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Laser Hazard Analysis For LASIRIS™ Model MAG-501L-670M-1000-45°-K Diode Laser Associated With High Resolution Pulsed Scanner

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Abstract

A laser hazard analysis and safety assessment was performed for the LASIRIS™ Model MAG-501L-670M-1000-45°-K diode laser associated with the High Resolution Pulse Scanner based on the ANSI Standard Z136.1-2000, American National Standard for the Safe Use of Lasers and the ANSI Standard Z136.6-2000, American National Standard for the Safe Use of Lasers Outdoors. The laser was evaluated for both indoor and outdoor use.

Summary

During the initial (CW laser operation) setup phase personnel exposed to the LASIRIS™ Model MAG-501L-670M-1000-45°-K diode laser output are required to wear laser safety eyewear of at least OD 2.88.

The LASIRIS™ Model MAG-501L-670M-1000-45°-K is provided with a 45-degree fan angle optic set installed; although, other fan angle optic sets are available.

The eye safe distances (as a function of the fan angle) for the initial (CW operation) setup phase are:

NOHD versus Fan Angle

(degrees)	NOHD (meters)
15	16.09
30	8.05
45	5.37
60	4.02

For the Normal (pulsed) operation of the LASIRIS™ Model MAG-501L-670M-1000-45°-K diode laser, with a 45-degree fan angle optic set installed and with a 60-centimeter engineering barrier, the only allowable exposure of the two pulse exposures is:

1-microsecond pulse @ 30 hertz.

Other allowable operational parameters for the diode laser as a function of the various fan angles are:

Fan Angle Eye Safe Operation

PRF (Hz)	1 μsec	10 μsec
30	30°	-
30	45°	-
30	60°	60°
60	45°	-

Outdoor Operation in Navigable Air Space

Under worst case conditions for the pulse operation, the laser must be greater than 18,501 meters from the center on the airport run ways for unobstructed, line-of-sight, view to the visual interference zones.

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High Resolution Pulsed Scanner

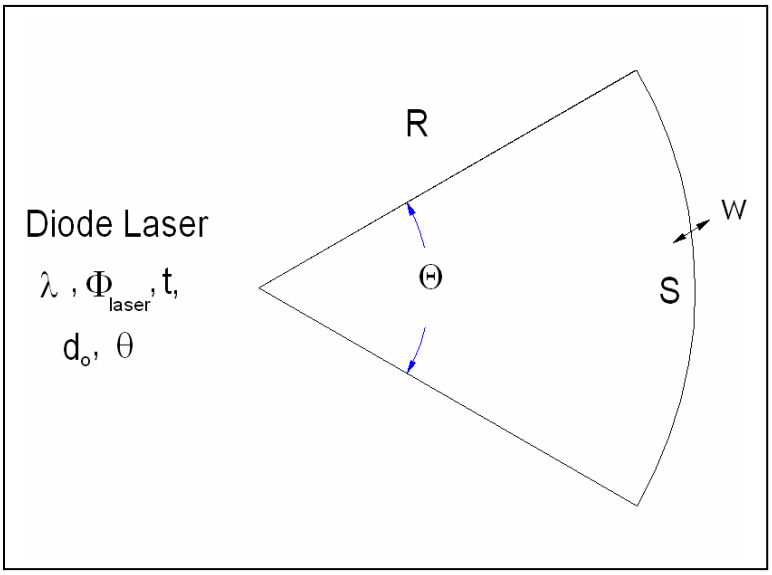


Figure 1

Schematic of the diode laser output geometry

I. Introduction

The LASIRIS™ Model MAG-501L-670M-1000-45°-K diode laser is provided with a 45-degree fan angle optic set installed. Other fan angle optical sets for: 15, 30, 60 degrees are available for installation on the LASIRIS™ Magnum Series diode lasers incorporated in the high-resolution pulse scanner. Whereas; the pulsed mode is the typical mode of operation for the high-resolution pulsed scanner diode laser, the initial setup requires the laser to be operated in the CW mode of operation.

II. Laser Parameters

LASIRIS™

Model:	MAG-501L-670M-1000-45°-K
Laser Hazard Class:	3b
Radiant Wavelength:	671.2 nm
Radiant Output:	750 mw (after the fan angle optic set)
Pulse Exposure:	1 s or 10 s (computer selectable)
Pulse Repetition Rate:	30 Hz or 60 Hz
Line Width:	Adjustable at various locations from the laser
Fan Angle Optic Sets:	15, 30, 45, 60 degrees

III. Hazard Analysis

This laser hazard analysis is presented in two parts. Part (1) addresses the CW operation of the diode lasers during initial system set. Part (2) addresses the pulsed operation of the diode laser typical to the normal operation of the pulsed scanner.

A. MPE Determination

The determination methods for the appropriate **Maximum Permissible Exposure** (*MPE*) of the two primary modes of operation of the laser diode are presented as follows.

1. CW Operation (Initial Set Up)

The MPE for lasers in the visible portion of the spectrum is presented in *Table 5a* of the current ANSI standard.

$$MPE_{rule1} = 1.8 \cdot t^{0.75} \times 10^{-3} \; J/cm^2$$

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

$$400 \;\; nm \le \lambda \le 700 \;\; nm$$
$$18 \times 10^{-6} \text{ sec} \le t \le 10 \;\; \text{sec}$$

The appropriate exposure duration (t) for Laser Hazard Class 2 “blink” response is given as a quarter second [*ANSI Std. Z136.1-2000 (Table 4a)*].

$T = 0.25 \text{ sec}$ $\qquad$ $400 \ nm \le \lambda \le 700 \ nm$

$$MPE_{rule1} = 1.8 \cdot T^{0.75} \times 10^{-3} \ J/cm^2$$

The MPE in terms of CW watts per square centimeters can be expressed as follows.

$$MPE_{CW} = \frac{1.8 \cdot T^{0.75} \times 10^{-3} \ J/cm^2}{T \ \text{sec}}$$

$$MPE_{CW} = 1.8 \cdot T^{-0.25} \times 10^{-3} \ w/cm^2$$

The **Class 2 MPE** for the "blink" response:

$$MPE_{CW} = 1.8 \cdot (0.25)^{-0.25} \times 10^{-3} \ w/cm^2$$

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

2. Pulsed Operation (Typical)

The appropriate MPE for a pulsed laser is the smallest value MPE determined by the application of ANSI Rule 1 through ANSI Rule 3 [*ANSI Std. Z136.1-2000 (8.2.3)*].

$$MPE = \min\left(MPE_{rule}, \ MPE_{rule2}, \ MPE_{rule3}\right)$$

The allowed exposure durations for the pulsed operation of the laser diode are:

(a) 1 microsecond
(b) 10 microsecond

(a) 1-microsecond MPE Determination

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

The form of the single pulse MPE is presented in: *ANSI Std. Z136.1-2000 (Table 5a)* and is a function of the single pulse exposure.

$$MPE_{rule1} = 1.8 \cdot t^{0.75} \times 10^{-3} \, J/cm^2 \qquad 400 \;\; nm \le \lambda \le 700 \;\; nm$$

$$18 \times 10^{-6} \text{ sec} \le t \le 10 \;\; \text{sec}$$

There are two primary pulse exposures: (a) 1-microsecond, and (b) 10-microseconds.

(a) $t = 1 \;\; \mu\text{sec}$

$$MPE_{rule1} = 1.8 \cdot \left(10^{-6}\right)^{0.75} \times 10^{-3} \, J/cm^2$$

$$MPE_{rule1} = 56.9 \times 10^{-9} \, J/cm^2$$

(b) $t = 10 \;\; \mu\text{sec}$

$$MPE_{rule1} = 1.8 \cdot \left(10 \times 10^{-6}\right)^{0.75} \times 10^{-3} \, J/cm^2$$

$$MPE_{rule1} = 320 \times 10^{-9} \, J/cm^2$$

<u>Table 1</u>

Single Pulse MPE

Exposure (Second)	MPE_{rule1} (J/cm^2)
1 sec	56.9×10^{-9}
10 sec	320×10^{-9}

Rule 2:

The average power MPE for thermal and photochemical hazards [*ANSI Std. Z136.1-2000 (8.2.3 – Rule 2)*] is expressed as:

$$MPE_{rule2} = \frac{MPE_{CW}}{PRF}$$

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

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

$$500\ nm \le \lambda \le 700\ nm$$

$$10\ \sec < t \le 30 \times 10^{3}\ \sec$$

(a) For $PRF = 30\ Hz$:

$$MPE_{rule2} = \frac{10^{-3}\ {}^{w}\!/_{cm^2}}{30\ \sec^{-1}}$$

$$MPE_{rule2} = 33.3 \times 10^{-6}\ {}^{J}\!/_{cm^2}$$

(b) For $PRF = 60\ Hz$:

$$MPE_{rule2} = \frac{10^{-3}\ {}^{w}\!/_{cm^2}}{60\ \sec^{-1}}$$

$$MPE_{rule2} = 16.7 \times 10^{-6}\ {}^{J}\!/_{cm^2}$$

Table 2

Average Power Pulse MPE

PRF ($\sec^{-1}$)	MPE_{rule1} (J/cm^2)
30	33.3×10^{-6}
60	16.7×10^{-6}

Rule 3:

The multiple-pulse MPE for thermal hazard is the product of the single pulse MPE and a **Multiple Pulse Correction Factor** (C_p) [*ANSI Std. Z136.1-2000 (8.2.3 – Rule 3)*].

$$MPE_{rule3} = C_p \cdot MPE_{rule1}$$

The multiple-pulse correction factor is a function of the number of pulses (*n*) in the exposure [*ANSI Std. Z136.1-2000 (Table 6)*].

$$C_p = n^{-0.25}$$

The number of pulses in the exposure is the product of the PRF and standard exposure duration.

$$n = PRF \cdot T$$

The standard exposure for the "blink response" (Class 2 Laser Hazard) is given as a quarter second [*ANSI Std. Z136.1-2000 (Table 4a)*].

(a) For $PRF = 30\ Hz$:

$$n = \left(30\ \sec^{-1}\right) \cdot \left(0.25\ \sec\right) = 7.5$$

$$n = 8$$

Fractional pulse counts are rounded up to the next integer pulse count.

(b) For $PRF = 60\ Hz$:

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

$$n = 15$$

The Multiple Pulse Correction Factor is given in *ANSI Std. Z136.1-2000 (Table 6)*.

$$C_p = n^{-0.25}$$

The multiple pulse correction factors for the two PRF operations are as follows:

(a) For n=8:

$$C_{p@30Hz} = (8)^{-0.25} = 0.595$$

(b) For n=15:

$$C_{p@60Hz} = (15)^{-0.25} = 0.508$$

Table 3

Multiple Pulse Correction Factor

PRF ($\sec^{-1}$)	n	C_p
30	8	0.595
60	15	0.508

$$MPE_{rule3} = C_p \cdot MPE_{rule1}$$

For { $PRF = 30\ Hz$ & $t = 1\ \mu\sec$ }:

$$MPE_{rule3} = (0.595) \cdot \left(56.9 \times 10^{-9}\right) J/cm^2$$

$$MPE_{rule3(30Hz-1\mu s)} = 33.9 \times 10^{-9}\ J/cm^2$$

For { $PRF = 30\ Hz$ & $t = 10\ \mu\text{sec}$ }:

$$MPE_{rule3} = (0.595)\cdot\left(320\times10^{-9}\right) J/cm^2$$

$$MPE_{rule3(30Hz-10\mu s)} = 190\times10^{-9}\ J/cm^2$$

For { $PRF = 60\ Hz$ & $t = 1\ \mu\text{sec}$ }:

$$MPE_{rule3} = (0.508)\cdot\left(56.9\times10^{-9}\right) J/cm^2$$

$$MPE_{rule3(60Hz-1\mu s)} = 28.9\times10^{-9}\ J/cm^2$$

For { $PRF = 60\ Hz$ & $t = 10\ \mu\text{sec}$ }:

$$MPE_{rule3} = (0.508)\cdot\left(320\times10^{-9}\right)\ J/cm^2$$

$$MPE_{rule3(60Hz-10\mu s)} = 163\times10^{-9}\ J/cm^2$$

Table 4

Multiple-Pulse MPE

PRF (sec^{-1})	1 μsec	10 μsec
30	$33.9\times10^{-9}\ J/cm^2$	$190\times10^{-9}\ J/cm^2$
60	$28.9\times10^{-9}\ J/cm^2$	$163\times10^{-9}\ J/cm^2$

Table 5

Appropriate MPE Determination

Mode	ANSI Rule	t (Second)	PRF $(\sec^{-1})$	MPE	Note
CW	CW	0.25	N/A	$2.55\times10^{-3}\ w/cm^2$	Appropriate
Pulse	1	1×10^{-6}	Single	$56.9\times10^{-9}\ J/cm^2$	
	2	0.25	30	$33.3\times10^{-6}\ J/cm^2$	
	3	1×10^{-6}	30	$33.9\times10^{-9}\ J/cm^2$	Appropriate
Pulse	1	10×10^{-6}	Single	$320\times10^{-9}\ J/cm^2$	
	2	0.25	30	$33.3\times10^{-6}\ J/cm^2$	
	3	10×10^{-6}	30	$190\times10^{-9}\ J/cm^2$	Appropriate
Pulse	1	1×10^{-6}	Single	$56.9\times10^{-9}\ J/cm^2$	
	2	0.25	60	$16.7\times10^{-6}\ J/cm^2$	
	3	1×10^{-6}	60	$28.9\times10^{-9}\ J/cm^2$	Appropriate
Pulse	1	10×10^{-6}	Single	$320\times10^{-9}\ J/cm^2$	
	2	0.25	60	$16.7\times10^{-6}\ J/cm^2$	
	3	10×10^{-6}	60	$163\times10^{-9}\ J/cm^2$	Appropriate

Table 6

Summary of Appropriate MPE

Mode	t (Second)	PRF $(\sec^{-1})$	MPE
CW	0.25	N/A	$2.55\times10^{-3}\ w/cm^2$
Pulse	1×10^{-6}	30	$33.9\times10^{-9}\ J/cm^2$
Pulse	10×10^{-6}	30	$190\times10^{-9}\ J/cm^2$
Pulse	1×10^{-6}	60	$28.9\times10^{-9}\ J/cm^2$
Pulse	10×10^{-6}	60	$163\times10^{-9}\ J/cm^2$

B Allowable Emission/Exposure Limit

The **Allowable Emission/Exposure Limit** (*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))*].

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

Class 2 AEL (visible lasers only)

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

The limiting aperture is given as: **7 mm** [*ANSI Std. Z136.1-2000 (Table 8)*].

$$Class\ \ 2\ \ AEL = MPE_{0.25\sec} \cdot \frac{\pi}{4}\left(0.7\ \ cm\right)^2$$

$$Class\ \ 2\ \ AEL = \left(0.385\ \ cm^2\right) \cdot MPE_{0.25\sec}$$

Table 7

Summary of Appropriate Class 2 AEL

Mode	t (Second)	PRF $(\sec^{-1})$	MPE	AEL
CW	0.25	N/A	$2.55\times10^{-3}\ w/cm^2$	$982\times10^{-6}\ w$
Pulse	1×10^{-6}	30	$33.9\times10^{-9}\ J/cm^2$	$13.1\times10^{-9}\ J$
Pulse	10×10^{-6}	30	$190\times10^{-9}\ J/cm^2$	$73.2\times10^{-9}\ J$
Pulse	1×10^{-6}	60	$28.9\times10^{-9}\ J/cm^2$	$11.1\times10^{-9}\ J$
Pulse	10×10^{-6}	60	$163\times10^{-9}\ J/cm^2$	$62.8\times10^{-9}\ J$

C. Minimum Optical Density

The **minimum optical density** ($OD_{\min}$) of the laser safety eyewear is calculated as for the CW mode of operation (worst case).

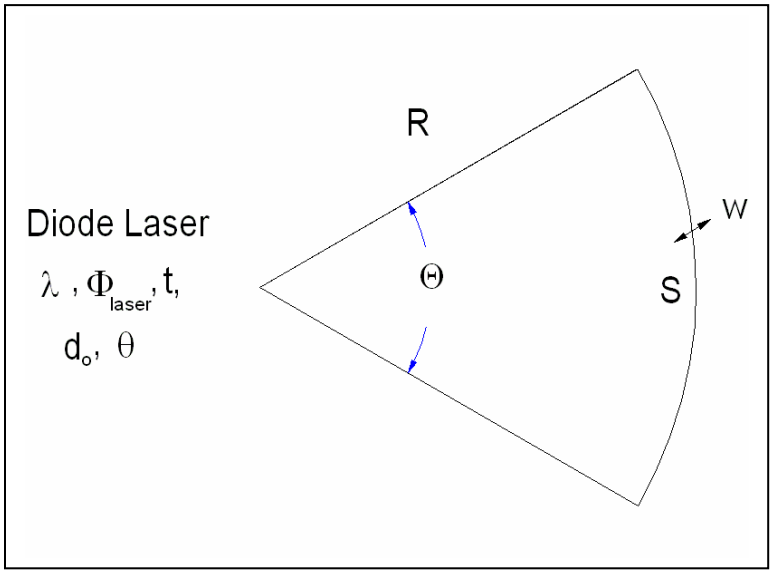
$$OD_{\min} = \log_{10}\left[\frac{\Phi}{Class\ \ 2\ \ AEL_{CW}}\right]$$

$$OD_{\min} = \log_{10}\left[\frac{750\times10^{-3}\,w}{982\times10^{-6}\,w}\right]$$

$$OD_{\min} = 2.88$$

D. Nominal Ocular Hazard Distance

The **Nominal Ocular Hazard Distance** (*NOHD*) is the line-of-sight distance from the laser at which the ocular exposure is considered eye safe.



1. CW Hazard Analysis

The initial setup for the High Resolution Scanner requires the LASIRIS™ diode laser to be operated CW. This is the most hazardous condition for the laser scanner operation.

Irradiance (Power Density)

The **irradiance** (*E*), also referred to as the "power density", is the **average radiant power** (Φ) per unit **area** (A). The average irradiance is assumed to be uniform over the affected area and can be expressed as follows.

$$E = \frac{\Phi}{A}$$

The **beam area** (*A*) is the product of the fan **arc** (*S*) and the **beam width** (*w*).

$$A = w \cdot S$$

The fan arc can be expressed as a function of the **fan angle**, in radians (θ) and the **radial distance** (*R*).

$$S = \theta \cdot R$$

$$A = w \cdot \theta \cdot R$$

The average irradiance (*E*) can be expressed as the radiant power distributed over the beam area.

$$E = \frac{\Phi}{w \cdot \theta \cdot R}$$

Where;

E:	Irradiance $\left(watts/cm^2\right)$ a.k.a. Power Density
Φ:	Radiant power $\left(watts\right)$
w:	Beam width (defined as 0.7 cm)
θ:	Fan Angle (in radians)
R:	Radial distance (in centimeters)

Nominal Ocular Hazard Distance (*NOHD*) can be defined as the radial distance from the laser where the average irradiance (E_{NOHD}) is equaled to the Class 2 MPE (page 8).

$$E_{NOHD} = MPE_{Class\,2}$$

$$\frac{\Phi}{w \cdot \theta \cdot R_{NOHD}} = 1.8 \cdot T^{-0.25} \times 10^{-3}\ watts/cm^2$$

$$R_{NOHD} = \frac{\Phi}{w \cdot \theta \cdot \left(1.8 \cdot T^{-0.25} \times 10^{-3}\ watts/cm^2\right)}$$

Evaluation of the radial NOHD (CW Operation)

For beam dimensions less than or equal to 7 mm the beam width used is defined to be 7 mm [*ANSI Std. Z136.1-2000 (9.2.2.1 – 3rd paragraph)*].

$$R_{NOHD} = \frac{750 \times 10^{-3}\, watts}{(0.7\ \ cm) \cdot \theta \cdot \left(\frac{\pi}{180^{\circ}}\right) \cdot \left(1.8 \cdot (0.25)^{-0.25} \times 10^{-3}\, watts / cm^{2}\right)}$$

The radial NOHD (as a function of the fan angle) can be expressed as follows:

$$R_{NOHD} = \frac{24,\ 116\ \ cm}{\theta}$$

Where θ is in degrees.

Table 8

NOHD versus Fan Angle

(degrees)	NOHD (cm)	NOHD (meters)
15	1608	16.08
30	804	8.04
45	536	5.36
60	402	4.02

2. Pulse Operation

The **average radiant exposure** (*H*), also referred to as the *energy density*, is the average **radiant pulse energy** (*Q*) distributed over the **beam area** (*A*).

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

The average radiant energy can be expressed at the product of the radiant power and the exposure duration.

$$Q = \Phi \cdot t$$

The average radiant exposure can then be expressed as.

$$H = \frac{\Phi \cdot t}{A}$$

The radial NOHD for the pulsed operation can likewise be expressed as the radial distance where the average radiant exposure is equaled to the appropriate MPE for a Class 2 laser exposure.

$$H_{NOHD} = MPE_{Class\,2}$$

$$\frac{\Phi \cdot t}{w \cdot \theta \cdot R_{NOHD}} = \left(0.25 \cdot PRF\right)^{-0.25} \cdot \left(1.8 \cdot t^{0.75} \times 10^{-3} \, {}^{J}\!/_{cm^2} \right)$$

$$R_{NOHD} = \frac{\Phi \cdot t}{w \cdot \theta \cdot \left(\frac{\pi}{180}\right) \cdot \left(0.25 \cdot PRF\right)^{-0.25} \cdot \left(1.8 \cdot t^{0.75} \times 10^{-3} \, {}^{J}\!/_{cm^2} \right)}$$

For { $PRF = 30\ \ Hz$ }, the NOHD is:

$$R_{NOHD} = \frac{\left(750 \times 10^{-3}\, watts\right) \cdot t}{\left(0.7\ \ cm\right) \cdot \theta \cdot \left(\frac{\pi}{180}\right) \cdot \left(0.25\ \ \sec \cdot 30\ \ \sec^{-1}\right)^{-0.25} \cdot \left(\ 1.8 \cdot t^{0.75} \times 10^{-3}\ J/cm^{2}\right)}$$

$$R_{NOHD} = \frac{\left(102\ \ watts\right) \cdot t}{\theta \cdot \left(\ 1.8 \cdot t^{0.75} \times 10^{-3}\ J/cm\ \right)}$$

$$R_{NOHD} = \frac{\left(56.4 \times 10^{3}\ \right) \cdot t^{0.25}}{\theta} cm$$

<u>Table 9</u>

NOHD (@ 30 Hz) Function of Fan Angle & Time

	1 μsec	10 μsec
15°	119 cm	212 cm
30°	59.5 cm	106 cm
45°	39.7 cm	70.5 cm
60°	29.7 cm	52.9 cm

Note: Shaded NOHD values are outside the physical barrier (60 cm).

For { $PRF = 60\ \ Hz$ }:

$$R_{NOHD} = \frac{\left(750 \times 10^{-3}\, watts\right) \cdot t}{\left(0.7\ \ cm\right) \cdot \theta \cdot \left(\frac{\pi}{180}\right) \cdot \left(0.25\ \ \sec \cdot 60\ \ \sec^{-1}\right)^{-0.25} \cdot \left(\ 1.8 \cdot t^{0.75} \times 10^{-3}\ J/cm^{2}\right)}$$

$$R_{NOHD} = \frac{\left(67.1 \times 10^{3}\ \right) \cdot t^{0.25}}{\theta}\, cm$$

<u>Table 10</u>

NOHD (@ 60 Hz) Function of Fan Angle & Time

	1 μsec	10 μsec
15°	141 cm	252 cm
30°	70.7 cm	126 cm
45°	47.2 cm	83.9 cm
60°	35.4 cm	62.9 cm

Note: Shaded NOHD values are outside the physical barrier (60 cm).

IV. Outdoor Operation

The outdoor operation of visible lasers, such as the LASIRIS™ Model MAG-501L-670M-1000-45°-K, are governed by the following standards: ANSI Std. Z136.6-2000, *American National Standard for the Safe Use of Laser Outdoors* and the *FAA Order 7400.2E, Chapter 29: Outdoor Laser Operations*.

Laser Use in Navigable Air Space

The use of visible lasers in **navigable air space** (*NAS*) 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. The radiant output wavelength of the LASIRIS™ Model MAG-501L-670M-1000-45°-K diode laser is in the visible part of the spectrum as defined by *ANSI Std. Z136.1-2000**, *ANSI Std. Z136.6-2000*†, and *FAA Order 7400.2E Chapter 29** and may pose a visual interference (distraction, disruption, or disorientation) concern for aircrews in NAS. Startle, dazzle, glare and flashblindness concerns apply only to visible light. The **Visual Interference Distances** (*VID*) such as: the **Sensitive Zone Exposure Distance** (*SZED*) (*CZED*) and the **Critical Zone Exposure Distances** and the **Laser Free Zone Distance** (*LFZD*) are the various distances the laser must be from the boundaries of the respective **visual interference zones** (*VIZ*). The laser irradiance or radiant exposure at these boundaries must be no greater than the visual interference zones threshold levels. These distances should be evaluated to prevent the LASIRIS laser from presenting a visual interference hazard in navigable air space.

*Visible: 400 nm ≤ ≤ 700 nm,
†Visible: 380 nm ≤ ≤ 780 nm

A. Flight Hazard Distance

The **Flight Hazard Distances** (*FHD*) are the distances from laser to where the irradiance/radiant exposure limits defines the boundary of the various hazard and visual interference zones.

1. Normal Flight Zone

The **Normal Flight Zone** (*NFZ*) is all the air space about the laser that is not included in any of the 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/radiant exposure at this boundary is defined to be the ocular *MPE*. Ocular exposure at or greater than this distance would present no more than a Class 1 Laser hazard to invisible laser light and a Class 2 Laser 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.

*Note: There are no Class 2 single pulse lasers [*ANSI Std.Z136.1-2000 (Table 2)*]. Class 2 applies to CW or multiple pulse visible lasers only.

2. 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 visual interference levels are presented in *ANSI Standard Z136.6-2000 (Table 5)*.

The sensitive zone about the vicinity of an airport is established at the discretion of the local FAA authority [*ANSI Std. Z136.6-2000 (page 43 note to figure 6)*].

The radiant exposure (H_{SZ}) limit for the sensitive zone is given as:

ANSI Std. Z136.6-2000 (Table 5)

$$H_{SZ} = 25 \times 10^{-6} \, {}^{J}\!/_{cm^2} \qquad 380nm \le \lambda \le 780nm$$

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

The irradiance (E_{SZ}) limit for the sensitive zone is given as:

ANSI Std. Z136.6-2000 (Table 5)

$$E_{SZ} = 100 \times 10^{-6} \, {}^{w}\!/_{cm^2} \qquad 380nm \le \lambda \le 780nm$$

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

The laser radiant exposure / irradiance must not exceed these limits anywhere within the sensitive zone.

3. 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 CZ extends from the ground level to the height of 10-thousand feet above ground level (AGL) and out to a radial distance of ten Nautical Miles (18.5 km) from the center of the airport runways, and includes the Laser Free Zone (LFZ).

The radiant exposure (H_{CZ}) limit for the critical zone is given as:

ANSI Std. Z136.6-2000 (*Table 5*)

$$H_{CZ} = 1.25 \times 10^{-6} \, {}^{J}\!/_{cm^2} \qquad 380nm \le \lambda \le 780nm$$

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

The irradiance (E_{CZ}) for the critical zone is given as:

ANSI Std. Z136.6-2000 (*Table 5*)

$$E_{CZ} = 5.0 \times 10^{-6} \, {}^{w}\!/_{cm^2} \qquad 380nm \le \lambda \le 780nm$$

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

The laser radiant exposure / irradiance must not exceed these limits anywhere within the critical zone.

4. 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 LFZ extends from the ground level to two–thousand feet AGL and out to two-Nautical miles (3.7 km) from the airport runway center line and out to 5 Nautical miles (9.2 km) along the approach path from the edge of the runway.

The radiant exposure (H_{LFZ}) limit for the laser-free zone is given as:

ANSI Std. Z136.6-2000 (*Table 5*)

$$H_{LFZ} = 12.5 \times 10^{-9} \, {}^{J}\!/_{cm^2} \qquad 380nm \le \lambda \le 780nm$$

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

The irradiance (E_{LFZ}) limit for the laser-free zone is given as:

ANSI Std. Z136.6-2000 (*Table 5*)

$$E_{LFZ} = 50 \times 10^{-9} \, {}^{w}\!/_{cm^2} \qquad 380nm \le \lambda \le 780nm$$

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

The laser radiant exposure / irradiance must not exceed these limits anywhere within the laser free zone.

B. Evaluation of the Laser Separation Distances from the Visual Interference Zones

1. CW Operation

Similar to the Nominal Ocular Hazard Distance (*NOHD*) determination (page 18) the Flight Hazard Distances (*FHD*) can be defined as the radial distance from the laser where the average irradiance (E_{FHD}) is equaled to the specific visual interference zone levels (E_{VIZ}).

$$E_{FHD} = E_{VIZ}$$

Effective Irradiance

The irradiance levels (measured or calculated) must be multiplied by the photopic luminous efficiency coefficient obtained from Table 1: Photopic Luminous Efficiency Function ($V(\lambda)$) (*ANSI Std. Z136.6-2000, page 31*) in order to correct for visual sensitivity of the human eye [*ANSI Std. Z136.6-2000 (Table 5: Visual Interference Levels – notes)*].

$$E_{eff} = V(\lambda) \cdot E_{laser}$$

The laser irradiance (E_{laser}) can be expressed as the laser beam power distributed over the laser beam area (assuming a uniform distribution).

$$E_{laser} = \frac{\Phi}{w \cdot \theta \cdot R_{FHD}}$$

The effective (laser) irradiance at the boundary of the visual interference zone distances can be expressed as:

$$E_{eff} = V(\lambda) \cdot \frac{\Phi}{w \cdot \theta \cdot R_{FHD}} = E_{VIZ}$$

For the LASIRIS laser ($\lambda = 671.2 \ \ nm$) the Photopic luminous efficiency coefficient is:

$V(671.2nm) \sim 0.0321$ ANSI Std. Z136.6-2000 (Table 1)

$$E_{eff} = \frac{\Phi}{w \cdot \theta \cdot R_{FHD}} \left(32.1 \times 10^{-3}\right) = E_{VIZ}$$

The beam width (in the axis not affected by the fan angle optic) will expand as a function of distance from the laser.

$$w = w_{exit} + \phi \cdot \left(R_{FHD}\right)$$

Where;

w:	Beam width – not in fan angle axis (in centimeters)
w_{exit}:	Beam width at exit (in centimeters)
ϕ:	Expansion angle (in radians)
R_{FHD}:	Flight hazard distance from the laser (in centimeters)

The beam width (w) or "line width" at distances after the focal distance (R_{focus}) can be expressed as:

$$w = w_{focus} + \phi \cdot \left(R_{FHD} - R_{focus}\right)$$

The "focusing" and "projection distance" parameters are given in the "on-line" specifications for the LASIRIS Magnum Lasers.

The focusing angle (ϕ), which is also the expansion angle after beam waist distance can be estimated from the ratio of the difference in "line thickness" (Δw) to the difference in "projection distance" (ΔR) given in the "Focusing and Depth-Of-Field Performance" charts for the LASIRIS Magnum Series diode lasers.

$$\phi \approx \frac{\Delta w}{\Delta R}$$

$$\phi \approx \frac{1200 \times 10^{-6} m - 600 \times 10^{-6} m}{4\ m - 2\ m}$$

$$\phi \approx \frac{600 \times 10^{-6} m}{2\ m}$$

$$\phi \approx 300 \times 10^{-6}\, radians$$

Continuing to develop the relationship from page 26:

$$\frac{\Phi \cdot \left(32.1 \times 10^{-3}\right)}{\left[w_{focus} + \phi \cdot \left(R_{FHD} - R_{focus}\right)\right] \cdot \theta \cdot R_{FHD}} = E_{VIZ}$$

$$\frac{\Phi \cdot \left(32.1 \times 10^{-3}\right)}{\left(\theta \cdot w_{focus}\right) \cdot R_{FHD} - \left(\phi \cdot \theta \cdot R_{focus}\right) \cdot R_{FHD} + \left(\phi \cdot \theta\right) \cdot \left(R_{FHD}\right)^2} = E_{VIZ}$$

$$E_{VIZ} = \frac{\Phi \cdot \left(32.1 \times 10^{-3}\right)}{\left(w_{focus} - \phi \cdot R_{focus}\right) \cdot \theta \cdot R_{FHD} + \left(\phi \cdot \theta\right) \cdot \left(R_{FHD}\right)^2}$$

$$\left(w_{focus} - \phi \cdot R_{focus}\right) \cdot \theta \cdot R_{FHD} + \left(\phi \cdot \theta\right) \cdot \left(R_{FHD}\right)^2 = \frac{\Phi \cdot \left(32.1 \times 10^{-3}\right)}{E_{VIZ}}$$

The FHZ distance can be calculated from this second order quadratic equation.

$$\left(\phi \cdot \theta\right) \cdot \left[R_{FHD}\right]^2 + \left(w_{focus} - \phi \cdot R_{focus}\right) \cdot \theta \cdot \left[R_{FHD}\right] - \left(\frac{\Phi \cdot \left(32.1 \times 10^{-3}\right)}{E_{VIZ}}\right) = 0$$

The line width (w_{focus}) at a distance of four meters is given in the data sheet for the LASIRIS Magnum Series diode lasers as 1.2 millimeters.

Incorporating the LASIRIS Model MAG-501L-670M-1000-45°-K parameters;

$$\left(300\times10^{-6}\cdot\theta\cdot\frac{\pi}{180^{\circ}}\right)\cdot\left[R_{FHD}\right]^{2}+\left(0.12\ \ cm-\left(300\times10^{-6}\right)\cdot 400\ \ cm\right)\cdot\theta\cdot\frac{\pi}{180^{\circ}}\cdot\left[R_{FHD}\right]$$
$$-\left(\frac{\left(750\times10^{-3}\,watts\right)\cdot\left(32.1\times10^{-3}\right)}{E_{VIZ}}\right)=0$$

The FHD distance from the laser for each FHZ boundary can be calculated for the LASIRIS Model MAG-501L-670M-1000-45°-K by solving the second order quadratic equation as follows:

$$\left(5.24\times10^{-6}\cdot\theta\right)\cdot\left[R_{FHD}\right]^{2}+\left(0.12\ \ cm-0.12\ \ cm\right)\cdot\theta\cdot\frac{\pi}{180^{\circ}}\cdot\left[R_{FHD}\right]-\left(\frac{24.1\times10^{-3}\,watts}{E_{VIZ}}\right)=0$$

$$\left(5.24\times10^{-6}\cdot\theta\right)\cdot\left[R_{FHD}\right]^{2}+\left(0\right)\cdot\theta\cdot\left[R_{FHD}\right]-\left(\frac{24.1\times10^{-3}\,watts}{E_{VIZ}}\right)=0$$

$$\left[5.24\times10^{-6}\cdot\theta\right]\cdot\left(R_{FHD}\right)^{2}-\left[\frac{24.1\times10^{-3}\,watts}{E_{VIZ}}\right]=0$$

$$\left[5.24\times10^{-6}\cdot\theta\right]\cdot\left(R_{FHD}\right)^{2}=\frac{24.1\times10^{-3}\,watts}{E_{VIZ}}$$

$$\left(R_{FHD}\right)^{2}=\frac{24.1\times10^{-3}\,watts}{\left[5.24\times10^{-6}\cdot\theta\right]\ \cdot E_{VIZ}}$$

$$R_{FHD}=\sqrt{\frac{4.59\times10^{3}\,watts}{\theta\cdot E_{VIZ}}}$$

(a) Sensitive Zone (SZ) Separation Distance

The minimum distance that the (LASIRIS) laser must be from the boundary of the sensitive zone (R_{SZ}) can be determined as follows.

$$R_{SZ} = \sqrt{\frac{4.59 \times 10^{3}\, watts}{\theta \cdot E_{SZ}}}$$

$$R_{SZ} = \sqrt{\frac{4.59 \times 10^{3}\, watts}{\left(100 \times 10^{-6}\, watts / cm^{2} \right) \cdot \theta}}$$

$$R_{SZ} = \sqrt{\frac{45.9 \times 10^{6}\, cm^{2}}{\theta}}$$

Table 11 presents the minimum distance the (LASIRIS) laser must be from the boundary of the sensitive zone.

Table 11

Laser Separation Distances from the Boundary of the Sensitive Zone as a Function of Fan Angle

Fan Angle (degrees)	R_{SZ} (meters)
15	17.5
30	12.4
45	10.1
60	8.75

(b) Critical Zone (CZ) Separation Distance

The minimum distance that the (LASIRIS) laser must be from the critical zone (R_{CZ}) boundary can be determined as follows.

$$R_{CZ} = \sqrt{\frac{4.59 \times 10^{3}\, watts}{\theta \cdot E_{CZ}}}$$

$$R_{CZ} = \sqrt{\frac{4.59 \times 10^{3}\, watts}{\left(5 \times 10^{-6}\, watts / cm^{2} \right) \cdot \theta}}$$

$$R_{CZ} = \sqrt{\frac{918 \times 10^{6}\, cm^{2}}{\theta}}$$

Table 12 presents the minimum distance the (LASIRIS) laser must be from the boundary of the Critical Zone.

Table 12

Laser Separation Distances from the Boundary of the Critical Zone as a Function of Fan Angle

Fan Angle (degrees)	R_{CZ} (meters)
15	78.2
30	55.3
45	45.2
60	39.1

(c) Laser Free Zone (*LFZ*) Separation Distance

The minimum distance that the (LASIRIS) laser must be from the Laser Free Zone (R_{LFZ}) can be determined as follows.

$$R_{LFZ} = \sqrt{\frac{4.59 \times 10^{3}\, watts}{\theta \cdot E_{LFZ}}}$$

$$R_{LFZ} = \sqrt{\frac{4.59 \times 10^{3}\, watts}{\left(50 \times 10^{-9}\, watts / cm^{2} \right) \cdot \theta}}$$

$$R_{LFZ} = \sqrt{\frac{91.8 \times 10^{9}\, cm^{2}}{\theta}}$$

Table 13 presents the minimum distance the (LASIRIS) laser must be from the boundary of the Laser Free Zone.

Table 13

Laser Separation Distances from the Boundary of the Laser Free Zone Distances as a Function of Fan Angle

Fan Angle (degrees)	R_{LFZ} (meters)
15	782
30	553
45	452
60	391

Table 14 summarizes the minimum distances the laser must be from the boundary of the various visual interference zones.

Table 14

Summary of Laser Separation Distances from the Boundaries of the Flight Hazard and Visual Interference Zones for the CW Laser Operation

	Normal	Visual Interference Distance		
Fan Angle (degrees)	NOHD (meters)	SZ (meters)	CZ (meters)	LFZ (meters)
15	16.1	17.5	78.2	782
30	8.04	12.4	55.3	553
45	5.35	10.1	45.2	452
60	4.02	8.75	39.1	391

2. Pulse Operation

The typical operation of the LASIRIS™ Model MAG-501L-670M-1000-45°-K is the "pulsed mode". Evaluation of the Flight Hazard Distances for pulsed operation is similar to the evaluation for the CW mode operation.

The Flight Hazard Distance is that distance from the laser where the cross-section radiant exposure is equaled to the Flight Hazard Zone radiant exposure level.

$$H_{FHD} = H_{VIZ}$$

Similar to the effective irradiance the effective radiant exposure (H_{eff}) is the product of the radiant exposure (H_{laser}) and the Photopic Luminous Efficiency Function ($V(\lambda)$).

$$H_{eff} = V(\lambda) \cdot H_{laser}$$

The radiant exposure as a function of the radial distance (R) can be expressed as:

$$H_{laser}(R) = \frac{Q}{A(R)} = \frac{Q}{w \cdot (\theta \cdot R)}$$

The effective radiant exposure is set equal to the radiant exposure (H_{VIZ}) at the boundary of the visual interference zone(s).

$$H_{eff} = H_{VIZ}$$

$$V(\lambda)\cdot\left[\frac{Q}{w\cdot\theta\cdot R_{FHD}}\right]=H_{VIZ}$$

$$\frac{Q\cdot\left(32.1\times10^{-3}\right)}{w\cdot\theta\cdot R_{FHD}}=H_{VIZ}$$

For multiple-pulse visible lasers the appropriate radiant energy is the sum of the radiant pulse energy delivered in a quarter second exposure [*ANSI Std. Z136.6-2000 (8.2.3)*].

$$Q=Q_o\cdot\left(0.25\sec\ \times PRF\right)$$

The average radiant pulse energy output (Q_o) of the LASIRIS™ Model MAG-501L-670M-1000-45°-K is the product of the radiant output power and the diode laser "on" duration and the number of pulses delivered in a quarter second.

$$\frac{\left(32.1\times10^{-3}\right)\cdot Q_o\cdot\left(0.25\sec\ \times PRF\right)}{w\cdot\theta\cdot R_{FHD}}=H_{VIZ}$$

$$Q_o=V(\lambda)\cdot\Phi\cdot t$$

$$\frac{(\Phi\cdot t)\cdot\left(32.1\times10^{-3}\right)\cdot\left(0.25\ \sec\cdot PRF\right)}{w\cdot\theta\cdot R_{FHD}}=H_{VIZ}$$

$$\frac{(\Phi\cdot t)\cdot\left(8.03\times10^{-3}\sec\cdot PRF\right)}{\left[w_{focus}+\phi\cdot\left(R_{FHD}-R_{focus}\right)\right]\ \cdot\theta\cdot R_{FHD}}=H_{VIZ}$$

Similar to the CW evaluation, the expression for the pulsed operation minimum flight hazard and visual interference distances from the laser to the boundaries, of the various visual interference zones (*VIZ*) for pulsed operation is a second ordered quadratic equation (where angles are in radians). See Appendix for the algebraic derivation.

$$(\phi \cdot \theta) \cdot [R_{FHD}]^2 + (w_{focus} - \phi \cdot R_{focus}) \cdot \theta \cdot [R_{FHD}] - \left(\frac{\Phi \cdot t \cdot (8.03 \times 10^{-3} \ \sec \cdot PRF)}{H_{VIZ}} \right) = 0$$

The FHD that the laser must be from the boundary for each FHZ can be determined for the LASIRIS™ Model MAG-501L-670M-1000-45°-K by solving the second order quadratic equation (where the fan angle is in degrees).

$$\left(300 \times 10^{-6} \cdot \frac{\pi}{180} \cdot \theta \right) \cdot [R_{FHD}]^2 + (0.12 \ \ cm - 0.12 \ \ cm) \cdot \theta \cdot \frac{\pi}{180^\circ} \cdot [R_{FHD}] - \left(\frac{750 \times 10^{-3} watts \cdot 8.03 \times 10^{-3} \sec \cdot (t) \cdot PRF}{H_{VIZ}} \right) = 0$$

Hence:

$$(5.24 \times 10^{-6} \cdot \theta) \cdot [R_{FHD}]^2 + (0) \cdot \theta \cdot [R_{FHD}] - \left(\frac{750 \times 10^{-3} watts \cdot (t) \ \cdot (8.03 \times 10^{-3} \cdot \sec \cdot PRF)}{H_{VIZ}} \right) = 0$$

$$[5.24 \times 10^{-6} \cdot \theta] \cdot (R_{FHD})^2 - \left[\frac{(6.02 \times 10^{-3} watts) \cdot (t) \ \cdot PRF}{H_{VIZ}} \right] = 0$$

$$R_{FHD} = \sqrt{\frac{6.02 \times 10^{-3} \cdot (t) \ watts \cdot PRF}{[5.24 \times 10^{-6} \cdot \theta] \cdot H_{VIZ}}}$$

The minimum range (R_{FHD}) or *FHD* that the laser must be from the boundary of the visual interference zone (*VIZ*) can generally be expressed as:

$$R_{FHD} = \sqrt{\frac{1.15 \times 10^{3} watts \cdot (t) \ \cdot PRF}{\theta \cdot H_{VIZ}}}$$

(a) **One-Microsecond Pulse @ 30 Hertz**.

(1) Sensitive Zone (SZ) Laser Separation Distance for: 1-Microsecond Pulse Exposure @ 30 hertz.

The minimum distance that the (LASIRIS) laser pulsed scanner must be from the boundary of the Sensitive Zone (R_{SZ}) can be determined as follows.

$$R_{SZ-1\mu s@30Hz} = \sqrt{\frac{1.15\times10^{3}\,watts\cdot(t)\ \cdot PRF}{\theta\cdot H_{SZ}}}$$

$$R_{SZ-1\mu s@30Hz} = \sqrt{\frac{1.15\times10^{3}\,watts\cdot\left(10^{-6}\,\mathrm{sec}\right)\ \cdot 30\ \ \mathrm{sec}^{-1}}{\theta\cdot H_{SZ}}}$$

$$R_{SZ-1\mu s@30Hz} = \sqrt{\frac{34.5\times10^{-3}\,joules}{\theta\cdot H_{SZ}}}$$

$$R_{SZ-1\mu s@30Hz} = \sqrt{\frac{34.5\times10^{-3}\,joules}{\left(\ 25\times10^{-6}\ joules/cm^{2}\right)\cdot\theta}}$$

In general, the distance the (LASIRIS) laser pulsed scanner must be from the boundary of the Sensitive Zone (*SZ*) as a function of the Fan Angle can be expressed as:

$$R_{SZ-1\mu s@30Hz} = \sqrt{\frac{1.38\times10^{3}\,cm^{2}}{\theta}}$$

$$R_{SZ-1\mu s@30Hz} = \left(\frac{1}{100}\right) \cdot \sqrt{\frac{1.38\times10^{3}}{\theta}} \quad meters$$

Table 15 presents the minimum distance the (LASIRIS) laser pulsed scanner must be from the boundary of the Sensitive Zone (as a function of the fan angle) for: one-microsecond pulse exposure duration at a 30 hertz PRF.

Table 15

Laser Separation Distances from the Boundary of the Sensitive Zone as a Function of Fan Angle and 1-Microsecond Pulse @ 30 Hertz

Fan Angle (degrees)	R_{SZ} (meters)	NOHD (meters)
15	0.10	1.19
30	0.07	0.60
45	0.06	0.40
60	0.05	0.30

NOTES:
1. Shaded values are not applicable
2. When the visual interference distance is less than the NOHD the NOHD takes precedence because the MPE takes precedence in this case [ANSI Std. Z136.6-2000 (Table 5- notes)].

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(2) Critical Zone (*CZ*) Laser Separation Distance for: 1-Microsecond Pulse Exposure @ 30 hertz.

The minimum distance that the (LASIRIS) laser pulsed scanner must be from the boundary of the Critical Zone (R_{CZ}) can be determined as follows.

$$R_{CZ-1\mu s@30Hz} = \sqrt{\frac{34.5\times10^{-3}\ joules}{\theta \cdot H_{CZ}}}$$

$$R_{CZ-1\mu s@30Hz} = \sqrt{\frac{34.5\times10^{-3}\ joules}{\theta \cdot \left(1.25\times10^{-6}\ joules/cm^{2}\right)}}$$

$$R_{CZ-1\mu s@30Hz} = \sqrt{\frac{27.6\times10^3 cm^2}{\theta}}$$

$$R_{CZ-1\mu s@30Hz} = \left(\frac{1}{100}\right)\cdot\sqrt{\frac{27.6\times10^3}{\theta}} \quad meters$$

Table 16 presents the minimum distance the (LASIRIS) laser pulsed scanner must be from the boundary of the Critical Zone (as a function of the fan angle) for: one-microsecond pulse exposure duration at a 30 hertz PRF.

Table 16

Laser Separation Distances from the Boundary of the Critical Zone as a Function of Fan Angle and 1-Microsecond Pulse @ 30 Hertz

Fan Angle (degrees)	R_{CZ} (meters)	NOHD (meters)
15	0.43	1.19
30	0.30	0.60
45	0.25	0.40
60	0.21	0.30

NOTES:
1. Shaded values are not applicable (see note 2).
2. When the visual interference distance is less than the NOHD the NOHD takes precedence because the MPE takes precedence in this case [ANSI Std. Z136.6-2000 (Table 5- notes)].

(3) Laser Free Zone (*LFZ*) Separation Distance for: 1-Microsecond Pulse Exposure @ 30 hertz.

The minimum distance that the (LASIRIS) laser pulsed scanner must be from the boundary of the Laser Free Zone (R_{LFZ}) can be determined as follows.

$$R_{LFZ-1\mu s@30Hz} = \sqrt{\frac{34.5\times10^{-3}\ joules}{\theta\cdot H_{LFZ}}}$$

$$R_{LFZ-1\mu s@30Hz} = \sqrt{\frac{34.5\times10^{-3}\ joules}{\theta\cdot\left(12.5\times10^{-9}\ joules/cm^2\right)}}$$

$$R_{LFZ-1\mu s@30Hz} = \sqrt{\frac{2.76\times10^{6}\ cm^2}{\theta}}$$

$$R_{LFZ-1\mu s@30Hz} = \left(\frac{1}{100}\right)\cdot\sqrt{\frac{2.76\times10^{6}}{\theta}}\quad meters$$

Table 17 presents the minimum distance the (LASIRIS) laser pulsed scanner must be from the boundary of the Laser Free Zone (as a function of the fan angle) for: one-microsecond pulse exposure duration at a 30 hertz PRF.

Table 17

Laser Separation Distances from the Boundary of the Laser Free Zone as a Function of Fan Angle and 1-Microsecond Pulse @ 30 Hertz

Fan Angle (degrees)	R_{LFZ} (meters)	NOHD (meters)
15	23.9	1.19
30	16.9	0.60
45	13.8	0.40
60	11.9	0.30

NOTES:
1. Shaded values are not applicable.

Table 18 presents a summary of the minimum distance the (LASIRIS) laser pulsed scanner must be from the boundary of the Laser Free Zone (as a function of the fan angle) for: one-microsecond pulse exposure duration at a 30 hertz PRF.

Table 18

Summary of Laser Separation Distances from the Boundaries of the Flight Hazard and Visual Interference Zones for: 1-Microsecond Pulse @ 30 Hertz

	Normal	Visual Interference Distance		
Fan Angle (degrees)	NOHD (meters)	SZ (meters)	CZ (meters)	LFZ (meters)
15	1.19	0.096	0.43	23.9
30	0.60	0.068	0.30	16.9
45	0.40	0.055	0.25	13.8
60	0.30	0.048	0.21	11.9

NOTES:
1. Shaded values are not applicable (see note 2).
2. When the visual interference distance is less than the NOHD the NOHD takes precedence because the MPE takes precedence in this case [ANSI Std. Z136.6-2000 (Table 5- notes)].

(b) **Ten-Microsecond Pulse @ 30 Hertz**.

(1) Sensitive Zone (SZ) Laser Separation Distance for: 10-Microsecond Pulse Exposure @ 30 hertz.

The distance from the (LASIRIS) laser pulsed scanner to the boundary of the Sensitive Zone (R_{SZ}) can be determined as follows.

$$R_{SZ-10\mu s@30Hz} = \sqrt{\frac{1.15\times10^{3}\,watts\cdot(t)\ \cdot PRF}{\theta\cdot H_{SZ}}}$$

$$R_{SZ-10\mu s@30Hz} = \sqrt{\frac{1.15\times10^{3}\,watts\cdot\left(10\times10^{-6}\,\sec\right)\cdot 30\ \sec^{-1}}{\theta\cdot H_{SZ}}}$$

$$R_{SZ-10\mu s@30Hz} = \sqrt{\frac{345\times10^{-3}\,joules}{\theta\cdot H_{SZ}}}$$

$$R_{SZ-10\mu s@30Hz} = \sqrt{\frac{345\times10^{-3}\,joules}{\left(25\times10^{-6}\ joules/cm^{2}\right)\cdot\theta}}$$

$$R_{SZ-10\mu s@30Hz} = \sqrt{\frac{13.8\times10^{3}\,cm^{2}}{\theta}}$$

$$R_{SZ-10\mu s@30Hz} = \left(\frac{1}{100}\right)\cdot\sqrt{\frac{13.8\times10^{3}}{\theta}}\quad meters$$

Table 19 presents the minimum distance the (LASIRIS) laser pulsed scanner must be from the boundary of the Sensitive Zone (as a function of the fan angle) for: ten-microsecond pulse exposure duration at a 30 hertz PRF.

Table 19

Laser Separation Distances from the Boundary of the Sensitive Zone as a Function of Fan Angle and 10-Microsecond Pulse @ 30 Hertz

Fan Angle (degrees)	R_{SZ} (meters)	NOHD (meters)
15	0.30	1.19
30	0.21	0.60
45	0.18	0.40
60	0.15	0.30

NOTES:
1. Shaded values are not applicable (see note 2).
2. When the visual interference distance is less than the NOHD the NOHD takes precedence because the MPE takes precedence in this case [ANSI Std. Z136.6-2000 (Table 5- notes)].

(2) Critical Zone (CZ) Laser Separation Distance for: 10-Microsecond Pulse Exposure @ 30 hertz.

The minimum distance from the (LASIRIS) laser pulsed scanner must be from the boundary of the Critical Zone (R_{CZ}) can be determined as follows.

$$R_{CZ-10\mu s@30Hz} = \sqrt{\frac{345\times10^{-3}\ joules}{\theta\cdot H_{CZ}}}$$

$$R_{CZ-10\mu s@30Hz} = \sqrt{\frac{345\times10^{-3}\ joules}{\theta\cdot\left(1.25\times10^{-6}\ joules/cm^2\right)}}$$

$$R_{CZ-10\mu s@30Hz} = \sqrt{\frac{276\times10^{3}\,cm^2}{\theta}}$$

$$R_{CZ-10\mu s@30Hz} = \left(\frac{1}{100}\right)\cdot\sqrt{\frac{276\times10^{3}}{\theta}}\quad meters$$

Table 20 presents the minimum distance the (LASIRIS) laser pulsed scanner must be from the boundary of the Critical Zone (as a function of the fan angle) for: ten-microsecond pulse exposure duration at a 30 hertz PRF.

Table 20

Laser Separation Distances from the Boundary of the Critical Zone as a Function of Fan Angle and 10-Microsecond Pulse @ 30 Hertz

Fan Angle (degrees)	R_{CZ} (meters)
15	1.36
30	0.96
45	0.78
60	0.68

(3) Laser Free Zone (LFZ) Laser Separation Distance for: 10-Microsecond Pulse Exposure @ 30 hertz.

The minimum distance from the (LASIRIS) laser pulsed scanner must be from the boundary of the Laser Free Zone (R_{LFZ}) can be determined as follows.

$$R_{LFZ-10\mu s@30Hz} = \sqrt{\frac{345\times10^{-3}\ joules}{\theta\cdot H_{LFZ}}}$$

$$R_{LFZ-10\mu s@30Hz} = \sqrt{\frac{345\times10^{-3}\ joules}{\theta\cdot\left(12.5\times10^{-9}\ joules/cm^{2}\right)}}$$

$$R_{LFZ-10\mu s@30Hz} = \sqrt{\frac{27.6\times10^{6}\,cm^{2}}{\theta}}$$

$$R_{LFZ-10\mu s@30Hz} = \left(\frac{1}{100}\right)\cdot\sqrt{\frac{27.6\times10^{6}}{\theta}}\quad meters$$

Table 21 presents the minimum distance the (LASIRIS) laser pulsed scanner must be from the boundary of the Laser Free Zone (as a function of the fan angle) for: ten-microsecond pulse exposure duration at a 30 hertz PRF.

Table 21

Laser Separation Distances from the Boundary of the Laser Free Zone as a Function of Fan Angle and 10-Microsecond Pulse @ 30 Hertz

Fan Angle (degrees)	R_{CZ} (meters)
15	13.6
30	9.59
45	7.83
60	6.78

Table 22 presents a summary of the minimum distances the (LASIRIS) laser pulsed scanner must be from the boundaries of the Visual Interference Zones (as a function of the fan angle) for: ten-microsecond pulse at a 30 hertz PRF.

Table 22

Summary of Laser Separation Distances from the Boundaries of the Flight Hazard and Visual Interference Zones for: 10-Microsecond Pulse @ 30 Hertz

	Normal	Visual Interference Distance		
Fan Angle (degrees)	NOHD (meters)	SZ (meters)	CZ (meters)	LFZ (meters)
15	1.19	0.30	1.36	13.6
30	0.60	0.21	0.96	9.59
45	0.40	0.18	0.78	7.83
60	0.30	0.15	0.68	6.78

NOTES:
1. Shaded values are not applicable (see note 2).
2. When the visual interference distance is less than the NOHD the NOHD takes precedence because the MPE takes precedence in this case [ANSI Std. Z136.6-2000 (Table 5- notes)].

(c) **One-Microsecond Pulse @ 60 Hertz**.

(1) Sensitive Zone (SZ) Laser Separation Distance for: 1-Microsecond Pulse Exposure @ 60 hertz.

The minimum distance the (LASIRIS) laser pulsed scanner must be from the boundary of the Sensitive Zone (R_{SZ}) can be determined as follows.

$$R_{SZ-1\mu s@60Hz} = \sqrt{\frac{1.15\times10^{3}\,watts\cdot(t)\ \cdot PRF}{\theta\cdot H_{FHZ}}}$$

$$R_{SZ-1\mu s@60Hz} = \sqrt{\frac{1.15\times10^{3}\,watts\cdot\left(1\times10^{-6}\,\sec\right)\cdot 60\ \sec^{-1}}{\theta\cdot H_{FHZ}}}$$

$$R_{SZ-1\mu s@60Hz} = \sqrt{\frac{69\times10^{-3}\,joules}{\theta\cdot H_{SZ}}}$$

$$R_{SZ-1\mu s@60Hz} = \sqrt{\frac{69\times10^{-3}\,joules}{\left(25\times10^{-6}\,joules/cm^{2}\right)\cdot\theta}}$$

$$R_{SZ-1\mu s@60Hz} = \sqrt{\frac{2.76\times10^{3}\,cm^{2}}{\theta}}$$

$$R_{SZ-1\mu s@60Hz} = \left(\frac{1}{100}\right)\cdot\sqrt{\frac{2.76\times10^{3}}{\theta}}\quad meters$$

Table 23 presents the minimum distance the (LASIRIS) laser pulsed scanner must be from the boundary of the Sensitive Zone (as a function of the fan angle) for: one-microsecond pulse exposure duration at a 60 hertz PRF.

Table 23

Laser Separation Distances from the Boundary of the Sensitive Zone as a Function of Fan Angle and 1-Microsecond Pulse @ 60 Hertz

Fan Angle (degrees)	R_{SZ} (meters)	NOHD (meters)
15	0.14	1.19
30	0.10	0.60
45	0.08	0.40
60	0.07	0.30

NOTES:
1. Shaded values are not applicable (see note 2).
2. When the visual interference distance is less than the NOHD the NOHD takes precedence because the MPE takes precedence in this case [ANSI Std. Z136.6-2000 (Table 5- notes)].

(2) Critical Zone (CZ) Laser Separation Distance for: 1-Microsecond Pulse Exposure @ 60 hertz.

The minimum distance from the (LASIRIS) laser pulsed scanner must be from the boundary of the Critical Zone (R_{CZ}) can be determined as follows.

$$R_{CZ-1\mu s@60Hz} = \sqrt{\frac{69\times10^{-3}\ joules}{\theta\cdot H_{CZ}}}$$

$$R_{CZ-1\mu s@60Hz} = \sqrt{\frac{69\times10^{-3}\ joules}{\theta\cdot\left(1.25\times10^{-6}\ joules/cm^2\right)}}$$

$$R_{CZ-1\mu s@60H} = \sqrt{\frac{55.2\times10^{3}cm^2}{\theta}}$$

$$R_{CZ-1\mu s@60H} = \left(\frac{1}{100}\right)\cdot\sqrt{\frac{55.2\times10^{3}}{\theta}}\quad meters$$

Table 24 presents the minimum distance the (LASIRIS) laser pulsed scanner must be from the boundary of the Critical Zone (as a function of the fan angle) for: one-microsecond pulse exposure duration at a 60 hertz PRF.

Table 24

Laser Separation Distances from the Boundary of the Critical Zone as a Function of Fan Angle and 1-Microsecond Pulse @ 60 Hertz

Fan Angle (degrees)	R_{CZ} (meters)	NOHD (meters)
15	0.61	1.19
30	0.43	0.60
45	0.35	0.40
60	0.30	0.30

NOTES:
1. Shaded values are not applicable (see note 2).
2. When the visual interference distance is less than the NOHD the NOHD takes precedence because the MPE takes precedence in this case [ANSI Std. Z136.6-2000 (Table 5- notes)].

(3) Laser Free Zone (LFZ) Laser Separation Distance for: 1-Microsecond Pulse Exposure @ 60 hertz.

The minimum distance the (LASIRIS) laser pulsed scanner to the boundary of the Laser Free Zone (R_{LFZ}) can be determined as follows.

$$R_{LFZ-1\mu s@60Hz} = \sqrt{\frac{69\times10^{-3}\ joules}{\theta \cdot H_{LFZ}}}$$

$$R_{LFZ-1\mu s@60Hz} = \sqrt{\frac{69\times10^{-3}\ joules}{\theta \cdot \left(12.5\times10^{-9}\ joules/cm^2\right)}}$$

$$R_{LFZ-1\mu s@60Hz} = \sqrt{\frac{5.52\times10^{6}\,cm^2}{\theta}}$$

$$R_{LFZ-1\mu s@60Hz} = \left(\frac{1}{100}\right)\cdot\sqrt{\frac{5.52\times10^{6}}{\theta}} \quad meters$$

Table 25 presents the minimum distance the (LASIRIS) laser pulsed scanner must be from the boundary of the Laser Free Zone (as a function of the fan angle) for: ten-microsecond pulse exposure duration at a 60 hertz PRF.

Table 25

Laser Separation Distance from the Boundary of the Laser Free Zone as a Function of Fan Angle and 1-Microsecond Pulse @ 60 Hertz

Fan Angle (degrees)	R_{CZ} (meters)
15	6.07
30	4.29
45	3.50
60	3.03

Table 26 presents a summary of the minimum distances the (LASIRIS) laser pulsed scanner must be from the boundaries of the various visual interference zones (as a function of the fan angle) for: One-microsecond pulse exposure duration at a 60 hertz PRF.

Table 26

Summary of Laser Separation Distances from the Boundaries of the Flight Hazard and Visual Interference Zones for: 1-Microsecond Pulse @ 60 Hertz

	Normal	Visual Interference Distance		
Fan Angle (degrees)	NOHD (meters)	SZ (meters)	CZ (meters)	LFZ (meters)
15	1.19	0.14	0.61	6.07
30	0.60	0.10	0.43	4.29
45	0.40	0.08	0.35	3.50
60	0.30	0.07	0.30	3.03

NOTES:
1. Shaded values are not applicable (see note 2).
2. When the visual interference distance is less than the NOHD the NOHD takes precedence because the MPE takes precedence in this case [ANSI Std. Z136.6-2000 (Table 5- notes)].

(d) **Ten-Microsecond Pulse @ 60 Hertz**.

(1) Sensitive Zone (SZ) Laser Separation Distance for: 10-Microsecond Pulse Exposure @ 60 hertz.

The minimum distance the (LASIRIS) laser pulsed scanner must be from the boundary of the Sensitive Zone (R_{SZ}) can be determined as follows.

$$R_{SZ-10\mu s@60Hz} = \sqrt{\frac{1.15\times10^{3}\,watts\cdot(t)\ \cdot PRF}{\theta\cdot H_{SZ}}}$$

$$R_{SZ-10\mu s@60Hz} = \sqrt{\frac{1.15\times10^{3}\,watts\cdot\left(10\times10^{-6}\,\text{sec}\right)\cdot 60\ \text{sec}^{-1}}{\theta\cdot H_{SZ}}}$$

$$R_{SZ-10\mu s@60Hz} = \sqrt{\frac{690\times10^{-3}\,joules}{\theta\cdot H_{SZ}}}$$

$$R_{SZ-10\mu s@60Hz} = \sqrt{\frac{690\times10^{-3}\,joules}{\left(25\times10^{-6}\,joules/cm^{2}\right)\cdot\theta}}$$

$$R_{SZ-10\mu s@60Hz} = \sqrt{\frac{27.6\times10^{3}\,cm^{2}}{\theta}}$$

$$R_{SZ-10\mu s@60Hz} = \left(\frac{1}{100}\right)\cdot\sqrt{\frac{27.6\times10^{3}}{\theta}}\quad meters$$

Table 27 presents the minimum distance the (LASIRIS) laser pulsed scanner must be from the boundary of the Sensitive Zone (as a function of the fan angle) for: ten-microsecond pulse exposure duration at a 60 hertz PRF.

Table 27

Laser Separation Distances from the Boundary of the Sensitive Zone as a Function of Fan Angle and 10-Microsecond Pulse @ 60 Hertz

Fan Angle (degrees)	R_{SZ} (meters)	NOHD (meters)
15	0.43	1.19
30	0.30	0.60
45	0.25	0.40
60	0.21	0.30

NOTES:
1. Shaded values are not applicable (see note 2).
2. When the visual interference distance is less than the NOHD the NOHD takes precedence because the MPE takes precedence in this case [ANSI Std. Z136.6-2000 (Table 5- notes)].

(2) Critical Zone (CZ) Laser Separation Distance for: 10-Microsecond Pulse Exposure @ 60 hertz.

The minimum distance that the (LASIRIS) laser pulsed scanner must be from the boundary of the Critical Zone (R_{CZ}) can be determined as follows.

$$R_{CZ-10\mu s@60Hz} = \sqrt{\frac{690\times10^{-3}\ joules}{\theta\cdot H_{CZ}}}$$

$$R_{CZ-10\mu s@60Hz} = \sqrt{\frac{690\times10^{-3}\ joules}{\theta\cdot\left(1.25\times10^{-6}\ joules/cm^2\right)}}$$

$$R_{CZ-10\mu s@60Hz} = \sqrt{\frac{552\times10^{3}cm^2}{\theta}}$$

$$R_{CZ-10\mu s@60Hz} = \left(\frac{1}{100}\right)\cdot\sqrt{\frac{552\times10^{3}}{\theta}}\quad meters$$

Table 28 presents the minimum distance the (LASIRIS) laser pulsed scanner must be from the boundary of the Critical Zone (as a function of the fan angle) for: ten-microsecond pulse exposure duration at a 60 hertz PRF.

Table 28

Laser Separation Distances from the Boundary of the Critical Zone as a Function of Fan Angle and 10-Microsecond Pulse @ 60 Hertz

Fan Angle (degrees)	R_{CZ} (meters)
15	1.92
30	1.36
45	1.11
60	0.96

(3) Laser Free Zone (LFZ) Separation Distance for: 10-Microsecond Pulse Exposure @ 60 hertz.

The minimum distance the (LASIRIS) laser pulsed scanner must be from the boundary of the Laser Free Zone (R_{LFZ}) can be determined as follows.

$$R_{LFZ-10\mu s@60Hz} = \sqrt{\frac{690\times10^{-3}\ joules}{\theta\cdot H_{LFZ}}}$$

$$R_{LFZ-10\mu s@60Hzs} = \sqrt{\frac{690\times10^{-3}\ joules}{\theta\cdot\left(12.5\times10^{-9}\ joules/cm^2\right)}}$$

$$R_{LFZ-10\mu s@60Hz} = \sqrt{\frac{55.2\times10^{6}\ cm^2}{\theta}}$$

$$R_{LFZ-10\mu s@60Hz} = \left(\frac{1}{100}\right)\cdot\sqrt{\frac{55.2\times10^{6}}{\theta}}\quad meters$$

Table 29 presents the minimum distance the (LASIRIS) laser pulsed scanner must be from the boundary of the Laser Free Zone (as a function of the fan angle) for: ten-microsecond pulse exposure duration at a 60 hertz PRF.

Table 29

Laser Separation Distances from the Boundary of the Laser Free Zone as a Function of Fan Angle and 10-Microsecond Pulse @ 60 Hertz

Fan Angle (degrees)	R_{CZ} (meters)
15	19.2
30	13.6
45	11.1
60	9.59

Table 30 presents a summary of the minimum distance the (LASIRIS) laser pulsed scanner must be from the boundary of the Laser Free Zone (as a function of the fan angle) for: ten-microsecond pulse exposure duration at a 60 hertz PRF.

Table 30

Summary of Laser Separation Distances from the Boundaries of the Flight Hazard and Visual Interference Zones for: 10-Microsecond Pulse @ 60 Hertz

	Normal	Visual Interference Distance		
Fan Angle (degrees)	NOHD (meters)	SZ (meters)	CZ (meters)	LFZ (meters)
15	1.19	0.43	1.92	19.2
30	0.60	0.30	1.36	13.6
45	0.40	0.25	1.11	11.1
60	0.30	0.21	0.96	9.59

NOTES:
1. Shaded values are not applicable (see note 2).
2. When the visual interference distance is less than the NOHD the NOHD takes precedence because the MPE takes precedence in this case [ANSI Std. Z136.6-2000 (Table 5- notes)].

Laser Separation Distances from the Center of the Airport Flight Lines

Table 31

Laser Separation Distances to the Center of the Airport Flight Line for the LASIRIS Laser CW Operation

	Critical Zone	Laser Free Zone
Airport to Boundary	18,500 meters	9,200 meters
Laser to Boundary	78.2 meters	783 meters
Laser to Airport	**18,578 meters**	9,982 meters

Table 32

Laser Separation Distances to the Center of the Airport Flight Line for the LASIRIS Laser Pulsed Operation (Worst Case)

	Critical Zone	Laser Free Zone
Airport to Boundary	18,500 meters	9,200 meters
Laser to Boundary	1 meters	10 meters
Laser to Airport	**18,501 meters**	9,210 meters

Under worst case conditions for the (LASIRIS) laser scanner, the scanner must be greater than 18,501 meters (pulse operation) and 18,578 meters (CW operation) from the center of the airport flight lines for unobstructed line-of-sight view to the various visual interference zone boundaries.

V. Conclusion

CW Operation

The minimum optical density required of the laser safety eyewear is **2.88**.

The NOHD for the various fan angles available to the LASIRIS Model MAG-501L-670M-1000-45°-K:

Table 31

NOHD versus Fan Angle

(degrees)	NOHD (meters)
15	16.1
30	8.05
45	5.37
60	4.02

Pulse Operation

Operating parameters of the LASIRIS Model MAG-501L-670M-1000-45°-K for eye safe viewing at the 60-centimeter engineering barrier:

Table 32

Fan Angle Eye Safe Operation

PRF (Hz)	1 μsec	10 μsec
30	30°	-
30	45°	-
30	60°	60°
60	45°	-

Shaded areas are outside the 60 cm engineering barrier.

Outdoor Operation in Navigable Air Space

Under worst case conditions for the pulse operation of the laser must be: greater than 18,501 meters (pulse operation) and 18,578 meters (CW operation) from the center on the airport flight lines.

VI. Appendix

The continued algebraic derivation from page 32:

$$\frac{(\Phi \cdot t)\cdot(0.25\ \sec\cdot PRF)\cdot(0.0321)}{\left[w_{focus}+\phi\cdot\left(R_{FHD}-R_{focus}\right)\right]\ \cdot\theta\cdot R_{FHD}}=H_{VIZ}$$

$$(\Phi \cdot t)\cdot(0.25\ \sec\cdot PRF)\cdot(0.0321)=H_{VIZ}\cdot\left[w_{focus}+\phi\cdot\left(R_{FHD}-R_{focus}\right)\right]\ \cdot\theta\cdot R_{FHD}$$

$$1=\left[\frac{H_{VIZ}}{(\Phi \cdot t)\cdot\left(8.03\times10^{-3}\sec\cdot PRF\right)}\right]\cdot\left[w_{focus}+\phi\cdot\left(R_{FHD}-R_{focus}\right)\right]\ \cdot\theta\cdot R_{FHD}$$

$$1=\left[\frac{H_{VIZ}}{(\Phi \cdot t)\cdot\left(8.03\times10^{-3}\ \sec\cdot PRF\right)}\right]\cdot\left[w_{focus}\cdot\theta\cdot R_{FHD}+\phi\cdot\theta\cdot R_{FHD}^{2}-\phi\cdot\theta\cdot R_{focus}\cdot R_{FHD}\right]$$

$$\left[\frac{H_{VIZ}}{(\Phi \cdot t)\cdot\left(8.03\times10^{-3}\sec\cdot PRF\right)}\right]\cdot\left[w_{focus}\cdot\theta\cdot R_{FHD}+\phi\cdot\theta\cdot R_{FHD}^{2}-\phi\cdot\theta\cdot R_{focus}\cdot R_{FHD}\right]\ -1=0$$

Multiplying by: $(\Phi \cdot t)\cdot\left(8.03\times10^{-3}\sec\cdot PRF\right)$ dividing by (H_{VIZ}) yields:

$$\left[w_{focus}\cdot\theta\cdot R_{FHD}+\phi\cdot\theta\cdot R_{FHD}^{2}-\phi\cdot\theta\cdot R_{focus}\cdot R_{FHD}\right]\ -\frac{(\Phi \cdot t)\cdot\left(8.03\times10^{-3}\sec\cdot PRF\right)}{H_{VIZ}}=0$$

$$[\phi\cdot\theta]\cdot R_{FHD}^{2}+[w_{focus}\cdot\theta]\cdot R_{FHD}-[\phi\cdot\theta\cdot R_{focus}]\cdot R_{FHD}-\frac{(\Phi \cdot t)\cdot\left(8.03\times10^{-3}\sec\cdot PRF\right)}{H_{VIZ}}=0$$

Hence;

$$(\phi\cdot\theta)\cdot[R_{FHD}]^{2}+\left(w_{focus}-\phi\cdot R_{focus}\right)\cdot\theta\cdot[R_{FHD}]-\left(\frac{\Phi\cdot t\cdot\left(8.03\times10^{-3}\sec\cdot PRF\right)}{H_{VIZ}}\right)=0$$

VII. Reference

ANSI Standard Z136.1-2000, American National Standard for the Safe Use of Lasers

ANSI Standard Z136.6-2000, American National Standard for the Safe Use of Lasers Outdoors

FAA Order 7400.2E, Chapter 29: Outdoor Laser Operations

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