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OBSERV ATV2000i Laser Illuminator Hazard Analysis

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Abstract

A laser safety and hazard analysis was performed, for the OBSERV® ATV2000i Laser Illuminator based Intrusion Detection System, based on the 2000 version of the American National Standards Institute's (ANSI) Standard Z136.1, *for Safe Use of Lasers* and the 2000 version of the ANSI Standard Z136.6, *for Safe Use of Lasers Outdoors*.

Summary

1. Personnel working within close proximity of the OBSERV Surveillance system are required to wear laser safety eyewear with a minimum optical density of 2.88 (Typical Operation with nighttime enhancement) and 3.07 (Extraordinary Operation with nighttime enhancement). Should personnel have to interact with the laser prior to the beam expanding optics the required minimum OD is 3.86 (AEL based). The laser safety eyewear currently in use is rated at **7.50** in the wavelength NIR range and is more than adequate for all possible operations of the illumination laser.

2. The NOHD and EOHD, including nighttime enhance values, are much shorter than the target range for all possible operations of the illumination laser. Personnel in the target location are outside the laser hazard zone and are safe from hazardous exposure.

3. The surveillance camera field of view is always somewhat larger than the illuminating laser spot allowing the system operator to terminate laser operation should unauthorized personnel enter the field of view at a distance much closer to the surveillance system than the target range.

T= 10 Max Dimension, Min Divergence

Range (km)	PRF (Hz)	Gate Length (km)	t (sec)	Pulse Energy (joules)	MPE (J/cm^2)	NOHD Day (Meters)	NOHD night (Meters)	EOHD Day (Meters)	EOHD Night (Meters)	Maximum OD_{min} night
5	30	0.5	1.67E-06	2.12E-05	4.48E-08	29	41	238	310	2.30
7.5	20	0.75	2.50E-06	3.18E-05	4.96E-08	36	50	280	364	2.43
10	15	1	3.33E-06	4.23E-05	5.33E-08	42	58	313	407	2.53
15	10	1.5	5.00E-06	6.35E-05	5.90E-08	51	69	367	476	2.66
30	5	3	1.00E-05	1.27E-04	7.02E-08	70	94	480	621	2.88

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II. Introduction

The OBSERV model ATV2000i laser illuminator is integrated with a gated camera and central to a real time long range monitored LIDAR surveillance system. The laser consists of an array of 150 laser diodes producing a rectangular output spot with a spatially uniform energy density. The laser is co-aligned with the gated camera optic system. The camera's field of view is always somewhat greater than the illuminating laser spot within the field of view and is displayed on surveillance TV monitor. The CW diode array is pulsed on and off and gated to the surveillance camera to provide a high signal to noise ratio. The camera's gate on delay time is adjusted, by range, to allow for the round trip time for the leading edge of the laser pulse, from the laser to the target, to return to the camera. The laser pulse width is tied to the gate length on time of the camera, as a function of the target range, which achieves the high signal image to noise ratio of the monitored target. The gate length is a function of the camera's adjusted range. For this particular model the gate length is set at 10% of the adjusted target range of the camera. The laser pulse repetition rate is tied to the target range and is continuously adjustable and tracks as the target range is adjusted.

The diode laser power level is adjustable, up to a typical operation maximum level (12.7 watts CW), by the laser operator to achieve optimum image intensity and contrast on the surveillance monitor. The extraordinary maximum power (19.6 watts CW) is password protected and is not generally accessible to the laser operator.

The laser operator can adjust the camera's field of view and the focus range out to 30 kilometers, real time while observing the surveillance monitor. The exit dimensions of the laser and the beam divergence (for each axis) is tied to the camera optical system and follows the camera's adjustment.

The detailed hazard analysis presented here is based on the maximum power level for the Typical Operation. A summary EXCEL® spreadsheet for both Typical Operation and Extraordinary Operation is presented in the Appendix.

III. Laser Parameters

Manufacture:	OBSERV
Model:	ATV2000i
Type:	Diode Array
Class:	4
Wavelength:	861 nm
Maximum Radiant Power CW): (pass word override)	19.6 watts
(Typical) Maximum Radiant Power (CW):	12.7 watts
Operated:	Pulsed
Gate Length:	0.50 km – 3.00 km @ 10% of Range
Pulse width:	Determined by the gate length
Pulse Energy:	Determined by the pulse width
Pulse Repetition Frequency:	5 kHz @ 30 km – 30 kHz @ 5 km
Beam Shape:	Rectangular
Maximum Beam Dimension at minimum beam divergence:	5.7 mm (horizontal) x 8.5 mm (vertical)
Minimum Beam Divergence:	5.3 mr @ 1/e (horizontal) x 4.8 mr @ 1/e (vertical)
Maximum Beam Divergence:	20.4 mr @ 1/e (horizontal) x 16.8 mr @ 1/e (vertical)

Pulse Parameter Determination

The operations manual cites "the maximum pulse length is a percentage of the maximum range (6.5 % - Standard Mode and 10% - Override Mode).

(*Gate Length*) = (0.065) x (*Maximum Range*)

$$l_{gate} = (0.065) \cdot R$$

$$Pulse\ Length = \frac{Gate\ Length}{Speed\ of\ Light}$$

$$t = \frac{l_{gate}}{C}$$

$$Pulse\ Energy = (Radiant\ Power) \times (Pulse\ Length)$$

$$Q = \Phi \cdot t$$

Table 1

Laser Parameters as a Function of Range

(Standard Mode, $\overline{\Phi} = 12.7$ watts)

Range (km)	Gate Length (km)	Pulse Repetition Frequency (kHz)	Pulse Length (μ sec)	Pulse Energy (μ J)
5	0.500	30	1.67	21.2
7.5	0.750	20	2.50	31.8
10	1.00	15	3.33	42.3
15	1.50	10	5.00	63.5
30	3.00	5	10.0	127

Values are from the System Analytical Model (EXCEL calculator) presented in the Appendix (page 31).

III. Laser Hazard Analysis

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

a. Maximum Permissible Exposure Determination

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)*].

1. Daytime Laser Operations

The current laser exposure limits presented in *ANSI Std.Z136.1-2000 (Table 5a)* are based on typical outdoor daylight and indoor standard lighting levels.

(a) ANSI Rule 1

$$MPE_{rule1} = 5 \cdot C_A \times 10^{-7} \, J/cm^2 \qquad (\textit{ANSI Std. Z136.1-2000 \{Table 5a\}})$$

$$C_A = 10^{2(\lambda - 0.7)} \qquad (\textit{ANSI Std. Z136.1-2000 \{Table 6\}})$$

$$= 10^{2(0.861 - 0.7)}$$

$$C_A = 2.10$$

$$MPE_{rule1} = 5 \cdot (2.10) \times 10^{-7} \, J/cm^2$$

$$MPE_{rule1} = 1.05 \times 10^{-6} \, J/cm^2$$

(b) ANSI Rule 2 (Average Power per pulse)

$$MPE_{rule2}(T) = \frac{MPE_T}{n_T}$$ (*ANSI Std. Z136.1-2000 (8.2.3 – Rule 2*)

$$T = 10 \ \text{sec}$$ (*ANSI Std. Z136.1-2000 {Table 4a}*)

The number of pulses emitted during the standard exposure (*T*) is the product of the Pulse Repetition Frequency (*PRF*) and the exposure time.

$$n_T = (PRF \cdot T)$$

(*ANSI Std. Z136.1-2000 {Table 5a}*)

$$MPE_T = 1.8 \cdot C_A \cdot T^{0.75} \times 10^{-3} \ J/cm^2 \quad (700 \ nm < \lambda \leq 1050 \ nm)$$
$$(18 \times 10^{-6} \ \text{sec} < t \leq 10 \ \text{sec})$$

$$MPE_{10\,\text{sec}} = 1.8 \cdot (2.10) \cdot (10)^{0.75} \times 10^{-3} \ J/cm^2$$

$$MPE_{10\,\text{sec}} = 21.2 \times 10^{-3} \ J/cm^2$$

$$MPE_{rule2}(10) = \frac{21.2 \times 10^{-3} \ J/cm^2}{10 \cdot PRF}$$

Table 2

ANSI Rule 2 – MPE at Various Ranges

Range (km)	PRF (kHz)	MPE_{rule2} (J/cm^2)
5	30	70.8×10^{-9}
7.5	20	106×10^{-9}
10	15	142×10^{-9}
15	10	212×10^{-9}
30	5	425×10^{-9}

Values are from the System Analytical Model (EXCEL calculator) presented in the Appendix (page 31).

(c) ANSI Rule 3 (Multiple Pulse for Thermal Hazards)

$$MPE_{rule3} = C_p \cdot MPE_{thermal} \qquad (ANSI\ Std.\ Z136.1\text{-}2000\ \{8.2.3 - Rule\ 3\})$$

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

$$MPE_{rule3} = \left(n^{-0.25}\right) \cdot MPE_{rule1}$$

$$MPE_{rule3} = \left(10 \cdot PRF\right)^{-0.25} \cdot \left(1.05 \times 10^{-6}\ J/cm^2\right)$$

Table 3

ANSI Rule 3 MPE at Various Ranges (PRF)

Range (km)	PRF (kHz)	MPE_{rule3} (J/cm^2)
5	30	44.8×10^{-9}
7.5	20	49.6×10^{-9}
10	15	53.3×10^{-9}
15	10	59.0×10^{-9}
30	5	70.2×10^{-9}

Values are from the System Analytical Model (EXCEL calculator) presented in the Appendix (page 31).

(d) Appropriate MPE (Daytime)

Table 4

Appropriate MPE at Various Ranges

$$(l_{V-\max},\ l_{H-\max}\ \ for\ \ \theta_{\min})$$

Range (km)	PRF (kHz)	MPE_{rule1} (J/cm^2)	MPE_{rule2} (J/cm^2)	MPE_{rule3} (J/cm^2)	Appropriate MPE (J/cm^2)
5	30	1.05×10^{-6}	70.8×10^{-9}	44.8×10^{-9}	44.8×10^{-9}
7.5	20	1.05×10^{-6}	106×10^{-9}	49.6×10^{-9}	49.6×10^{-9}
10	15	1.05×10^{-6}	142×10^{-9}	53.3×10^{-9}	53.3×10^{-9}
15	10	1.05×10^{-6}	212×10^{-9}	59.0×10^{-9}	59.0×10^{-9}
30	5	1.05×10^{-6}	425×10^{-9}	70.2×10^{-9}	70.2×10^{-9}

Values are from the System Analytical Model (EXCEL calculator) presented in the Appendix (page 31).

2. Nighttime Laser Operations

The OBSERV® Laser Illuminator based Intrusion Detection System is intended for operations at night.

(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 a NEOH factor may need to be evaluated (Safety with Lasers and Other Optical Sources, Sliney & Wolbarsht). This NEOH factor is applicable to the IR diode (861 nm) output of the OBSERV® Laser Illuminator based Intrusion Detection System. 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 the standardize 7 mm (*ANSI Std. Z136.1*) to the **maximum of 9 mm** (in a 20 year old person). 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}*.

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

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

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

$$NEOH = 1.65$$

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

(b) Increased Hazard

Nighttime MPE

The ANSI MPE, for laser wavelengths in the retinal hazard region, can be de-rated by the nighttime enhanced ocular hazard (*NEOH*) to evaluate nighttime laser operation hazards.

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

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

Table 5

Nighttime MPE for Various Ranges (PRF)

$$(l_{V-\max},\ l_{H-\max}\ \ for\ \ \theta_{\min})$$

Range (km)	PRF (kHz)	Appropriate MPE - Day (J/cm^2)	Appropriate MPE - Night (J/cm^2)
5	30	44.8×10^{-9}	27.2×10^{-9}
7.5	20	49.6×10^{-9}	30.1×10^{-9}
10	15	53.3×10^{-9}	32.3×10^{-9}
15	10	59.0×10^{-9}	35.8×10^{-9}
30	5	70.2×10^{-9}	42.5×10^{-9}

Values are from the System Analytical Model (EXCEL calculator) presented in the Appendix (page 31).

B. Allowable Emission Limits

1. Daytime Values

The Class 1 AEL for an 861 nm pulsed laser source is the product of the appropriate MPE and the area of limiting aperture indicated in *Table 8* of the *ANSI Std. Z136.1*.

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

$$= MPE \cdot \frac{\pi}{4} \cdot (D_f)^2 \qquad (\textit{ANSI Std. Z136.1-2000 \{Equation 18\}})$$

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

$$= MPE \cdot \frac{\pi}{4} \cdot (0.7\ cm)^2$$

$$AEL = (0.385\ cm^2) \cdot MPE$$

Table 6

Appropriate AEL (day)

Range (km)	PRF (kHz)	Appropriate MPE - Day (J/cm^2)	AEL (J)
5	30	44.8×10^{-9}	17.3×10^{-9}
7.5	20	49.6×10^{-9}	19.1×10^{-9}
10	15	53.3×10^{-9}	20.5×10^{-9}
15	10	59.0×10^{-9}	22.7×10^{-9}
30	5	70.2×10^{-9}	27.0×10^{-9}

Values are from the System Analytical Model (EXCEL calculator) presented in the Appendix (pages 31 & 32).

2. Nighttime Values

$$AEL = \left(0.385\ \ cm^2\right) \cdot MPE_{night}$$

Table 7

Appropriate AEL (night)

Range (km)	PRF (kHz)	Appropriate MPE - Night (J/cm^2)	AEL - Night (J)
5	30	27.2×10^{-9}	10.5×10^{-9}
7.5	20	30.1×10^{-9}	11.6×10^{-9}
10	15	32.3×10^{-9}	12.4×10^{-9}
15	10	35.8×10^{-9}	13.8×10^{-9}
30	5	42.5×10^{-9}	16.4×10^{-9}

Values are from the System Analytical Model (EXCEL calculator) presented in the Appendix (pages 31 & 32).

C. OD_{min} Calculations

The worst case, must conservative Optical Density (OD) is calculated by assuming the entire laser output enters the eye. The worst case minimum OD ($OD_{\min}$) can be calculated as follows:

$$OD_{\min} = \log_{10}\left[\frac{Q_o}{Class\ \ 1\ \ AEL}\right] \quad (ANSI\ Std.\ Z136.6\text{-}2000\ \{B4\})$$

$$= \log_{10}\left[\frac{Q_o(\max)}{Class\ \ 1\ \ AEL}\right]$$

Table 8

Daytime AEL Based Minimum OD for Various Ranges & PRFs for Typical Operation (Standard Mode) Maximum Power Level

Range (km)	PRF (kHz)	Pulse Energy (μ J)	AEL (J)	$OD_{\min}$
5	30	21.2	17.3×10^{-9}	3.09
7.5	20	31.8	19.1×10^{-9}	3.22
10	15	42.3	20.5×10^{-9}	3.31
15	10	63.5	22.7×10^{-9}	3.45
30	5	127	27.0×10^{-9}	3.67

Values are from the System Analytical Model (EXCEL calculator) presented in the Appendix (pages 31 & 32).

$$OD_{\min}(\max - day) = 3.76$$

Nighttime Values

$$OD_{\min}(night) = \log_{10}\left[\frac{Q_o(\max)}{Class\ \ 1\ \ AEL_{night}}\right]$$

Table 9

Nighttime AEL Based Minimum OD for Various Ranges & PRFs for Typical Operation (Standard Mode) Maximum Power Level

Range (km)	PRF (kHz)	Pulse Energy (μ J)	AEL_{night} (J)	$OD_{\min}(night)$
5	30	21.2	10.5×10^{-9}	3.31
7.5	20	31.8	11.6×10^{-9}	3.44
10	15	42.3	12.4×10^{-9}	3.53
15	10	63.5	13.8×10^{-9}	3.66
30	5	127	16.4×10^{-9}	**3.89**

Values are from the System Analytical Model (EXCEL calculator) presented in the Appendix (pages 31 & 32).

However if the minimum beam area is greater than the area of the limiting aperture (D_f) then the actual $OD_{\min}$ is less than the value calculated using the AEL based method.

$$A_{\lim}(D_f) = 0.385\ cm^2 < A_{beam}(\min) = (1.7\ cm)\cdot(2.3\ cm) = 3.91\ cm^2$$

The minimum optical density ($OD_{\min}$) needed for protection is based on the minimum approach distance to the laser since the radiant-exposure (*H*) decreases with the distance from the laser (*ANSI Std. Z136.6-2000 {3.3.5}*). The various minimum OD calculations for each operation condition are based on the radiant exposure at the laser exit. The operational beam areas at the exit are all larger than the area of the limiting aperture.

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

$$\overline{H_o} = \frac{Q_o}{A_{o-\max}}$$

$$= \frac{Q_o}{l_o(V)\cdot l_o(H)} \qquad \text{(Max beam dimension for } \theta_{\min}\text{)}$$

$$= \frac{Q_o}{(8.5\ cm)\cdot(5.7\ cm)}$$

$$\overline{H_o} = \frac{Q_o}{48.5\ cm^2}$$

Daytime Values

Table 10

OD_{min} – Daytime (Standard Mode)

$$(l_{V-\max},\ l_{H-\max}\ \ for\ \ \theta_{\min})$$

Range (km)	PRF (kHz)	Pulse Energy (J)	Radiant Exposure (J/cm2)	Appropriate MPE - Day (J/cm^2)	OD_{min}
5	30	21.2×10^{-6}	437×10^{-9}	44.8×10^{-9}	0.99
7.5	20	31.8×10^{-6}	655×10^{-9}	49.6×10^{-9}	1.12
10	15	42.3×10^{-6}	874×10^{-9}	53.3×10^{-9}	1.21
15	10	63.5×10^{-6}	1.31×10^{-6}	59.0×10^{-9}	1.35
30	5	127×10^{-6}	2.62×10^{-6}	70.2×10^{-9}	1.57

Values are from the System Analytical Model (EXCEL calculator) presented in the Appendix (pages 31 & 32).

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

$$OD_{\min} = \log_{10}\left[\frac{\left(\frac{Q_o}{A_{\min}}\right)}{MPE}\right]$$

$$A_{\min} = l_{\min}(V) \times l_{\min}(H)$$

$$= (2.3\ cm) \cdot (1.7\ cm) \quad \text{(Min beam dimension for } \theta_{\max}\text{)}$$

$$A_{\min} = 3.91\ cm^2$$

The smallest beam area at exit is larger than the area of the limiting aperture.

$$A_{\lim} = 0.385\ cm^2 < A_{\min} = 3.91\ cm^2$$

$$OD_{\min} = \log_{10}\left[\frac{\left(\dfrac{Q_o}{3.91\ cm^2}\right)}{MPE}\right]$$

Table 11

OD_{min} – Daytime (Standard Mode)

$(l_{V-\min},\ l_{H-\min}\ for\ \theta_{\max})$

Range (km)	PRF (kHz)	Pulse Energy (J)	Radiant Exposure (J/cm2)	Appropriate MPE - Day (J/cm^2)	OD_{min}
5	30	21.2×10^{-6}	5.41×10^{-6}	44.8×10^{-9}	2.08
7.5	20	31.8×10^{-6}	8.12×10^{-6}	49.6×10^{-9}	2.21
10	15	42.3×10^{-6}	10.8×10^{-6}	53.3×10^{-9}	2.31
15	10	63.5×10^{-6}	16.2×10^{-6}	59.0×10^{-9}	2.44
30	5	127×10^{-6}	32.5×10^{-6}	70.2×10^{-9}	2.67

Values are from the System Analytical Model (EXCEL calculator) presented in the Appendix (pages 31 & 32).

Nighttime Values

The nighttime value uses the NEOH factor, an estimate of the worst case increased hazard due the larger pupil sizes that occur at low light levels

(nighttime operations). The actual $OD_{\min}$ may be less than that calculated using the worst case nighttime hazard enhancement.

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

$$OD_{\min} = \log_{10}\left[\frac{\left(\frac{Q_o}{A_{o-\max}}\right)}{\left(\frac{MPE}{NEOH}\right)}\right]$$

$$= \log_{10}\left[\frac{(NEOH \cdot Q_o)}{(A_{o-\max} \cdot MPE)}\right]$$

$$OD_{\min} = \log_{10}\left[\frac{1.65 \cdot Q_o}{(48.5\ cm^2) \cdot MPE}\right]$$

Table 12

OD_{min} – Nighttime (Standard Mode)

$$(l_{V-\max},\ l_{H-\max}\ for\ \theta_{\min})$$

Range (km)	**PRF (kHz)**	**Pulse Energy (J)**	**Radiant Exposure (J/cm2)**	**Appropriate MPE (J/cm^2)**	**OD_{min}**
5	30	21.2×10^{-6}	437×10^{-9}	44.8×10^{-9}	1.21
7.5	20	31.8×10^{-6}	655×10^{-9}	49.6×10^{-9}	1.34
10	15	42.3×10^{-6}	874×10^{-9}	53.3×10^{-9}	1.43
15	10	63.5×10^{-6}	1.31×10^{-6}	59.0×10^{-9}	1.56
30	5	127×10^{-6}	2.62×10^{-6}	70.2×10^{-9}	1.79

Values are from the System Analytical Model (EXCEL calculator) presented in the Appendix (pages 31 & 32).

Smallest Beam Dimension with Largest Beam Divergence

$$OD_{\min} = \log_{10}\left[\frac{\left(\frac{Q_o}{A_{o-\min}}\right)}{\left(\frac{MPE}{NEOH}\right)}\right]$$

$$= \log_{10}\left[\frac{(NEOH \cdot Q_o)}{(A_{o-\min} \cdot MPE)}\right]$$

$$OD_{\min} = \log_{10}\left[\frac{1.65 \cdot Q_o}{(3.91\ cm^2) \cdot MPE}\right]$$

Table 13

OD_{min} – Nighttime (Standard Mode)

$(l_{V-\min},\ l_{H-\min}\ for\ \theta_{\max})$

Range (km)	PRF (kHz)	Pulse Energy (J)	Radiant Exposure (J/cm2)	Appropriate MPE $_{night}$ (J/cm^2)	OD $_{min}$
5	30	21.2×10^{-6}	5.41×10^{-6}	27.2×10^{-9}	2.30
7.5	20	31.8×10^{-6}	8.12×10^{-6}	30.1×10^{-9}	2.43
10	15	42.3×10^{-6}	10.8×10^{-6}	32.3×10^{-9}	2.53
15	10	63.5×10^{-6}	16.2×10^{-6}	35.8×10^{-9}	2.66
30	5	127×10^{-6}	32.5×10^{-6}	42.5×10^{-9}	**2.88**

Values are from the System Analytical Model (EXCEL calculator) presented in the Appendix (pages 31 & 32).

3. Appropriate OD min

The appropriate minimum OD necessary for the laser safety eyewear is the largest of the $OD_{\min}$ values calculate (**OD 2.88**). Assuming that the beam is not focused to a cross-sectional area smaller than the minimum beam area at the exit of the **OBSERV® Laser Illuminator based Intrusion Detection System**.

$$OD_{\min} = 2.88$$

Typical OD, @ 681 nm, of laser safety eyewear (Laz-R-Shield™) is **7.50** which is more than adequate even for the AEL based $OD_{\min}$ even adjusted for nighttime total darkness.

D. Nominal Ocular Hazard Distance

The Nominal Ocular Hazard Distance (*NOHD*) is that "eye safe" distance from the laser where the radiant exposure (H_r) at a range, r, is defined to be equaled to the appropriate MPE.

1. Daytime Value

The radiant exposure at the range (R) of the rectangular output beam of the **OBSERV® Laser Illuminator based Intrusion Detection System** can be determined as:

Assuming no atmospheric transmission loss ($\tau_{air} = 1$).

$$H_r = \frac{Q_o}{A_r}$$

$$H_r = \frac{Q_o}{(l_{o-V} + r\theta_V)\cdot(l_{o-H} + r\theta_H)} \quad (\textit{ANSI Std.Z136.1-2000 \{Eq. B47\}})$$

$$H_{r_{NOHD}} = \frac{Q_o}{(l_{o-V} + r_{NOHD}\theta_V)\cdot(l_{o-H} + r_{NOHD}\theta_H)} \equiv MPE$$

$$MPE = \frac{Q_o}{(l_{o-V})\cdot(l_{o-H}) + (\theta_V \cdot l_{o-H} \cdot r_{NOHD}) + (\theta_H \cdot l_{o-V} \cdot r_{NOHD}) + (\theta_V \cdot \theta_H)\cdot r_{NOHD}^2}$$

$$MPE = \frac{Q_o}{(l_{o-V} \cdot l_{o-H}) + (\theta_V \cdot l_{o-H} \cdot + \theta_H \cdot l_{o-V})\cdot r_{NOHD} + (\theta_V \cdot \theta_H)\cdot r_{NOHD}^2}$$

$$(l_{o-V} \cdot l_{o-H}) + (\theta_V \cdot l_{o-H} \cdot + \theta_H \cdot l_{o-V})\cdot r_{NOHD} + (\theta_V \cdot \theta_H)\cdot r_{NOHD}^2 = \frac{Q_o}{MPE}$$

Second Order (Quadratic) Equation

$$(\theta_V \cdot \theta_H)\cdot r_{NOHD}^2 + (\theta_V \cdot l_{o-H} \cdot + \theta_H \cdot l_{o-V})\cdot r_{NOHD} + (l_{o-V} \cdot l_{o-H}) - \frac{Q_o}{MPE} = 0$$

Solution for a Second Order (Quadratic) Equation

$$r_{NOHD} = Pos\left[\frac{-b \pm \sqrt{b^2 - 4ac}}{2a}\right]$$

$$r_{NOHD} \equiv NOHD$$

Daytime

$$NOHD_{day} = \frac{b + \sqrt{b^2 - 4ac}}{2a}$$

$$a = \theta_V \cdot \theta_H$$
$$b = l_{0-H} \cdot \theta_V + l_{0-V} \cdot \theta_H$$
$$c = (l_{o-V} \cdot l_{o-H}) - \frac{Q_o}{MPE}$$

For maximum exit beam dimension with minimum beam divergence:

$\left(l_{V-\max},\ l_{H-\max}\ \ for\ \ \theta_{\min}\right)$:

$$
\begin{aligned}
a &= \theta_{V-\min} \cdot \theta_{H-\min} \\
&= \left(4.8\times10^{-3}\,radians\right)\cdot\left(5.3\times10^{-3}\,radians\right) \\
a &= 25.4\times10^{-6}
\end{aligned}
$$

$$
\begin{aligned}
b &= l_{0-H-\max} \cdot \theta_{V-\min} + l_{0-V-\max} \cdot \theta_{H-\min} \\
&= \left(5.7\ \ cm\right)\cdot\left(4.8\times10^{-3}\right)+\left(8.5\ \ cm\right)\cdot\left(5.3\times10^{-3}\right) \\
&= \left(27.4\times10^{-3}\,cm\right)+\left(45.1\times10^{-3}\,cm\right) \\
b &= 72.4\times10^{-3}\,cm
\end{aligned}
$$

$$
\begin{aligned}
c &= \left(l_{o-V-\max} \cdot l_{o-H-\max}\right)-\frac{Q_o}{MPE} \\
&= \left(8.5\ \ cm\right)\cdot\left(5.7\ \ cm\right)-\frac{Q_o}{MPE} \\
c &= 48.5-\frac{Q_o}{MPE}
\end{aligned}
$$

$$EOHD_{day} = \frac{b+\sqrt{b^2-4ac_G}}{2a}$$

$$c_G = 48.5-\frac{G\cdot Q_o}{MPE}$$

Nighttime Value

$$NOHD_{night} = \frac{b+\sqrt{b^2-4ac_{night}}}{2a}$$

$$c_{night} = 48.5 - \frac{NEOH \cdot Q_o}{MPE}$$

$$EOHD_{night} = \frac{b + \sqrt{b^2 - 4ac_{N-G}}}{2a}$$

$$c_{N-G} = 48.5 - \frac{NEOH \cdot G \cdot Q_o}{MPE}$$

Table 14

NOHD & EOHD for Various Ranges (Standard Mode)

Maximum Initial Beam Dimension – Minimum Beam Divergence

$$(l_{V-\max},\ l_{H-\max}\ \ for\ \ \theta_{\min})$$

Range (km)	PRF (kHz)	NOHD day (m)	EOHD day (m)	NOHD night (m)	EOHD night (m)
5	30	29	238	41	310
7.5	20	36	280	50	364
10	15	42	313	58	407
15	10	51	367	69	476
30	5	70	480	94	621

Values are from the System Analytical Model (EXCEL calculator) presented in the Appendix (pages 31 & 32).

$l_{V-\min},\ l_{H-\min}\ \ for\ \ \theta_{\max}$

$$\begin{aligned} a &= \theta_{V-\max} \cdot \theta_{H-\max} \\ &= \left(16.8 \times 10^{-3}\, radians\right) \cdot \left(20.4 \times 10^{-3}\, radians\right) \\ a &= 343 \times 10^{-6} \end{aligned}$$

$$
\begin{aligned}
b &= l_{0-H-\min} \cdot \theta_{V-\max} + l_{0-V-\min} \cdot \theta_{H-\max} \\
&= (1.7\ \ cm) \cdot (16.8 \times 10^{-3}) + (2.3\ \ cm) \cdot (20.4 \times 10^{-3}) \\
&= (28.6 \times 10^{-3}\, cm) + (46.9 \times 10^{-3}\, cm) \\
b &= 75.5 \times 10^{-3}\, cm
\end{aligned}
$$

$$
\begin{aligned}
c &= (l_{o-V-\min} \cdot l_{o-H-\min}) - \frac{Q_o}{MPE} \\
&= (2.3\ \ cm) \cdot (1.7\ \ cm) - \frac{Q_o}{MPE} \\
c &= 3.91 - \frac{Q_o}{MPE}
\end{aligned}
$$

$l_{V-\min},\ l_{H-\min}\ \ for\ \ \theta_{\max}$

$$EOHD_{day} = \frac{b + \sqrt{b^2 - 4ac_G}}{2a}$$

$$c_G = 3.91 - \frac{G \cdot Q_o}{MPE}$$

Nighttime Values ($l_{V-\min},\ l_{H-\min}\ \ for\ \ \theta_{\max}$)

$$NOHD_{night} = \frac{b + \sqrt{b^2 - 4ac_{night}}}{2a}$$

$$c_{night} = 3.91 - \frac{NEOH \cdot Q_o}{MPE}$$

$$EOHD_{night} = \frac{b + \sqrt{b^2 - 4ac_{N-G}}}{2a}$$

$$c_{N-G} = 3.91 - \frac{NEOH \cdot G \cdot Q_o}{MPE}$$

Table 15

NOHD & EOHD for Various Ranges (Standard Mode)

Minimum Initial Beam Dimension – Maximum Beam Divergence

$$(l_{V-\min},\ l_{H-\min}\ \ for\ \ \theta_{\max})$$

Range (km)	PRF (kHz)	NOHD day (m)	EOHD day (m)	NOHD night (m)	EOHD night (m)
5	30	1.0	5.9	1.3	7.5
7.5	20	1.2	6.8	1.5	8.8
10	15	1.3	7.6	1.7	9.8
15	10	1.5	8.9	1.9	11.4
30	5	2.0	11.5	2.5	14.8

Values are from the System Analytical Model (EXCEL calculator) presented in the Appendix (pages 31 & 32).

F. Interactive Controls

Personnel located at the surveillance system target location are outside the NHZ of the laser for both the NOHD and the EOHD and are safe from hazardous exposure to the illumination laser.

The illumination laser is co-aligned with the gated camera optic system. The camera's field of view is always somewhat greater than the illuminating laser spot within the field of view and is displayed on surveillance TV monitor. This allows the system operator to detect the presence of personnel, closer to the surveillance system than the target range, before they enter the laser beam and allows the laser operator to terminate laser operations to prevent a hazardous exposure.

It is assumed that the surveillance system operator should be able to detect the presence of personnel about to enter the NHZ and terminate laser operations within 2 seconds. NOHD and EOHD, based on this reduced (T = 2 sec) exposure is present in EXCEL® spreadsheet in the Appendix.

IV. Conclusions

1. Personnel working within close proximity of the OBSERV Surveillance system are required to wear laser safety eyewear with a minimum optical density of 2.88 (Typical Operation with nighttime enhancement) and 3.07 (Extraordinary Operation with nighttime enhancement). Should personnel have to interact with the laser prior to the beam expanding optics the required minimum OD is 3.86 (AEL based). The laser safety eyewear currently in use is rated at **7.50** in the wavelength NIR range and is more than adequate for all possible operations of the illumination laser.

2. The NOHD and EOHD, including nighttime enhance values, are much shorter than the target range for all possible operations of the illumination laser. Personnel in the target location are outside the laser hazard zone and are safe from hazardous exposure.

3. The surveillance camera field of view is always somewhat larger than the illuminating laser spot allowing the system operator to terminate laser operation should unauthorized personnel enter the field of view at a distance much closer to the surveillance system than the target range.

V. Appendix – System Analytical Model

a. Typical Operation

NOHD & EOHD Calculations for Rectangular Beam

Parameters: Max Dimension, Min Divergence

Input			Calculated		
λ:	0.861	μm			
Power:	1.27E+01	watts	a=	2.54E-05	
VERT:	8.5	cm	b=	7.24E-02	
HORZ:	5.7	cm			
θ–vert:	4.80E-03	Radians	C_A=	2.10	
θ–horz:	5.30E-03	Radians	Gain=	34.4	7x 50 mm
τ_{air}	1.00E+00		Night Haz=	1.65	
% of R:	1.00E+01	%			

T= 10 sec — Max Dimension, Min Divergence

Range (km)	PRF (Hz)	Cp	Gate Length (km)	t (sec)	Pulse Energy (joules)	MPE (J/cm^2)	NOHD Day (Meters)	NOHD night (Meters)	EOHD Day (Meters)	EOHD Night (Meters)
5	30	0.0427	0.500	1.67E-06	2.12E-05	4.48E-08	29	41	238	310
7.5	20	0.0473	0.750	2.50E-06	3.18E-05	4.96E-08	36	50	280	364
10	15	0.0508	1.000	3.33E-06	4.23E-05	5.33E-08	42	58	313	407
15	10	0.0562	1.500	5.00E-06	6.35E-05	5.90E-08	51	69	367	476
30	5	0.0669	3.000	1.00E-05	1.27E-04	7.02E-08	70	94	480	621

T= 2 sec — Max Dimension, Min Divergence

Range (km)	PRF (Hz)	Cp	Gate Length (km)	t (sec)	Pulse Energy (joules)	MPE (J/cm^2)	NOHD Day (Meters)	NOHD night (Meters)	EOHD Day (Meters)	EOHD Night (Meters)
5	30	0.0639	0.500	1.67E-06	2.12E-05	6.71E-08	21	31	192	251
7.5	20	0.0707	0.750	2.50E-06	3.18E-05	7.42E-08	27	39	226	295
10	15	0.0760	1.000	3.33E-06	4.23E-05	7.97E-08	32	45	254	330
15	10	0.0841	1.500	5.00E-06	6.35E-05	8.82E-08	39	54	298	386
30	5	0.1000	3.000	1.00E-05	1.27E-04	1.05E-07	55	74	390	505

Parameters: Min Dimensions, Max Divergence

	Input			Calculated
VERTmin=	2.3	cm	a=	4.69E-02
HORZmin=	1.7	cm	b=	7.55E-02
$\theta_{-V\text{-}max}$=	1.68E-02	radians		
$\theta_{-H\text{-}max}$=	2.04E-02	radians		

		DEM_{max}-θ_{min}		DEM_{min}-θ_{max}						
AEL	**Based**	**MPE**	**Based**	**MPE**	**Based**	**MPE**		AEL	H_o	H_o
OD_{min} (day)	OD_{min} (night)	OD_{min} (day)	OD_{min} (night)	OD_{min} (day)	OD_{min} (night)	**night** (J/cm^2)	AEL (J)	Night (J)	D_{max} J/cm^2	D_{min} J/cm^2
3.09	3.31	0.99	1.21	2.08	2.30	2.72E-08	1.73E-08	1.05E-08	4.37E-07	5.41E-06
3.22	3.44	1.12	1.34	2.21	2.43	3.01E-08	1.91E-08	1.16E-08	6.55E-07	8.12E-06
3.31	3.53	1.21	1.43	2.31	2.53	3.23E-08	2.05E-08	1.24E-08	8.74E-07	1.08E-05
3.45	3.66	1.35	1.56	2.44	2.66	3.58E-08	2.27E-08	1.38E-08	1.31E-06	1.62E-05
3.67	3.89	1.57	1.79	2.67	2.88	4.25E-08	2.70E-08	1.64E-08	2.62E-06	3.25E-05

Min Dimensions, Max Divergence

AEL OD_{min} day	**Based** OD_{min} night	**NOHD Day** (Meters)	**NOHD night** (Meters)	**EOHD Day** (Meters)	**EOHD Night** (Meters)
2.91	3.13	1.0	1.3	5.9	7.5
3.05	3.26	1.2	1.5	6.8	8.8
3.14	3.36	1.3	1.7	7.6	9.8
3.27	3.49	1.5	1.9	8.9	11.4
3.50	3.71	2.0	2.5	11.5	14.8

b. Extraordinary Operation (Password Protected Override)

NOHD & EOHD Calculations for Rectangular Beam

Parameters: Max Dimension, Min Divergence

	Input				Calculated	
λ:	0.861	μm				
Power:	1.96E+01	watts		a=	2.54E-05	
VERT:	8.5	cm		b=	7.24E-02	
HORZ:	5.7	cm				
θ–vert:	4.80E-03	Radians		C_A=	2.10	
θ–horz:	5.30E-03	Radians		Gain=	34.4	7x 50 mm
τ_{air}	1.00E+00			Night Haz=	1.65	
% of R:	1.00E+01	%				

T= 10 sec

Max Dimension, Min Divergence

Range (km)	PRF (Hz)	Cp	Gate Length (km)	t (sec)	Pulse Energy (joules)	MPE (J/cm²)	NOHD Day (Meters)	NOHD night (Meters)	EOHD Day (Meters)	EOHD Night (Meters)
5	30	0.0427	0.500	1.67E-06	3.27E-05	4.48E-08	39	55	300	389
7.5	20	0.0473	0.750	2.50E-06	4.90E-05	4.96E-08	48	66	351	455
10	15	0.0508	1.000	3.33E-06	6.53E-05	5.33E-08	55	75	393	509
15	10	0.0562	1.500	5.00E-06	9.80E-05	5.90E-08	67	90	460	594
30	5	0.0669	3.000	1.00E-05	1.96E-04	7.02E-08	91	120	600	775

T= 2 sec

Max Dimension, Min Divergence

Range (km)	PRF (Hz)	Cp	Gate Length (km)	t (sec)	Pulse Energy (joules)	MPE (J/cm²)	NOHD Day (Meters)	NOHD night (Meters)	EOHD Day (Meters)	EOHD Night (Meters)
5	30	0.0639	0.500	1.67E-06	3.27E-05	6.71E-08	30	42	242	315
7.5	20	0.0707	0.750	2.50E-06	4.90E-05	7.42E-08	37	51	285	370
10	15	0.0760	1.000	3.33E-06	6.53E-05	7.97E-08	43	59	319	413
15	10	0.0841	1.500	5.00E-06	9.80E-05	8.82E-08	52	71	373	484
30	5	0.1000	3.000	1.00E-05	1.96E-04	1.05E-07	72	96	488	631

Parameters: Min Dimensions, Max Divergence

	Input	
VERTmin=	2.3	cm
HORZmin=	1.7	cm
$\theta_{-V\text{-}max}$=	1.68E-02	radians
$\theta_{-H\text{-}max}$=	2.04E-02	radians

	Calculated
a=	4.69E-02
b=	7.55E-02

		DEM_{max}-θ_{min}		DEM_{min}-θ_{max}						
AEL	**Based**	**MPE**	**Based**	**MPE**	**Based**	**MPE**		AEL	H_o	H_o
OD_{min} day	OD_{min} night	OD_{min} day	OD_{min} night	OD_{min} day	OD_{min} night	**night** (J/cm^2)	AEL (J)	Night (J)	D_{max} J/cm^2	D_{min} J/cm^2
3.28	3.49	1.18	1.39	2.27	2.49	2.72E-08	1.73E-08	1.05E-08	6.74E-07	8.35E-06
3.41	3.63	1.31	1.53	2.40	2.62	3.01E-08	1.91E-08	1.16E-08	1.01E-06	1.25E-05
3.50	3.72	1.40	1.62	2.50	2.71	3.23E-08	2.05E-08	1.24E-08	1.35E-06	1.67E-05
3.63	3.85	1.53	1.75	2.63	2.85	3.58E-08	2.27E-08	1.38E-08	2.02E-06	2.51E-05
3.86	4.08	1.76	1.98	2.85	3.07	4.25E-08	2.70E-08	1.64E-08	4.05E-06	5.01E-05

Min Dimensions, Max Divergence

AEL OD_{min} day	**Based** OD_{min} night	**NOHD Day** (Meters)	**NOHD night** (Meters)	**EOHD Day** (Meters)	**EOHD Night** (Meters)
3.10	3.32	1.2	1.6	7.3	9.4
3.23	3.45	1.4	1.9	8.5	10.9
3.33	3.55	1.6	2.1	9.5	12.2
3.46	3.68	1.9	2.4	11.0	14.2
3.69	3.90	2.4	3.1	14.3	18.4

VI. 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.

VII. Abbreviations

AEL	Allowable Emission (Exposure) Limit
A_{lim}	Area of limiting aperture
ANSI	American National Standards Institute
C_p	Multiple-pulse correction factor
CW	Continuous wave
d_{aid}	Entrance diameter of optical aid
d_{exit}	Exit diameter of the telescope
D_f	Diameter of limiting aperture
d_o	Output beam diameter
EOHD	Extended Ocular Hazard Distance
H	Radiant Exposure, in J/cm^2
H_o	Output Radiant Exposure, in J/cm^2
Hp	Radiant Exposure of the beam over the limiting aperture
Hz	Hertz, cycle per second, sec^{-1}
J	Joules, unit of energy
LIDAR	LIght Detection And Ranging
Min[a,b]	Minimum of value of a and b
mJ	Millijoule, 10^{-3} joules
MPE	Maximum Permissible Exposure
MPE_{cw}	Continuous Wave Maximum Permissible Exposure
MPE_{rule1}	Single Pulse Maximum Permissible Exposure (Rule 1)
MPE_{rule2}	Per Pulse Maximum Permissible Exposure for T distributed over the number of pulses in T
MPE_{rule3}	Multiple Pulse Maximum Permissible Exposure (Rule 3)
mw	Milliwatts, 10^{-3} watts
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 eyewear
OD_{min}	Minimum Optical Density required of laser safety eyewear

PRF	Pulse Repetition Frequency
Q	Radiant Energy, in joules
Q_o	Output Radiant Energy, in joules
t	Exposure duration, pulse duration
T	Exposure duration, in seconds
w	Watts, (unit of power)
α	Viewing angle.
θ	Beam divergence
Φ	Radiant Power
λ	Wavelength
μm	Micrometer, 10^{-6} meters
τ	Transmission factor
τ_{aid}	Transmission factor of optical aid
τ_{atm}	Atmospheric transmission factor

VIII. Distributions

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