrupled YAG: **266 nm**, **20 mJ** @ 30 Hz, T = 60 seconds;

$$EOHD = \frac{1}{\theta} \cdot \sqrt{\frac{4 \cdot G_{eff} \cdot Q}{\pi \cdot MPE} - d_o^2}$$

$$= \frac{1}{500\times10^{-6}} \cdot \sqrt{\frac{4\cdot(0.98)\cdot(20\times10^{-3}\,J)}{\pi\cdot\left(1.67\times10^{-6}\,J/cm^2\right)} - (10.1\ cm)^2}$$

$$EOHD = 244\ \times10^{3}\,cm$$

$$EOHD = 2.44\ \ km$$

1. Summary Table

Table 17

Outdoor Operation (UV-1: Single Test)

(180 nm ≤ λ < 302 nm), 60-Second Exposure

Wavelength (nm)	Output (mJ)	MPE (J/cm^2)	OD_{min}	NOHD (Km)	EOHD (Km)
180-302	10 @ 30 Hz	1.67×10^{-6}	**1.87**	**1.74**	**1.72**
266	20 @ 30 Hz	1.67×10^{-6}	**2.18**	**2.46**	**2.44**

2. UV-2 Region (**315 nm ≤ λ < 400 nm**) - **Outdoor Operation**

Appropriate MPE Determination for T = 60 Seconds

(1) MPE Rule 1 (Single Pulse):

Exposure Range: 10^{-9} sec ≤ t ≤ 10 sec

$MPE_{rule1.}$ = 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}*

Photochemical limit = Thermal limit

(**315 nm $\leq$ λ < 400 nm**)

$$MPE_{rule1} = 0.56 \cdot \left(2 \times 10^{-9}\right)^{0.25} \,{}^{J}\!/\!_{cm^2}$$

$$MPE_{rule1} = 3.74 \times 10^{3} \,{}^{J}\!/\!_{cm^2}$$

(2) <u>MPE Rule 2 (CW/pulse)</u> (**315 nm $\leq$ λ < 400 nm**):
(315 nm $\leq$ λ < 400 nm)
T = 60 seconds

$$n = PRF \cdot T$$

$$= \left(30 \;\sec^{-1}\right) \cdot \left(60 \;\sec\right)$$

$$n = 1{,}800$$

$$MPE_{rule2} = \frac{MPE_{CW}(T)}{n(T)}$$

MPE = 1 J/cm^2, for: 10 sec < T $\leq$ 3 x 10^4 sec (*ANSI Std. Z136.**1**–2000 {Table 5a}*).

$$= \frac{1 \,{}^{J}\!/\!_{cm^2}}{1{,}800}$$

$$MPE_{rule2} = 556 \times 10^{-6} \,{}^{J}\!/\!_{cm^2}$$

(3) <u>MPE Rule 3 (Multiple-pulse)</u> (**315 nm $\leq$ λ < 400 nm**):

ANSI Rule 3 applies to the **thermal limit only** (*ANSI Std. Z136.**1**–2000 {8.2.3.1}*).

$$MPE_{rule3} = C_p \cdot MPE_{thermal} \qquad \text{\{Thermal limit form for MPE\}}$$

$$C_p = n^{-0.25} \qquad \textit{ANSI Std. Z136.1–2000 \{Table 6\})}$$

$$n = PRF \cdot T$$

$$= \left(30 \;\sec^{-1}\right) \cdot \left(60 \;\sec\right)$$

$$n = 1{,}800$$

(315 nm $\leq$ λ < 400 nm)

$$MPE_{rule3} = (1800)^{-0.25} \cdot 0.56 \cdot (2 \times 10^{-9})^{0.25} \; J/cm^2$$

$$= (0.154) \cdot \left(3.74 \times 10^{-3} \; J/cm^2\right)$$

$$MPE_{rule3} = 575 \times 10^{-6} \; J/cm^2$$

(4) Summary Table:

Table 18

Appropriate MPE (UV-2: Single Test Exposure)

(315 nm $\leq$ λ < 400 nm), 60-Second Exposure

ANSI Rule	MPE (J/cm^2)	Comment
1	3.74×10^{-3}	
2	**556×10^{-6}**	**Appropriate MPE**
3	575×10^{-6}	

b. Radiant Exposure vs. MPE (Outdoor Operation)

The Radiant Exposure (R) can be expressed in terms of the average radiant pulse energy ($\overline{Q}$) over the area (A) of the beam.

$$H = \frac{\overline{Q}}{A}$$

1. For the radiant output from **315 nm to 400 nm**, **20 mJ** @ 30 Hz, T = 60 seconds, outdoor operation at the exit of the telescope;

$$H_{exit} = \frac{20 \times 10^{-3} J}{\frac{\pi}{4} \cdot (10.1\ cm)^2}$$

$$H_{exit} = 250 \times 10^{-6}\ J/cm^2$$

$$H_{exit} < MPE = 556 \times 10^{-6}\ J/cm^2$$

2. For tripled YAG radiant output at **355 nm**, **35 mJ** @ 30 Hz, T = 60 seconds, outdoor operation;

$$H_{exit}(355nm) = \frac{35 \times 10^{-3} J}{\frac{\pi}{4} \cdot (10.1\ cm)^2}$$

$$H_{exit}(355nm) = 437 \times 10^{-6}\ J/cm^2$$

$$H_{exit}(355nm) < MPE = 556 \times 10^{-6}\ J/cm^2$$

<u>Table 19</u>

Outdoor Operation: At Telescope Exit

(Single Test Exposure - 60 Seconds)

Wavelength (nm)	**Output (mJ)**	**H_o (J/cm^2)**	**MPE (J/cm^2)**	**Comments**
315-400	20	250 x 10^{-6}	556 x 10^{-6}	Eye-safe at telescope
355	35	437 x 10^{-6}	556 x 10^{-6}	Eye-safe at telescope

c. Minimum Optical Density Calculations

For **large beam** lasers, in terms of the Radiant Exposure:

$$OD_{\min} = \log_{10}\left(\frac{H_p}{MPE}\right) \qquad \textit{ANSI Std. Z136.1–2000 \{Equation B98\}}$$

Where;

OD_{min}: The minimum Optical Density for laser safety eyewear.

H_p: The Radiant Exposure, of a beam larger than the limiting aperture, in joules per square centimeters.

MPE: The appropriate MPE, in joules per square centimeters for laser and exposure conditions.

For the 101-mm diameter (10.1 cm) beam at the exit of the telescope:

For the radiant output in the range of 315 nm to 400 nm, **20 mJ** @ 30 Hz, T = 60 seconds:

$$OD_{\min} = \log_{10}\left(\frac{H_p}{MPE}\right) \qquad \textit{ANSI Std. Z136.1–2000 \{Equation B98\}}$$

$$= \log_{10}\left(\frac{250\times10^{-6}\ J/cm^2}{556\times10^{-6}\ J/cm^2}\right)$$

$$= \log_{10}(0.45*)$$

$$OD_{\min} = -0.35$$

$$OD_{\min} = 0.00$$

* For logarithm arguments **less than 1**, the OD_{min} is then considered zero (Eye-Safe).

2. For tripled YAG: **355 nm**, **35 mJ** @ 30 Hz, T = 60 seconds;

$$OD_{\min} = \log_{10}\left(\frac{H_p}{MPE}\right) \qquad \textit{ANSI Std. Z136.1–2000 \{Equation B98\}}$$

$$= \log_{10}\left(\frac{Q_o \big/ A_{exit}}{MPE}\right)$$

$$= \log_{10}\left(\frac{35\times10^{-3}\,J \big/ 80.1\ cm^2}{556\times10^{-6}\,J \big/ cm^2}\right)$$

$$= \log_{10}(0.786\,*)$$

$$OD_{\min} = -0.10$$

$$OD_{\min} = 0.00$$

* For logarithm arguments **less than 1**, the OD_{min} is then considered zero (Eye-Safe).

The laser beam exiting the telescope remains eye-safe as long as the radiant exposure at the observer is less than the MPE. Because of the natural beam divergence and assuming that no focusing takes place, by outside optical elements, the beam should remain "eye-safe" along the propagation path.

d. NOHD Calculations

Recall that "authorized personnel" are required, by the Standard Operating Procedure, to wear the appropriate laser safety eyewear while in the NHZ (target area). The NOHD then would apply only to "unauthorized personnel" entering the NHZ or the target area with an accompanying possibility of exposure to the UV beam. It is assumed that any unauthorized entry (unauthorized exposure) would last for the entire duration of the specific laser test, would not reoccur on the same day and would not occur on successive days. Therefore the successive day **de-rating factor** (2.5) **is not applied to the MPE** in the NOHD calculation. The exposure, for a 60-second test, received by an unauthorized person would not pose a threat of ocular injury so long as the irradiance at the target area is below the MPE for the laser parameters (no re-focusing of the beam).

1. For the radiant output in the wavelength range from **315 nm to 400 nm**, **20 mJ @ 30 Hz**, T = 60 seconds;

$$NOHD = \frac{1}{\theta} \cdot \sqrt{\frac{4 \cdot Q_o}{\pi \cdot MPE} - d_o^2}$$ *ANSI Std. Z136.1–2000 {Equation B51}*

$$NOHD = \frac{1}{500 \times 10^{-6}} \cdot \sqrt{\frac{4 \cdot 20 \times 10^{-3}\, J}{\pi \cdot \left(556 \times 10^{-6}\, J/cm^2\right)} - (10.1\ cm)^2}$$

$$= \frac{1}{500 \times 10^{-6}} \cdot \sqrt{\left(45.8\ cm^2\right) - \left(102\ cm^2\right)}$$

$$= \left(2 \times 10^3\right) \sqrt{negative\ \ \text{arg}ument\,*}$$

$= 0.00$ cm

***NOHD* = 0.00 *km*   (Eye Safe)**

* This negative value is caused by the exit irradiance being less than the MPE. For this calculation the value of the square root (negative number) is considered to be zero. The exposure is eye safe.

2 For the tripled YAG: **355 nm**, **35 mJ @ 30 Hz**, T = 60 seconds;

$$NOHD = \frac{1}{\theta} \cdot \sqrt{\frac{4 \cdot Q_o}{\pi \cdot MPE} - d_o^2}$$ *ANSI Std. Z136.1–2000 {Equation B51}*

$$NOHD = \frac{1}{500 \times 10^{-6}} \cdot \sqrt{\frac{4 \cdot \left(35 \times 10^{-3}\, J\right)}{\pi \cdot \left(556 \times 10^{-6}\, J/cm^2\right)} - (10.1\ cm)^2}$$

$$= \frac{1}{500 \times 10^{-6}} \cdot \sqrt{\left(80.1\ cm^2\right) - \left(102\ cm^2\right)}$$

$$= \left(2 \times 10^3\right) \sqrt{negative\ \ \mathrm{arg}ument\,*}$$

$$= 0.00 \text{ cm}$$

***NOHD* = 0.00 *km*   (Eye Safe)**

* The negative argument is caused by the exit radiant exposure being less than the MPE. The exposure is eye safe.

Exposure of an unauthorized person to this laser output **does not pose** a threat of **ocular injury**, so long as the radiant exposure in the target area is less than the MPE for the laser conditions. Beam refocusing is not expected

e. <u>EOHD Calculation</u> **(315 nm** $\leq \lambda <$ **400 nm)**

It is again assumed that any optical viewing aid that might be used would be a standard, **7x 50mm** binocular with a 7x magnifying power and a 50 mm entrance aperture. The *ANSI Standard Z136.1–2000 {Table 9}* gives the transmission factor through the optical aid as **70%** for this **UV** region of the spectrum.

This wavelength range presents a hazard to the cornea. The effective gain of the optical is used for this wavelength range.

315 nm $\leq \lambda <$ **400 nm**, **20 mJ** @ 30 Hz, T = 60 seconds

Collecting Diameter (315 nm $\leq \lambda <$ **400 nm)**

$$D_c = \min\left[D_0,\ \ P \times D_f\right] \qquad \textit{ANSI Std. Z136.1–2000 \{Equation B56\}}$$

$$= \min\left[50\ \ mm,\ 7 \times 3.5\ \ mm\right]$$

$$= \min\left[50\ \ mm,\ 24.5\ \ mm\right]$$

$$D_c = 24.5\ \ mm$$

Effective Gain (315 nm $\le \lambda <$ 400 nm)

$$G_{eff} = \tau_\lambda \times \frac{\min\left(D_c^2,\ D_L^2\right)}{D_f^2} \qquad \textit{ANSI Std. Z136.1–2000 \{Equation B57\}}$$

$$= (0.7) \times \frac{\min\left[(24.5\ mm)^2, (50\ mm)^2\right]}{(3.5\ mm)^2}$$

$$G_{eff} = 34.3$$

EOHD **(315 nm $\le \lambda <$ 400 nm)**, $Q_o = 20\ mJ$

$$EOHD = \frac{1}{\theta} \cdot \sqrt{\frac{4 \cdot G_{eff} \cdot Q}{\pi \cdot MPE} - d_o^2}$$

$$= \frac{1}{500 \times 10^{-6}} \cdot \sqrt{\frac{4 \cdot (34.3) \cdot \left(20 \times 10^{-3} J\right)}{\pi \cdot \left(556 \times 10^{-6}\ J/cm^2\right)} - (10.1\ cm)^2}$$

$$EOHD = 76.7 \ \times 10^3 cm$$

$$EOHD = 767\ m$$

EOHD **(315 nm $\le \lambda <$ 400 nm)**, $Q_o = 35\ mJ$

$$EOHD = \frac{1}{\theta} \cdot \sqrt{\frac{4 \cdot G_{eff} \cdot Q}{\pi \cdot MPE} - d_o^2}$$

$$= \frac{1}{500 \times 10^{-6}} \cdot \sqrt{\frac{4 \cdot (34.3) \cdot (35 \times 10^{-3} J)}{\pi \cdot \left(556 \times 10^{-6} J/cm^2\right)} - (10.1\ cm)^2}$$

$$EOHD = 103\ \times 10^3 cm$$

$$EOHD = 1.03\ km$$

Summary Table

Table 20

Outdoor Operation (UV-2: Single Test)

60-Second Exposure (315 nm ≤ λ < 400 nm)

Wavelength (nm)	Output (mJ) @ 30 Hz	MPE (J/cm2)	OD_{min}	NOHD (m)	EOHD (km)
315-400	20	556×10^{-6}	0.00	0.00	0.767
355	35	556×10^{-6}	0.00	0.00	1.03

B. Visible Region (**400 nm** $\leq \lambda \leq$ **700 nm**)

CW HeNe Alignment Laser (λ = 633 nm)

1. Aversion Response MPE (T = 0.25 seconds)

   The CW MPE for the aversion response can be expressed as follows;

   a. MPE:

$$MPE = 1.8 \cdot t^{0.75} \times 10^{-3}\ J/cm^2$$

ANSI Std. Z136.1–2000 {Table 5a}

(18 x 10^{-6} sec < t < 10 sec)

(400 nm $\leq \lambda \leq$ 700 nm)

$$MPE_T = \frac{MPE(T)}{T}$$

$$MPE_{0.25\sec} = \frac{1.8 \cdot (0.25)^{0.75} \times 10^{-3} \, J/cm^2}{0.25\sec}$$

$$= \frac{636 \times 10^{-6} \, J/cm^2}{0.25\sec}$$

$$MPE_{0.25\sec} = 2.55 \times 10^{-3} \, w/cm^2$$

2. <u>Full Protection MPE</u> (T = 600 seconds)

   The MPE for this exposure is simply given as follows:

$$MPE_{CW} = 10^{-3} \, w/cm^2$$

*ANSI Std. Z136.**1**–2000 {Table 5a}*

(10 sec < t $\leq$ 3 x 10^4 sec)

Note: Full protection MPE applies to all exposures above 10 seconds.

3. <u>MPE Summary Table</u>

Table 21

Summary of MPE(s) For HeNe Laser Exposure

Wavelength (nm)	Output (mw)	Time (Seconds)	MPE (w/cm^2)	Comments
633	15	0.25	2.55 x 10^{-3}	Aversion
633	15	600	1 x 10^{-3}	Alignment

4. <u>AEL Determination for HeNe</u> ($\lambda = 633\ \ nm$)

$$Class\ \ 1\ \ AEL = MPE_{600\sec} \cdot A_{\lim}$$

$$= MPE_{600\sec} \cdot \frac{\pi}{4} \cdot \left(D_f\right)^2 \qquad \textit{ANSI Std. Z136.1–2000 \{Equation B23\}}$$

$$D_f = 0.7\ \ cm \qquad \textit{ANSI Std. Z136.1–2000\{Table 8\}}$$

$$= \left(10^{-3}\ {}^{w}\!/_{cm^2}\right)\frac{\pi}{4} \cdot \left(0.7\ \ cm\right)^2$$

$$= \left(10^{-3}\ {}^{w}\!/_{cm^2}\right)\left(0.385\ \ cm^2\right)$$

$$Class\ \ 1\ \ AEL = 385 \times 10^{-6}\, w$$

$$Class\ \ 2\ \ AEL = MPE_{0.25\sec} \cdot A_{\lim}$$

$$= \left(2.55 \times 10^{-3}\ {}^{w}\!/_{cm^2}\right)\left(0.385\ \ cm^2\right)$$

$$Class\ \ 2\ \ AEL = 980 \times 10^{-6}\, w$$

5. <u>Minimum Optical Density Calculation</u> (*Φ* = **15 mw** @ **633** nm)

Protection for a 0.25-second exposure (Class 2 Laser Hazard)

$$OD_{\min} = \log_{10}\left(\frac{\Phi_o}{Class\ \ 2\ \ AEL}\right)$$

$$= \log_{10}\left(\frac{15 \times 10^{-3}\, w}{980 \times 10^{-6}\, w}\right)$$

$$= \log_{10}(15.3)$$

$$OD_{\min} = 1.19$$

Protection for a 600-second exposure (Class 1 Laser Hazard) – Applicable for laser target alignment

$$OD_{\min} = \log_{10}\left(\frac{\Phi_o}{Class\ 1\ AEL}\right)$$

$$= \log_{10}\left(\frac{15\times10^{-3}\,w}{385\times10^{-6}\,w}\right)$$

$$= \log_{10}(39)$$

$$OD_{\min} = 1.59$$

The Uvex ® Laser Safety Eyewear currently in use (L268) has an OD rating of 1-2 at 633 nm and offers adequate protection.

6. <u>NOHD Calculation</u> (Φ = **15 mw** @ **633 nm**, T= 0.25 sec)

   The appropriate MPE to use for this eye safe viewing distance determination is that used for the "aversion response" where, T = 0.25 seconds

$$NOHD = \frac{1}{\theta}\cdot\sqrt{\frac{4\cdot\Phi_o}{\pi\cdot MPE} - d_o^2} \qquad \textit{ANSI Std. Z136.1–2000 \{Equation B50\}}$$

$$= \frac{1}{10^{-3}}\cdot\sqrt{\frac{4\cdot(15\times10^{-3}\,w)}{\pi\cdot 2.55\times10^{-3}\,{}^{w}\!/_{cm^2}} - (0.1\ cm)^2}$$

$$= (10^3)\cdot(2.74\ cm)$$

$$NOHD = 27.4\ meters$$

7. EOHD Calculation (Φ = **15 mw** @ **633 nm**, T= 0.25 sec)

   The viewing aid is assumed to be a standard 7x50mm (7x magnifying power, 50 mm) binocular. The actual optical gain for the visible wavelength can be expressed as:

$$G = \tau_\lambda \cdot P^2$$

$$\tau_\lambda = 0.9 \qquad \textit{ANSI Std.Z136.1–2000 \{Table 9\}}$$

$$= (0.9) \cdot (7)^2$$

$$G = 44.1$$

$$EOHD = \frac{1}{\theta} \cdot \sqrt{\frac{4 \cdot G \cdot \Phi_o}{\pi \cdot MPE} - d_o^2}$$

$$= \frac{1}{10^{-3}} \cdot \sqrt{\frac{4 \cdot (44.1) \cdot (15 \times 10^{-3}\, w)}{\pi \cdot \left(2.55 \times 10^{-3}\, {}^{w}\!/_{cm^2}\right)} - (0.1\ cm)^2}$$

$$= (10^3) \cdot (18.2\ cm)$$

$$EOHD = 182\ \ meters$$

8. Summary Table

Table 22

Outdoor Operations - Alignment (HeNe) Laser

(15 mw @ 633 nm)

Time (Seconds)	MPE (w/cm^2)	AEL (w)	OD_{min}	NOHD (meters)	EOHD (meters)
0.25	2.55×10^{-3}	980×10^{-6}	1.19	27.4	182
600	1×10^{-3}	385×10^{-6}	1.59	N/A*	N/A*

*Accidental, unprotected personnel exposure would be at the quarter second aversion response time.

C. Infrared Region (**1050 nm** $\leq \lambda \leq$ **1400 nm**)

There is a possibility that a small portion of the fundamental output of the YAG pump laser (1 mJ to **10 mJ @ 1064 nm**) can be used as a range finder.

The standard exposure for this wavelength is 10 seconds.

1. Appropriate MPE Determination

The MPE determined for the Indoor Operation is applicable for the Outdoor Operation because the standard exposure (10 second) is the same.

$$\textbf{MPE} = \mathbf{1.2 \times 10^{-6}\ J/cm^2}$$

2. NOHD vs. Radiant Energy

The NOHD (in kilometers) for a particular radiant energy (from ~1 to 10 mJ @ 30 Hz) can be read from the plot on the next page.

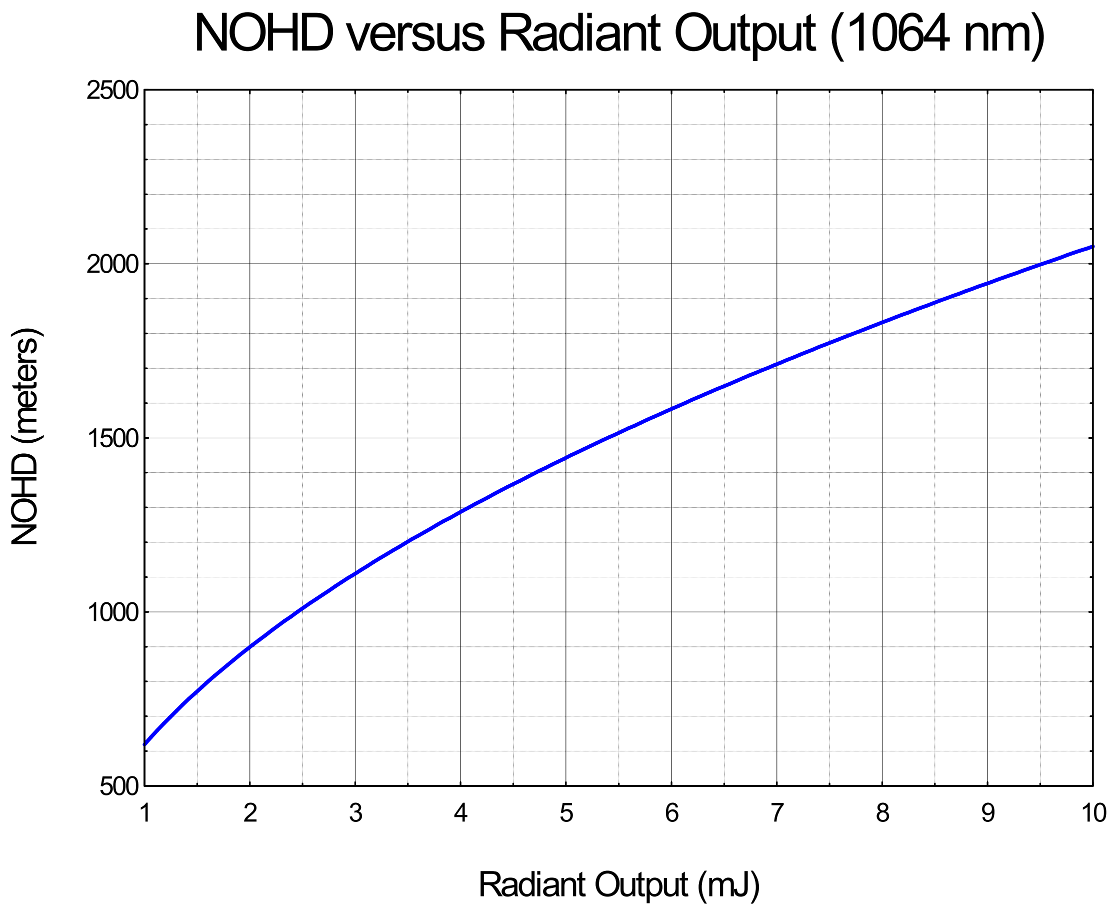

Figure 3

The NOHD as a function of the Radiant Output (at 1064 nanometers)

3. EOHD (**1064 nm**)

The actual gain of a 7x50mm binocular in the retinal hazard region can be expressed as

$$G = \tau_{aid} \cdot P^2 \qquad \textit{ANSI Std.Z136.1–2000 \{Equation B55 \& Example 42\}}$$

$$G_{1064nm} = (0.7) \cdot (7)^2 \qquad \tau_{aid} = 0.7,\ \textit{ANSI Std. Z136.1–2000 \{Table 8\}}$$

$$G_{1064nm} = 34.3$$

$$EOHD = \frac{1}{\theta} \cdot \sqrt{\frac{4 \cdot G \cdot Q_o}{\pi \cdot MPE} - d_o^2}$$

$$EOHD(Q_o) = \frac{1}{10^{-3}} \cdot \sqrt{\frac{4 \cdot (34.3) \cdot Q_o}{\pi \cdot \left(1.2 \times 10^{-6}\ J/cm^2\right)} - (10.1\ cm)^2}$$

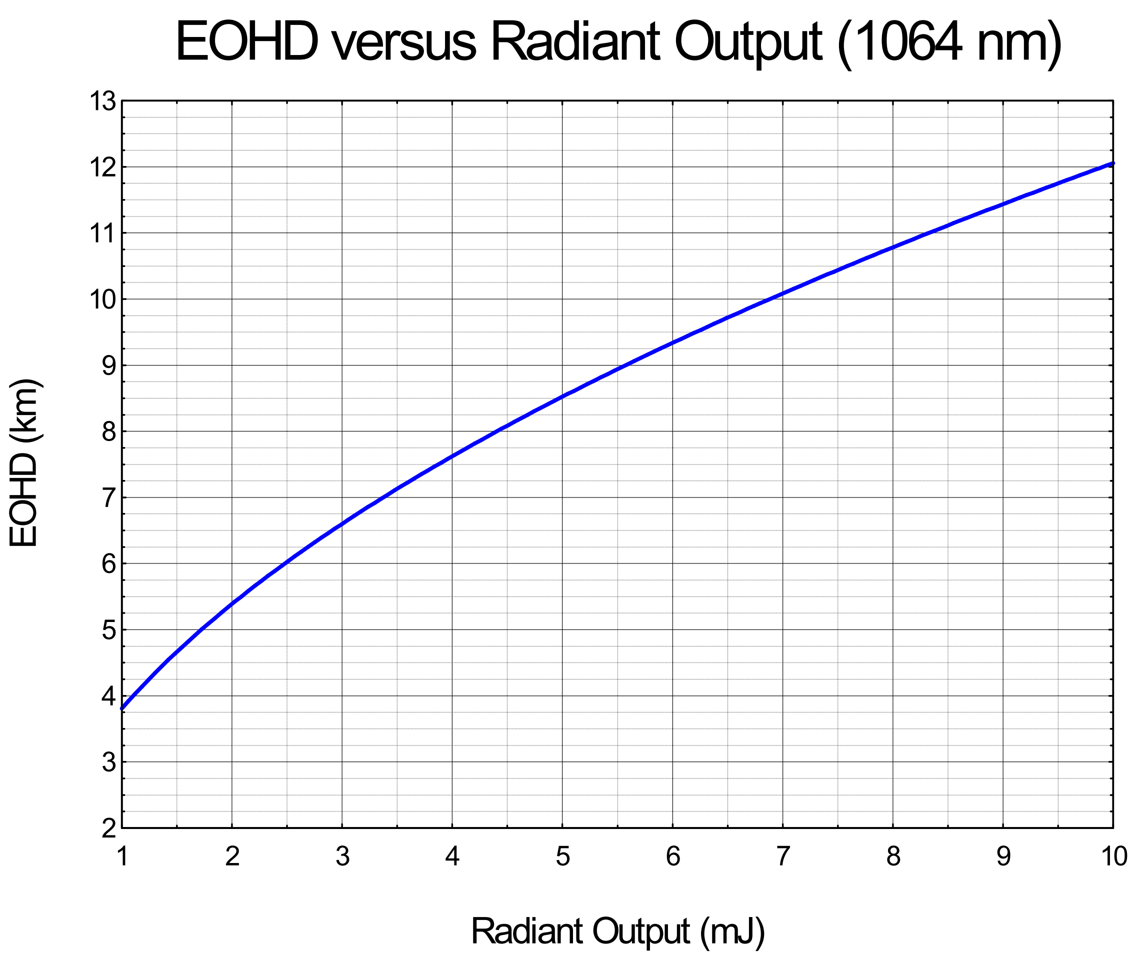

Figure 4

The EOHD as a function of the Radiant Output at 1064 nm

D. Infrared Region (**1500 nm ≤ λ <1800 nm**)

Appropriate MPE (1500 nm ≤ λ <1800 nm)

Rule 1 MPE (1500 nm ≤ λ <1800 nm)

$$MPE_{rule1} = 1 \ J\!\!\diagup_{cm^2}$$

*ANSI Std. Z136.**1**–2000 (Table 5a)*
(1500 nm < λ ≤ 1800 nm)
$(10^{-9} \text{ sec} \le T \le 10 \text{ sec})$

Rule 2 MPE (**1500 nm ≤ λ <1800 nm**)

$$MPE_{rule2} = \frac{MPE(T)}{n(T)}$$

$$T = 10 \text{ sec}$$

$$MPE_{rule2} = \frac{1 \ J\!\!\diagup_{cm^2}}{\left(30 \text{ sec}^{-1}\right)\cdot\left(10 \text{ sec}\right)}$$

$$MPE_{rule2} = 3.33 \times 10^{-3}$$

Rule 3 MPE (**1500 nm ≤ λ <1800 nm**)

$$MPE_{rule3} = C_p MPE_{thermal}$$

For radiant wavelengths in the region from 1500 nm to 1800 nm the value of $t_{\min}$ is 10 seconds. $T_{\min}$ is the maximum duration for which the value of the MPE is the same as the MPE for a one nanosecond exposure. When laser pulses occur within the duration of $t_{\min}$ the MPE value for a $t_{\min}$ exposure is distributed equally among these pulse because it is assumed that the energy delivered, by the laser pulses, with $t_{\min}$ act as if the total was delivered in a single pulse (*ANSI Std. Z136.**1**–2000 {8.2.3 – Rule 3 (note)}*).

$$t_{\min} = 10 \text{ sec}$$
$$C_p = n^{-0.25} = (1)^{-0.25} = 1$$

$$MPE_{rule3}(t_{\min}) = \frac{1 \ J\!\!\diagup_{cm^2}}{\left(30 \text{ sec}\right)\cdot\left(10 \text{ sec}\right)}$$

$$MPE_{rule3} = 3.33 \times 10^{-3}$$

Table 23

Appropriate MPE (1550 nm)

T = 10 Seconds

ANSI Rule	MPE (J/cm^2)	Comment
1	1	
2	3.33×10^{-3}	**Appropriate MPE**
3	3.33×10^{-3}	**Appropriate MPE**

Radiant Exposure (Q_{max} = 10 mJ)

$$H_{exit} = \frac{Q_{exit}}{A_{exit}}$$

$$H_{exit} = \frac{10 \times 10^{-3} J}{\frac{\pi}{4} \cdot (10.1\ cm)^2}$$

$$H_{exit} = 125 \times 10^{-6}\ J/cm^2$$

Eye Safe

$$H_{exit} < MPE$$

Table 24

Outdoor Operation (1550 nm): At Telescope Exit

(Single Test Exposure (60 seconds), T=10 seconds)

Wavelength (nm)	Output (mJ)	H_o (J/cm^2)	MPE (J/cm^2)	Comments
1550	10*	125×10^{-6}	3.33×10^{-3}	Eye-safe at telescope

* Maximum Output projected (requires laser modification to be achieved) probable output is likely <5 mJ.

E. UV Output Accumulative Effects

Unlike the visible or IR regions of the spectrum (which have standardized exposure times, 0.25 seconds and 10 seconds respectively) the UV exposure is an accumulative dose over 24 hours. As a result the MPE(s) and the NOHD(s) for the UV region will vary with the exposure time (laser event or the accumulative exposure time). The following plots present MPE(s) and NOHD(s) as a function of exposure time.

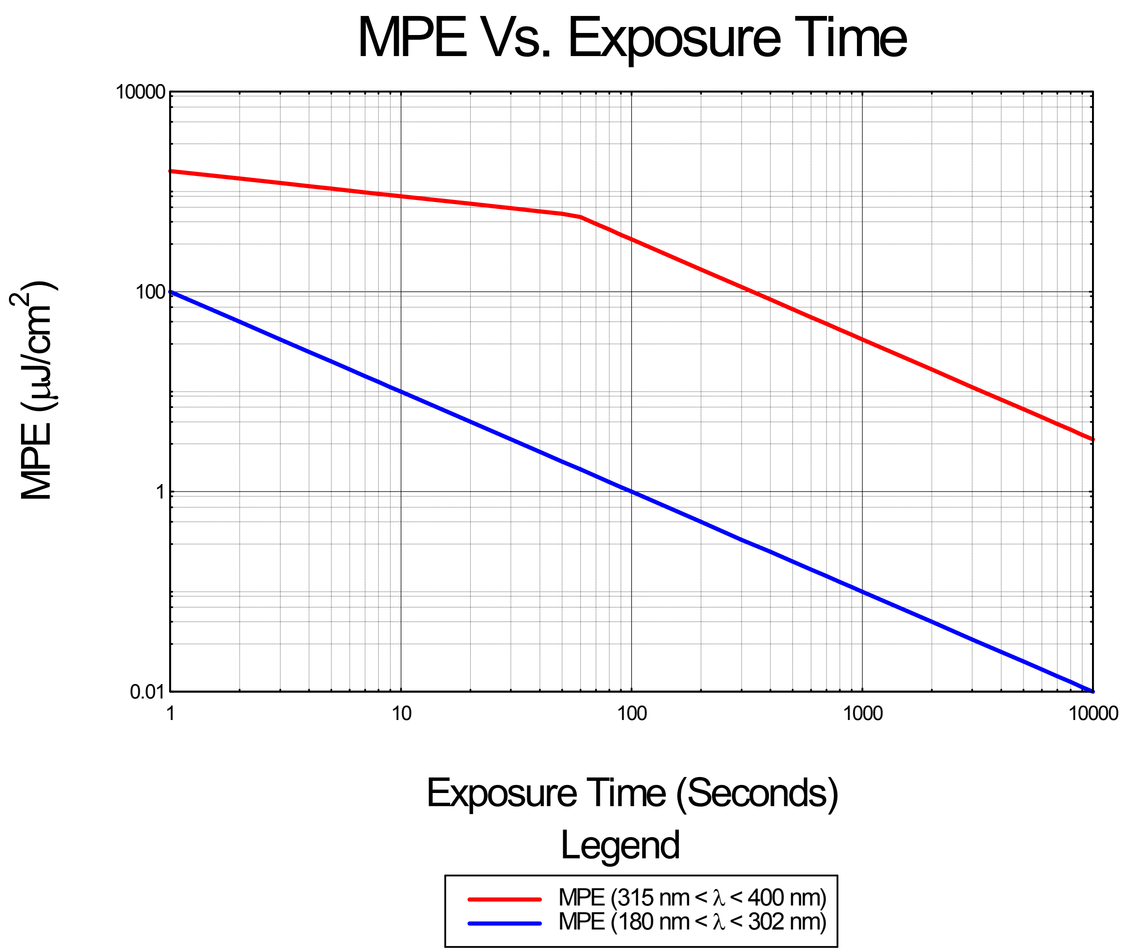

Figure 5

The per pulse MPE as a function of the accumulate exposure time for the ultraviolet region

Note that the MPE for the region (315 nm $\leq \lambda <$ 400 nm), at an exposure of ~58 seconds, changes from "Rule 3" determined to "Rule 2" determined as depicted by a change in the slope.

The NOHD(s) for exposures outside the expected 60-second test or for accumulative exposures can be read directly from the NOHD vs. Exposure plots below.

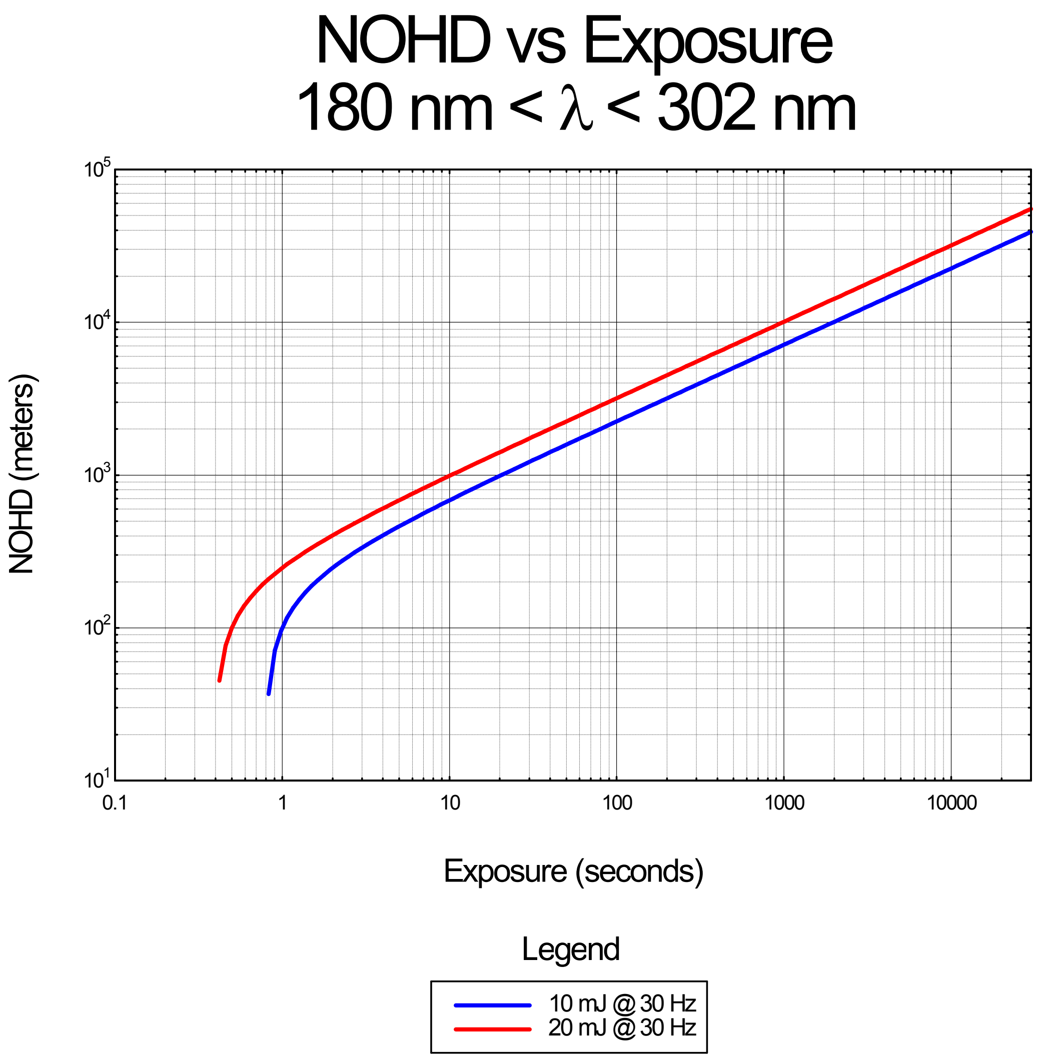

Figure 6

The NOHD as a function of the accumulated exposure time for the UV-1 ultraviolet region

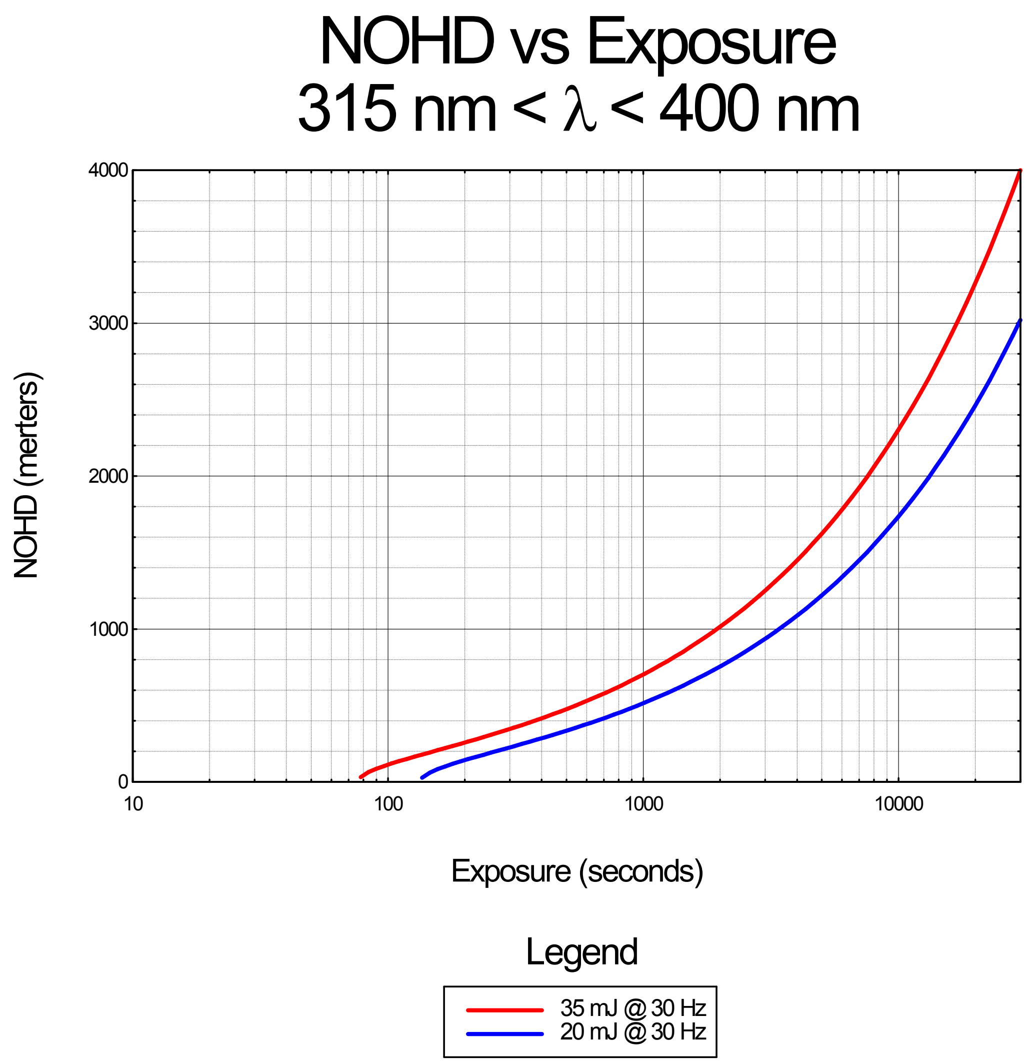

Figure 7

The NOHD as a function of the accumulated exposure time for the UV-2 ultraviolet region

F. Outdoor Operations and Navigable Air Space

The UV & IR radiant output wavelengths of the SRSS (B-70) is outside the visible portion of the spectrum as defined by *ANSI Std. Z136**.1**–2000**, and *ANSI Std. Z136**.6**–2000*† and does not pose a visual interference (distraction, disruption, or disorientation) concern for aircrews in navigable air space; however, the visible (633 nm) output of the HeNe alignment laser does pose a visual interference concern for aircrews should the laser beam enter into navigable airspace. Although the alignment laser is operated nearly horizontal; startle, dazzle, flashblindness and glare concerns apply to visible light and the minimum distance from the SRSS laser system to the boundaries of the sensitive zone (SZ), the critical zone, (*CZ*), and the Laser Free Zone (*LFZ*) about nearby airports needs to be determined.

* $400nm \le \lambda \le 700nm$ [*ANSI Std.Z136.1-2000(1.2)*]
† $380nm \le \lambda \le 780nm$ [*ANSI Std.Z136.6-2000(1.1.1)*]

Visible lasers* used in navigable air space pose hazards to aircrews beyond the *NOHD*. Air crew exposure to visible laser light, at levels below the *MPE*, pose special concerns due to startle and glare which can cause pilot distraction and vision impairments, such as flashblindness. The use of visible lasers in navigable air space has the potential to distract the pilot, disrupt critical flight crew activities, disorient the pilot or flight crew and in the extreme incapacitate the pilot.

* $400nm \le \lambda \le 700nm$ [*ANSI Std.Z136.1-2000(1.2)*]

Flight Hazard Distance

The **Flight Hazard Distance** (*FHD*) is the distance from laser where the irradiance defines the boundary of the various hazard zones.

Normal Flight Zone

The **Normal Flight Zone** (*NFZ*) is all the air space about the laser that is not include in any other visual interference zones. In the Normal Flight Zone the boundary of the Ocular Hazard Zone (distance from the laser over which an ocular hazard exists) is defined as the *NOHD*. The irradiance at this boundary is defined to be the *MPE*. Ocular exposures, at or greater than this distance, would present no more than a Class 2 hazard to visible laser light. Although considered eye safe, visible laser light can still present startle and glare concerns to flight crews, which could lead to distraction, disruption or disorientation.

Sensitive Zone

The **Sensitive Zone** (*SZ*) is the air space (including the ground) where exposure to visible laser light would interfere with critical tasks but **does not jeopardize** safety (*ANSI Std. Z136.**6**–2000 {4.7.2.1}*). The extent of the SZ is established by the local FAA office particular to the specifics of the particular local airport.

Critical Zone

The **Critical Zone** (*CZ*) is the ground and air space where "laser caused" visual interference with critical tasks **would jeopardize** the safe accomplishment of the task (*ANSI Std. Z136.**6**–2000 {4.7.2.2}*). The critical zone extends out to a 10 NM (18.4 km) radius about the reference point of the airport (*ANSI Std. Z136.**6**–2000 {Figure 5}*).

Laser–Free Zone

The **Laser-Free Zone** (*LFZ*) is the ground and air space where visual interference would be very serious and might prevent the accomplishment of critical tasks, such as aircraft operation about or around airports (*ANSI Std. Z136.6–2000 {4.7.2.3}*). The area within a two nautical mile (3.7 km) of each runway and extending out to 5 NM (9.2 km) along the guide path of the runway is designated as a LFZ (*ANSI Std. Z136.6–2000 {Figure 4}*).

Visual Interference Levels

The visual interference levels (VIL) presented in *ANSI Standard Z136.6–2000 {Table 5}* are established for expected aircrew exposure during periods of reduced ambient lighting (*ANSI Std. Z136.6–2000 {3.4}*). The maximum effective radiant exposure levels of visible laser light entering the visual interference zone boundaries are limited to these levels. The visual interference levels presented in *ANSI Std. Z136.6–2000 {Table 5}* are for the Photopic Luminous Efficiency of the eye at an exposure to 555 nm light.

The maximum allowed **Effective Irradiance** ($E_{eff\text{-}SZ}$), normalized for 555 nm light, at the boundary of the **sensitive zone** of a nearby airport is given as:

ANSI Std. Z136.6–2000 {Table 5}

$$E_{eff-SZ} = 100 \times 10^{-6}\ {}^{w}\!/_{cm^2}$$

$$380\ nm \le \lambda \le 780\ nm$$

$$T_{\max} \le 0.25\sec$$

The maximum allowed **Effective Irradiance** ($E_{eff\text{-}SZ}$), normalized for 555 nm light, at the boundary of **critical zone** is given as:

ANSI Std. Z136.6–2000 {Table 5}

$$E_{eff-CZ} = 5 \times 10^{-6}\ {}^{w}\!/_{cm^2}$$

$$380\ nm \le \lambda \le 780\ nm$$

$$T_{\max} \le 0.25\sec$$

The maximum allowed **Effective Irradiance** ($E_{eff\text{-}LFZ}$), normalized for 555 nm light, at the boundary of the **laser-free zone** is given as:

ANSI Std. Z136.6–2000 {Table 5}

$$E_{eff-LFZ} = 50 \times 10^{-9}\ {}^{J}\!/_{cm^2}$$

$$380\ nm \le \lambda \le 780\ nm$$

$$T_{\max} \le 0.25\sec$$

Effective Irradiance

The **Effective Irradiance** is defined to be the product of the radiant exposure of the visible laser and relative visual response (*ANSI Std. Z136.6–2000 {Table 1}*), which is a function of the laser wavelength.

$$E_{eff} = \nu_{\lambda} \cdot E$$

Where;
E_{eff}: Effective Irradiance (in w/cm^2)
ν_{λ}: Photopic Luminous Efficiency (relative visual response of the eye)
E: Laser Irradiance (in w/cm^2)

The Photopic luminous efficiency function (ν_{λ}) of the eye at 633 nm can be extrapolated from the tabulated values presented in *ANSI Std. Z136.6–2000 {Table1}*.

$$\nu_{(633nm)} = \nu_{(635nm)} + 2 \cdot \left(\frac{\nu_{(630nm)} - \nu_{(635nm)}}{5} \right)$$

$$= 0.215 + 2 \cdot \left(\frac{0.265 - 0.215}{5} \right)$$

$$= 0.215 + 0.020$$

$$\nu_{(633nm)} = 0.235$$

The irradiance limit ($E_{\lim}$) at 633 nm, to produce the effective radiant exposure levels presented for the visual interference levels in Table 5 of *ANSI Std. Z136.6–2000* are determined as a function of the Photopic luminous efficiency factor:

$$E_{\lim}(\lambda) = \frac{E_{eff}}{\nu_{\lambda}}$$

$$E_{\lim}(633\ nm) = \frac{E_{eff}}{v_{(633nm)}}$$

$$E_{\lim}(633\ nm) = \frac{E_{eff}}{0.235}$$

Table 25

Visual Interference Levels @ 633 nm

Visual Interference Zones	Effective Irradiance $\left(W/_{cm^2} \right)$	Irradiance Limit @ 633 nm $\left(W/_{cm^2} \right)$
Sensitive Zone	100×10^{-6}	426×10^{-6}
Critical Zone	5×10^{-6}	21.3×10^{-6}
Laser Free Zone	50×10^{-9}	213×10^{-9}

Distance from the HeNe Laser to the Visual Interference Zone

The distance from the laser to the boundary of the visual interference zones about an airport can be calculated using the Range Equation present in *ANSI Std. Z136.1–2000 (Equation B50)* substituting the appropriate visual interference zone level for the MPE value.

The distance from the laser to the boundaries of a visual interference zone ($\tau_{\lambda}(atmospheric) = 1.0$) are:

Distance to the Sensitive Zone Boundary

$$R_{SZ} = \frac{1}{\theta}\sqrt{\frac{4 \cdot \Phi_o}{\pi \cdot E_{\lim - SZ}(\lambda)} - d_o^2}$$

$$R_{SZ} = \left(\frac{1}{1 \times 10^{-3}}\right) \cdot \sqrt{\frac{4 \cdot \Phi_o}{\pi \cdot E_{\lim - SZ}(633nm)} - (0.1\ cm)^2}$$

$$R_{SZ} = \left(10^3\right) \cdot \sqrt{\frac{4 \cdot \left(15 \times 10^{-3} w\right)}{\pi \cdot \left(426 \times 10^{-6}\, {}^{w}\!/\!{}_{cm^2}\right)} - 10^{-3} cm^2}$$

$$R_{SZ} = 20.1 \times 10^3 cm$$

$$R_{SZ} = 201 \ m$$

Distance to the Critical Zone Boundary

$$R_{CZ} = \frac{1}{\theta}\sqrt{\frac{4 \cdot \Phi_o}{\pi \cdot E_{\lim - CZ}(\lambda)} - d_o^2}$$

$$R_{CZ} = \left(\frac{1}{10^{-3}}\right) \cdot \sqrt{\frac{4 \cdot (\Phi_o)}{\pi \cdot E_{\lim - CZ}(633nm)} - (0.1 \ cm)^2}$$

$$R_{CZ} = \left(10^3\right) \cdot \sqrt{\frac{4 \cdot \left(15 \times 10^{-3} w\right)}{\pi \cdot \left(21.3 \times 10^{-6}\, {}^{w}\!/\!{}_{cm^2}\right)} - 10 \times 10^{-3} cm^2}$$

$$R_{CZ} = 30 \times 10^3 cm$$

$$R_{CZ} = 300 \ m$$

Distance to the Laser Free Zone Boundary

$$R_{LFZ} = \frac{1}{\theta}\sqrt{\frac{4 \cdot \Phi_o}{\pi \cdot E_{\lim - LFZ}(\lambda)} - d_o^2}$$

$$R_{LFZ} = \left(\frac{1}{10^{-3}}\right) \cdot \sqrt{\frac{4 \cdot (\Phi_o)}{\pi \cdot E_{\lim - LFZ}(633nm)} - (0.1 \ cm)^2}$$

$$R_{LFZ} = \left(10^3\right)\sqrt{\frac{4\cdot\left(15\times10^{-3}\,w\right)}{213\times10^{-9}\,{}^{w}\!/_{cm^2}} - 0.01\ cm^2}$$

$$R_{LFZ} = 300\times10^{6}\,cm$$

$$R_{LFZ} = 3\ km$$

Table 26

Minimum Approach Distance of the SRSS B-70 Laser to the Boundaries of Visual Interference Zones of an Airport

Visual Interference Zone	Minimum Distance to Boundary (km)
Sensitive	0.2
Critical	0.3
Laser Free	3.0

The NOHD (for invisible as well as visible laser light) does apply in the Normal Flight Zone (**NFZ**). The NOHD of the SRSS lasers was determined to be on the order of three kilometers. Care shall be taken not to direct the SRSS laser outputs beam into navigable air space.

For the normal operation of the SRSS, the laser beam is directed toward the target or in the case of the HeNe to the SRSS. In both cases either the West Face of the Manzano Mountains or the East Face of the "Laser Hill" acts as a backstop to prevent the laser beams from entering into navigable air space. Care should also be taken to avoid specular reflections which may re-direct the laser output into occupied navigable air space.

E. Nighttime Effects

The SRSS laser has two possible outputs in the retinal hazard region during nighttime (moonless night) operations. The NEOH had been estimated as 1.65 (section I. B (6) Page 20).

1. Visible Output (633 nm)

(a) Nighttime MPE

$$MPE_{633nm}(night) = \frac{MPE_{633nm}}{1.65}$$

$$= \frac{2.55 \times 10^{-3}\ J/cm^2}{1.65}$$

$$MPE_{633nm}(night) = 1.54 \times 10^{-3}\ J/cm^2$$

(b) Nighttime Class 2 AEL

$$Class\ \ 2\ \ AEL_{633nm}(night) = \frac{AEL_{633nm}}{1.65}$$

$$= \frac{980 \times 10^{-6}\, w}{1.65}$$

$$Class\ \ 2\ \ AEL_{633nm}(night) = 593 \times 10^{-6}\, w$$

(c) Nighttime Minimum OD

$$OD_{\min_{633nm}}(night) = \log_{10}\left[\frac{\Phi_{633nm}}{Class\ \ 2\ \ AEL_{633nm}(night)}\right]$$

$$= \log_{10}\left[\frac{15 \times 10^{-3}\, w}{593 \times 10^{-6}\, w}\right]$$

$$OD_{\min_{633nm}}(night) = 1.40$$

$$NOHD_{633nm}(night) = \frac{1}{\theta} \cdot \sqrt{\frac{4 \cdot \Phi_o}{\pi \cdot MPE_{633nm}(night)} - d_o^2}$$

$$= \frac{1}{10^{-3}} \cdot \sqrt{\frac{4 \cdot (15 \times 10^{-3}\, w)}{\pi \cdot 1.54 \times 10^{-3}\, {}^{w}\!/_{cm^2}} - (0.1\ cm)^2}$$

$$= 3.52 \times 10^3\, cm$$

$$NOHD_{633nm}(night) = 35.2\ m$$

(d) Nighttime EOHD

$$EOHD_{633nm}(night) = \frac{1}{\theta} \cdot \sqrt{\frac{4 \cdot G \cdot \Phi_o}{\pi \cdot MPE_{633nm}(night)} - d_o^2}$$

$$= \frac{1}{10^{-3}} \cdot \sqrt{\frac{4 \cdot (44.1) \cdot (15 \times 10^{-3}\, w)}{\pi \cdot \left(1.54 \times 10^{-3}\, {}^{w}\!/_{cm^2}\right)} - (0.1\ cm)^2}$$

$$= 23.4 \times 10^3\, cm$$

$$EOHD_{633nm}(night) = 234\ meters$$

Table 27

Summary of Nighttime Values (633 nm)

MPE-night (mw /cm^2)	AEL-night (μw)	OD_{min}	NOHD -night (m)	EOHD -night (m)
1.54	593	1.40	35.2	234

2. IR (**1064 nm**) Telescope Output

(a) Nighttime MPE

$$MPE_{1064nm}(night) = \frac{MPE_{1064nm}}{1.65}$$

$$= \frac{1.2 \times 10^{-6} \ J/cm^2}{1.65}$$

$$MPE_{1064nm}(night) = 727 \times 10^{-9} \ J/cm^2$$

(b) Nighttime ODmin ($Q_{\max} = 10 \ \ mJ$)

$$OD_{\min_{1064nm}}(night) = \log_{10}\left[\frac{H_{1064nm}}{MPE_{1064nm}(night)}\right]$$

$$= \log_{10}\left[\frac{Q_{1064nm}/A_{exit}}{MPE_{1064nm}(night)}\right]$$

$$= \log_{10}\left[\frac{10 \times 10^{-3} J/80.1 \ cm^2}{727 \times 10^{-9} \ J/cm^2}\right]$$

$$= \log_{10}\left[\frac{125 \times 10^{-6} \ J/cm^2}{727 \times 10^{-9} \ J/cm^2}\right]$$

$$OD_{\min_{1064nm}}(night) = 2.23$$

(d) Nighttime NOHD (1064 nm)

$$NOHD_{1064nm}(night) = \frac{1}{\theta} \cdot \sqrt{\frac{4 \cdot Q_o}{\pi \cdot MPE_{1064nm}(night)} - d_o^2}$$

$$= \frac{1}{500 \times 10^{-6}} \cdot \sqrt{\frac{4 \cdot (10 \times 10^{-3}\, J)}{\pi \cdot 727 \times 10^{-9}\, J/cm^2} - (10.1\ cm)^2}$$

$$= 264 \times 10^3\, cm$$

$$NOHD_{1064nm}(night) = 2.64\ km$$

(e) Nighttime EOHD (1064 nm)

$$EOHD_{1064nm}(night) = \frac{1}{\theta} \cdot \sqrt{\frac{4 \cdot G \cdot Q_o}{\pi \cdot MPE_{1064nm}(night)} - d_o^2}$$

$$= \frac{1}{500 \times 10^{-3}} \cdot \sqrt{\frac{4 \cdot (34.3) \cdot (10 \times 10^{-3}\, J)}{\pi \cdot (727 \times 10^{-9}\, J/cm^2)} - (10.1\ cm)^2}$$

$$= 1.55 \times 10^6\, cm$$

$$EOHD_{1064nm}(night) = 15.5\ km$$

Table 28

Summary of Nighttime Values (1064 nm)

H_o ($\mu J/cm^2$)	MPE-night (nJ/cm^2)	OD_{min}	NOHD -night (km)	EOHD -night (km)
125	727	4.55	2.64	15.5

3. IR (1064 nm)

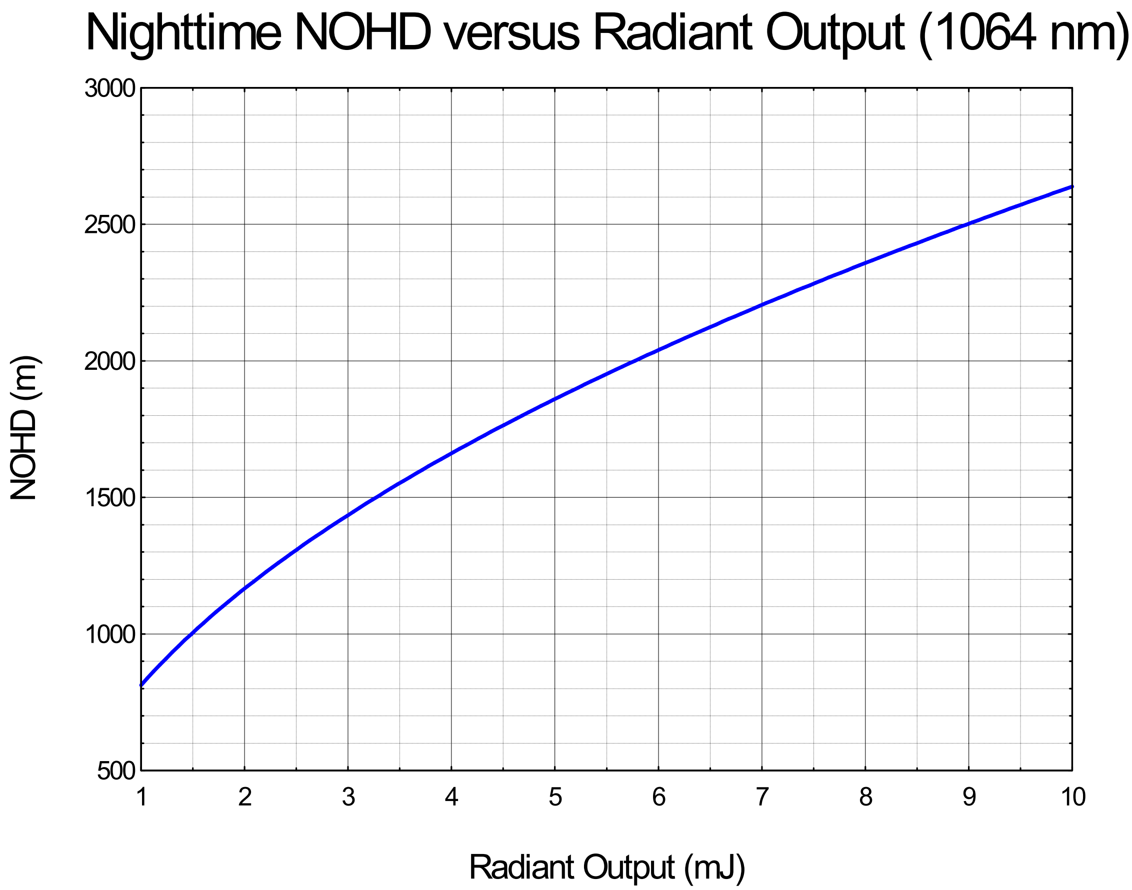

Figure 8

The NOHD for nighttime exposure as a function of the Radiant Output at 1064 nm

Should the Nd:YAG pump fundamental (1064 nm) be used as a rangefinder the output is expected to be in the range of 1 mJ to a maximum of 10 mJ per pulse. This wavelength is in the retinal hazard region and the state of the pupil of the eye at night has an effect on the NOHD and the EOHD.

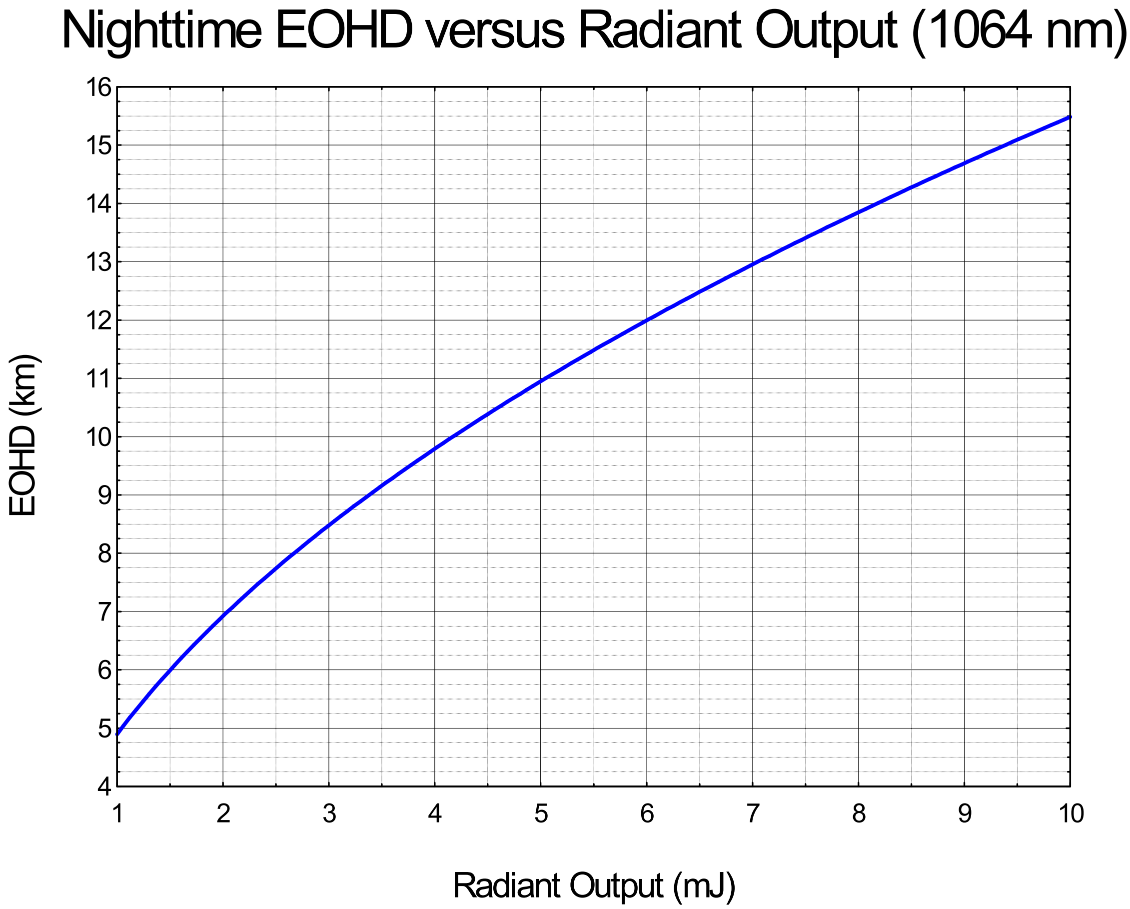

Figure 9

The EOHD for a nighttime exposure as function of the Radiant Output at 1064 nm

Laser hazard analysis for SRSS (UV specific) 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 for the SRSS should be re-accomplished.

IV. References

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

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

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.

V. Appendix

EXCEL Calculator

Coherent / Acculite Based SRSS

INSIDE of the Trailer

Pump Laser

	INPUT*	
t=	**2.00E-09**	**sec**
PRF=	**30**	**Hz**

ANSI Std.Z136.1 (Table 4a) Standard Exposure Times

T_{IR} =	10	sec
T_{vis} =	0.25	sec
T_{UV} =	30000	sec

INPUT

Output	λ (nm)	Q_o (J)	MPE_{rule1} (J/cm²)	MPE_{rule2} (J/cm²)	MPE_{rule3} (J/cm²)	MPE (J/cm²)	MPE2ndDay (J/cm²)	AEL (J)	OD_{min}
IR	**1064**	**0.500**	5.00E-06	1.69E-04	1.20E-06	**1.20E-06**	1.20E-06	4.62E-07	**6.03**
VIS	**532**	**0.250**	5.00E-07	7.95E-05	2.97E-07	**2.97E-07**	2.97E-07	1.14E-07	**6.34**
UV-2	**355**	**0.035**	3.74E-03	1.11E-06	1.22E-04	1.11E-06	**4.44E-07**	4.28E-08	**5.91**
UV-1	**266**	**0.020**	3.00E-03	3.33E-09	1.22E-04	3.33E-09	**3.33E-09**	3.21E-10	**7.79**

OPO/A **INPUT**

Output	λ (nm)	Q_o (J)	MPE_{rule1} (J/cm²)	MPE_{rule2} (J/cm²)	MPE_{rule3} (J/cm²)	MPE (J/cm²)	MPE2ndDay (J/cm²)	AEL (J)	OD_{min}
IR	**1550**	**0.010**	1	3.33E-03	3.33E-03	**3.33E-03**	3.33E-03	3.21E-04	**1.49**
IR	**1064**	**0.010**	5.00E-06	1.69E-04	1.20E-06	**1.20E-06**	1.20E-06	1.16E-07	**4.94**
UV-2	**>315**	**0.020**	3.74E-03	1.11E-06	1.22E-04	1.11E-06	**4.44E-07**	4.28E-08	**5.67**
UV-1	**>280-302**	**0.010**	3.00E-03	3.33E-09	1.22E-04	3.33E-09	**1.33E-09**	1.28E-10	**7.89**
UV-1	**180-280**	**0.010**	3.00E-03	3.33E-09	1.22E-04	**3.33E-09**	3.33E-09	3.21E-10	**7.49**

Optical Gain For 7x 50 mm Binoculars

G_{VIS} =	44.1
G_{NIR}=	34.3
$G_{uv<302}$ =	0.98

Luminous Efficiency

(nm)	ν(λ)
630	0.265
635	0.215

	ANSI Std.Z136.6 - Table 5	
Sensitive Zone	1.00E-04	w/cm²
Critical Zone	5.00E-06	w/cm2
Laser Free Zone	5.00E-08	w/cm2

Visual Interference

λ (nm)	Φ_o (w/J)	ν(λ)	$E(\lambda)_{lim\text{-}SZ}$ (w)	$E(\lambda)_{lim\text{-}CZ}$ (w)	$E(\lambda)_{lim\text{-}LFZ}$ (w)	R_{SZ} (m)	R_{CZ} (m)	R_{LFZ} (m)
633	0.015	0.235	4.26E-04	2.13E-05	2.13E-07	201	300	3.00E+03

*Blue Font values are calculator INPUT (laser and telescope exit) parameters.

OUTSIDE of the Trailer (Single Unauthorized Exposure)

Output Parameters

INPUT

d_o=	**10.1**	**cm**	D_{exit} =	80.1	cm
Θ=	**5.00E-04**	**radians**			
T=	**60**	**sec**			

Telescope Output Parameters:-

Output	λ (nm)	Q_o (J)	H_o (J/cm²)	MPE_{rule1} (J/cm²)	MPE_{rule2} (J/cm²)	MPE_{rule3} (J/cm²)	MPE (J/cm²)	OD_{min}	NOHD?
IR	1550	0.010	1.25E-04	1	3.33E-03	3.33E-03	3.33E-03	-1.43	Eye Safe
IR	1064	0.010	1.25E-04	5.00E-06	1.69E-04	1.20E-06	1.20E-06	2.02	NOHD
UV-2	355	0.035	4.37E-04	3.74E-03	5.56E-04	5.75E-04	**5.56E-04**	-0.10	Eye Safe
UV-2	>315	0.020	2.50E-04	3.74E-03	5.56E-04	5.75E-04	**5.56E-04**	-0.35	Eye Safe
UV-1	>280-302	0.010	1.25E-04	3.00E-03	1.67E-06	5.75E-04	**1.67E-06**	**1.87**	NOHD
UV-1	180-280	0.010	1.25E-04	3.00E-03	1.67E-06	5.75E-04	**1.67E-06**	**1.87**	NOHD
UV-1	266	0.020	2.50E-04	3.00E-03	1.67E-06	5.75E-04	**1.67E-06**	**2.18**	NOHD

Output	λ (nm)	Q_o (J)	H_o (J/cm²)	MPE (J/cm²)	NOHD (m)	Eye Safe?	G	EOHD m
IR	1550	0.010	1.25E-04	**3.33E-03**	0.00E+00	Yes	34.3	1.08E+02
IR	1064	0.010	1.25E-04	**1.20E-06**	2.05E+03	No	34.3	1.21E+04
UV-2	355	0.035	4.37E-04	**5.56E-04**	0.00E+00	Yes	34.3	1.03E+03
UV-2	>315	0.020	2.50E-04	**5.56E-04**	0.00E+00	Yes	34.3	7.67E+02
UV-1	>280-302	0.010	1.25E-04	**1.67E-06**	1.74E+03	No	0.98	1.72E+03
UV-1	180-280	0.010	1.25E-04	**1.67E-06**	1.74E+03	No	0.98	1.72E+03
UV-1	266	0.020	2.50E-04	**1.67E-06**	2.46E+03	No	0.98	2.44E+03

Alignment HeNe Laser: (Target back to trailer)

INPUT

$T_{aversion}$ = 0.25 sec T_{align} = 600 sec

d_o=	0.1	cm	**Φ =**	**0.015**	watts	D_f =	7	mm
Θ=	1.00E-03	radians	**NEOH=**	**1.65**				

Output	λ (nm)	$Φ_o$ (w)	MPE_{class1} (w/cm²)	MPE_{Class2} (w/cm²)	Class 1 AEL (w)	Class 2 AEL (w)	Aversion ODmin	Alignment ODmin
VIS	633	0.015	1.00E-03	2.55E-03	3.85E-04	9.80E-04	1.19	**1.59**

Retinal Hazards **DAY TIME** **NIGHT TIME**

λ (nm)	$Φ_o/Q_o$ (w/J)	MPE_{Class2} (w/cm²)	MPE_{night} (w/cm²)	NOHD (m)	EOHD (m)	AEL_{night} (w/J)	NOHD (m)	EOHD (m)	OD_{min} night
1064	0.010	N/A	7.27E-07	2.05E+03	1.21E+04	2.80E-07	2.64E+03	1.55E+04	2.23
633	0.015	2.55E-03	1.54E-03	27.4	182	5.93E-04	35.2	234	1.40

VI. Abbreviations & Symbols

A_{exit}	Area at the exit of the telescope
AEL	Allowable Emission (Exposure) Limit
$AEL_{2nd\ day}$	Successive day Allowable Emission (Exposure) Limit
AF	Air Force
AFRL	Air Force Research Laboratory
A_{lim}	Area of limiting aperture
ANSI	American National Standards Institute
C_p	Multiple-pulse correction factor
CW	Continuous wave
CZ	Critical Zone
d_{aid}	Entrance diameter of optical aid
D_c	Collecting diameter
d_{exit}	Exit diameter of the telescope
D_f	Diameter of limiting aperture
d_o	Output beam diameter
E	Irradiance, in w/cm^2
E_{eff}	Effective irradiance w/cm^2
E_{lim}	Visual interference irradiance limit
E_o	Output Irradiance, in w/cm^2
EOHD	Extended Ocular Hazard Distance
FHD	Flight Hazard Distance
G	Optical gain
G_{eff}	Effective gain
H	Radiant Exposure of the beam
HAZ	Hazard level
H_{exit}	Radiant Exposure at the exit of the telescope
H_f	Radiant Exposure over the limiting aperture
H_o	Radiant Exposure at the laser output
Hz	Hertz, cycle per second, sec^{-1}
IR	Infrared
J	Joules, unit of energy
LFZ	Laser Free Zone
Min[a,b]	Minimum of value of a and b

mJ	Millijoule, 10^{-3} Joules
MPE	Maximum Permissible Exposure
MPE_{cw}	Continuous Wave Maximum Permissible Exposure
MPE_{rule1}	Maximum Permissible Exposure based on ANSI Rule 1
MPE_{rule2}	Maximum Permissible Exposure based on ANSI Rule 2
MPE_{rule3}	Maximum Permissible Exposure based on ANSI Rule 3
$MPE_{thermal}$	Maximum Permissible Exposure based on the thermal limit
$MPE_{2nd\ day}$	Successive day Maximum Permissible Exposure
mw	Milliwatts, 10^{-3} watts
n	Number of pulses in the exposure
NEOH	Nighttime enhanced ocular hazard
NFZ	Normal flight zone
NIR	Near infrared
nm	Nanometer, 10^{-9} meters
NOHD	Nominal Ocular Hazard Distance
ns	Nanosecond, 10^{-9} seconds
NHZ	Nominal Hazard Zone
OD	Optical Density of the laser safety eye ware
OD_{min}	Minimum Optical Density required of laser safety eye ware
OPA	Optical Parametric Amplifier
OPO	Optical Parametric Oscillator
P	Magnifying power
PRF	Pulse Repetition Frequency
Q	Radiant Energy, in Joules
Q_o	Output Radiant Energy, in Joules
R	Range
R_{cz}	Range from the laser to the critical zone boundary
R_{LFZ}	Range from the laser to the laser free zone boundary
R_{sz}	Range from the laser to the sensitive zone boundary
SFG	Sum Frequency Generator
SRSS	Sandia Remote Sensing System
SZ	Sensitive Zone
t	Exposure duration, pulse duration
T	Exposure duration, in seconds
UV	Ultraviolet
VIL	Visual interference levels

w	Watts (unit of power)
θ	Beam divergence, in radians
Φ	Radiant Power in watts
λ	Wavelength
μm	Micrometer, 10-6 meters
τ	Transmission factor
τ_{aid}	Transmission factor of optical aid
τ_{atm}	Atmospheric transmission factor
v_{λ}	Photopic Luminous Efficiency (relative visual response of the eye)

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