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Extended Ocular Hazard Distances Associated With Intrabeam Aided Viewing Of The Sandia Remote Sensing System Airborne AURA Laser (Big Sky Variant)

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Abstract

A laser hazard analysis to determine the Extended Ocular Hazard Distances associated with a possible intrabeam aided viewing of the Sandia Remote Sensing System (SRSS) airborne AURA laser (Big Sky Laser Technology) was performed based on the 2000 version of the American National Standard Institute's (ANSI) Standard Z136.1, *for the Safe Use of Lasers*² and the 2000 version of the ANSI Standard Z136.6, *for the Safe Use of Lasers Outdoors*³. The AURA lidar system is installed in the instrument pod of a Proteus airframe and is used to perform *laser interaction* experiments and tests at various national test sites. The targets are located at various distances (ranges) from the airborne platform. Nominal Ocular Hazard Distance (NOHD) and maximum "eye-safe" dwell times for various operational altitudes associated with unaided intrabeam exposure of ground personnel were determined and presented in a previous SAND report¹. Although the target areas are controlled and the use of viewing aids are prohibited there is the possibility of the unauthorized use of viewing aids such as binoculars. This aided viewing hazard analysis is supplemental to the previous SAND report¹ for the laser hazard analysis of the airborne AURA.

Summary

If the use of viewing aids, such as a 7x50 binocular, is expected in the affected area of airborne AURA operation the minimum operational altitude of the Proteus [with the AURA laser active and the emitting light at a 20° degree forward angle and the Extended Ocular Hazard Distance (EOHD) is along the line of sight] is given as a function of emission characteristics as:

Minimum Operational Altitudes When 7x50 Binocular Use May Occur In the Affective Area of Airborne AURA Operation

Wavelength Range	Output (mJ)	EOHD (km)	Alt _{min} @ 20° (km)
UV	50	0.394	0.370
UV	60	0.432	0.406
IR	1.5	2.34	2.20
IR	2.0	2.7	2.54

Future Changes May Effect Laser Hazard Conditions

The laser hazard analysis presented here is valid for the current set of laser parameters and the expected flight conditions of the Proteus platform. Significant changes in the laser, the telescope system or the airborne platform will necessitate a laser safety review with a new laser hazard analysis.

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I. Introduction

The Sandia Remote Sensing System (SRSS) Airborne AURA laser is generally operated while the Proteus is airborne over an area of concern (target area). While the system is airborne, the cruising altitude is maintained so as to present a Class 1 laser hazard to personnel in the area affected by the airborne operation. For a typical operation the Proteus is at altitude of from 1 to 5 kilometers above ground level (AGL). The gimballed lidar system is designed to look forward by as much as 27 degrees (off of vertical) and be able to hold a point, locked on a target (until 27 degrees aft). During normal testing the Proteus can make up to four passes (over the target) per hour. Airborne operation is not expected to exceed 8 flight hours in a 24-hour period. The target area is strictly controlled and the use of viewing aids is prohibited.

The flash-lamp-pumped Nd:YAG laser manufactured by Big Sky Laser Technology (BSLT), is central to the LIDAR and produces two radiant outputs, one in the infrared (retinal hazard region) and one in the ultraviolet (corneal hazard region). The infrared (IR) output is used for “range-finding” and the ultraviolet (UV) output is used in “interaction measurements”. Each radiant output has a hazard distance associated with it. The hazard distances associated with unaided intrabeam viewing were determined and presented in a previous SAND report¹.

The laser may be operated with the emitted beam pointed forward while the Proteus is flying to (prior to target “lock-on”) and from the target area. For the current configuration of the Proteus the laser pointing is limited to $\pm 23^\circ$ fore/aft and $\pm 8^\circ$ port/starboard; however, before “target lock” during the cloud finding mode the forward looking angle is expected to be closer to 20° .

It is during the non-lock flight condition that the possibility exists that an unauthorized intrabeam aided viewing could occur. The existence of this aided viewing possibility requires a determination of the Extended Ocular Hazard Distance (EOHD) or the Safe Eye Exposure Distance (SEED) for intrabeam aided viewing of the airborne AURA LIDAR. Both the EOHD and the “SEED for aided viewing” are equivalent and interchangeable and are based on the Maximum Permissible Exposure (MPE) and the characteristics of the viewing aid. In general the viewing aid considered here is a 7x50 binocular because it is the primary viewing aid used by government agencies and the general public.

II. Big Sky Laser Parameters

Class 4 Laser:

Primary wavelength:	355 nm
Primary Radiant Output (typical):	50 mJ
Primary Radiant Output (maximum):	60 mJ
Secondary wavelength:	1064 nm
Secondary Radiant Output (typical):	0.5 mJ - 1.5 mJ
Secondary Radiant Output (maximum):	2 mJ
Pulse Width:	10 nanoseconds
Pulse Repetition Frequency:	30 Hz

System Telescope:

Beam Divergence:	500×10^{-6} radians
Exit Beam Diameter:	1.0 cm

Airborne Test Parameters

Operational Altitude Range	1 to 5 km
Point Angles	23° Forward to 23° Aft 8° Starboard to 8° Port
Typical Air Speed	90 Knots
Time on target (maximum)*	110 second
Target passes per hour (typical)	4
Flight time per 24-hours (typical)	8 hours (maximum)

**Dependent on Altitude and "Ground Speed"*

III. Appropriate Exposure

The MPE (derived for each to the three ANSI rules) is dependent on the exposure duration. Although *ANSI Std. Z136.1-2000 (Table 4a)* presents suggested exposures of: ten and 30,000 seconds for the IR and UV outputs respectively, the actual expected exposure is used in the MPE determination for the “aided viewing” hazard evaluation.

At the typical operational “ground speed” of 90-knots the Proteus aircraft (as it is flying to and from the target area), a ground observer whether or not using a viewing aid would at most (worst case condition) be exposed to one and only one laser pulse for each of the radiant outputs. (No aided viewing is allowing in the controlled area including target location of concern.)

In this case the appropriate exposure for both of the radiant outputs is “single pulse”.

It is assumed that this unauthorized aided viewing, single pulse exposure, would occur outside the controlled area and would be a unique occurrence that would not likely be repeated on the subsequent day.

IV. Maximum Permissible Exposure

A. UV Region ($180\text{ nm} < \lambda < 400\text{ nm}$)

The UV wavelength region from 180 nm to 400 nm is a “dual limit” region. The dual limits are comprised of the “**photochemical limit**” (the *left-hand* formula in *Table 5a* of the ANSI standard) and the “**thermal limit**” (the *right-hand* formula (notes) of *Table 5a* of the ANSI standard). The appropriate MPE is determined from the smallest value of these two limits [*ANSI Std. Z136.1-2000 (Table 5a)(notes)*].

Rule 1 (Single Pulse):

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

$$\begin{aligned}
\text{MPE}_{\text{s.p.}} &= \min [\text{photochemical limit, thermal limit}] && \{\text{Dual limit region}\} \\
&= \min [(0.56t^{0.25} \text{ J/cm}^2), \{0.56t^{0.25} \text{ J/cm}^2\}] && \{\text{Table 5a ANSI Std.}\} \\
&= 0.56 (10 \times 10^{-9})^{0.25} \text{ J/cm}^2
\end{aligned}$$

$$\text{MPE}_{\text{s.p.}} = 5.60 \times 10^{-3} \text{ J/cm}^2$$

Since it is assumed that this single pulse, aided viewing exposure is a unique occurrence with no subsequent or second day exposure, the single pulse MPE is not de-rated by a factor of 2.5 for successive day exposure.

B. MPE Determination For: The IR (1064 nm) Rangefinder

Infrared Region ($1050 \text{ nm} \leq \lambda < 1400 \text{ nm}$):

The fundamental wavelength of the Nd:YAG pump laser is 1064 nm. Although most of the IR pulse energy is used in the wavelength conversion to the third harmonic (355 nm) there is some energy “left over” at the fundamental wavelength. In the airborne AURA system, a small fraction of the residual 1064 nm light is retained in the output and is available to be used as a rangefinder pulse. The IR emission from the AURA system is expected to be about 1.5 millijoule (mJ) but could be as high as 2 mJ.

Rule 1 (Single Pulse):

The single pulse MPE form for a 10-nanosecond, 1064 nm laser pulse is given by *ANSI Std. Z136.1-2000 (Table 5a)* as:

$$\begin{aligned}
\text{MPE}_{\text{s.p.}} &= 5.0 C_c \times 10^{-6} \text{ J/cm}^2 && \left\{ \begin{array}{l} 1050 \text{ nm} \leq \lambda < 1400 \text{ nm} \\ 10^{-9} \text{ sec} \leq t < 50 \times 10^{-6} \text{ sec} \end{array} \right\}
\end{aligned}$$

$$\begin{aligned}
C_c &= 1.0 && \left\{ \begin{array}{l} \text{ANSI Std. Z136.1-2000 (Table 6)} \\ 1050 \text{ nm} \leq \lambda < 1150 \text{ nm} \end{array} \right\}
\end{aligned}$$

$$\text{MPE}_{\text{s.p.}} = 5.0 \times 10^{-6} \text{ J/cm}^2$$

Table 1

Single Pulse MPE

	Radiant Wavelength (nm)	MPE (J/cm ²)
UV	355	5.60 x 10 ⁻³
IR	1064	5.0 x 10 ⁻⁶

V. Nominal Ocular Hazard Distance

The nominal ocular hazard distance (NOHD) is the distance, line of sight, from the emitting source (laser) beyond which a Class 1 laser, “eye safe”, hazard exists. The NOHD applies to unaided intrabeam viewing only. The NOHD can be calculated by the formula presented in the appendix of the ANSI Standard.

$$NOHD = \frac{1}{\theta} \sqrt{\frac{4 \cdot Q}{\pi \cdot MPE}} - d_o^2 \quad cm$$

Where;

NOHD: Nominal Ocular Hazard Distance (in centimeters)

θ: Beam divergence (in radians)

Q: Radiant output (in joules)

MPE: Maximum Permissible Exposure (in joules/square centimeters)

d_o: Exit diameter of the laser (in centimeters)

A. Evaluation of the Single Pulse SEED for the UV output

1. Typical Operation (Q = 50 mJ):

$$NOHD_{50mJ} = \frac{1}{\left(500 \times 10^{-6}\right)} \sqrt{\frac{4 \cdot \left(50 \times 10^{-3} J\right)}{\pi \cdot \left(5.6 \times 10^{-3} J / cm^2\right)} - \left(1 cm\right)^2}$$

$$NOHD_{50mJ} = 6.44 \times 10^3 cm$$

$$NOHD_{50mJ} = 64.4 \text{ meters}$$

2. Maximum Output (Q = 60 mJ):

$$NOHD_{60mJ} = \frac{1}{\left(500 \times 10^{-6}\right)} \sqrt{\frac{4 \cdot \left(60 \times 10^{-3} J\right)}{\pi \cdot \left(5.6 \times 10^{-3} J / cm^2\right)} - \left(1 cm\right)^2}$$

$$NOHD_{60mJ} = 7.11 \times 10^3 cm$$

$$NOHD_{60mJ} = 71.1 \text{ meters}$$

B. Evaluation of the Single Pulse SEED for the IR output

1. Typical Operation (Q = 1.5 mJ):

$$NOHD_{1.5mJ} = \frac{1}{\left(500 \times 10^{-6}\right)} \sqrt{\frac{4 \cdot \left(1.5 \times 10^{-3} J\right)}{\pi \cdot \left(5.0 \times 10^{-6} J / cm^2\right)} - \left(1 cm\right)^2}$$

$$NOHD_{1.5mJ} = 39.0 \times 10^3 cm$$

$$NOHD_{1.5mJ} = 390 \text{ meters}$$

2. Maximum Output (Q = 2 mJ):

$$NOHD_{2mJ} = \frac{1}{\left(500 \times 10^{-6}\right)} \sqrt{\frac{4 \cdot \left(2.0 \times 10^{-3} J\right)}{\pi \cdot \left(5.0 \times 10^{-6} J / cm^2\right)} - \left(1 cm\right)^2}$$

$$NOHD_{2mJ} = 45.1 \times 10^3 cm$$

$$NOHD_{2mJ} = 451 \text{ meters}$$

The single pulse NOHD or SEED for both IR and UV emissions is given for typical and maximum outputs.

Table 2

**Single Pulse SEED Unaided Viewing
(No transmission factor adjustment)**

Wavelength (nm)	Pulse Energy (mJ)	SEED (meters)
355	50	64.4
355	60	71.1
1064	1.5	390
1064	2.0	451

C. Atmospheric Transmission Factor

For outdoor laser transmissions over distances less than 1 kilometer atmospheric transmission factors, generally, are not considered.

Atmospheric transmission factor is a function of the laser wavelength and the distance from the laser. If the atmospheric transmission factor is known the nominal ocular hazard distance can be estimated.

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

Where;

NOHD_{atm}: Nominal Ocular Hazard Distance atmospheric corrected

τ_{atm} : Atmospheric transmission f(wavelength, distance)

NOHD: Nominal Ocular Hazard Distance

VI. Extended Ocular Hazard Distance

The extended ocular hazard distance (EOHD) is similar to the NOHD but applies to intrabeam aided-viewing.

A. Aided Viewing

The use of optical aides such as a pair of 7x50 binoculars for intrabeam viewing will increase the viewing hazard by as much as the square of the magnifying power (optical gain) of the optical system [*ANSI Std. Z136.1-2000 (B6.4.3)*].

Increased Hazard

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

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

Where;

HAZ_↑: Represents the increased in the ocular hazard

MPE: Maximum Permissible Exposure

P: Magnifying Power

Optical Gain

The optical gain factor (G) represents the maximum increase in the ocular hazard of intrabeam viewing of the laser. In general, for a 7x50 binocular, for laser wavelengths in the retinal hazard region ($400 \text{ nm} \leq \lambda < 1.40 \text{ }\mu\text{m}$) with an assumed 100% optical transmission and the exit pupil is approximately equal to the limiting aperture ($D_{f(\text{visible})} = 7 \text{ mm}$) the optical gain (G) can be expressed as:

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

Where;

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

Maximum Gain

For example, a pair of (7x50) binoculars (viewing in the retinal hazard region) the maximum gain is:

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

Actual Gain

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

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

Where;

- G: Optical Gain
- P: Magnifying Power
- D_o: Diameter of objective optic
- D_e: Diameter of exit pupil
- τ_λ: Transmission factor of the optical system

Effective Gain

The effective optical gain is usually used when considering intrabeam aided viewing of laser sources at closer distances, where the collecting aperture is not necessarily the same as the diameter of the objective optic, generally in the retinal

hazard region; however, “the effective gain is useful for calculating the hazards for lasers with wavelengths outside the retinal hazard region ($302 \text{ nm} \leq \lambda_{\text{UV}} < 400 \text{ nm}$ and $1.4 \text{ }\mu\text{m} \leq \lambda < 2.8 \text{ }\mu\text{m}$) [ANSI Std. Z136.1-2000 (B6.4.3.2)]. The limiting aperture (diameter) in these wavelength regions are 3.5 mm for exposures of ten seconds or greater. For a single pulse (sub-microsecond) exposure in the UV region the limiting aperture is 1 mm [ANSI Std. Z136.1-2000 (Table 8)].

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

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

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

Where;

- G_{eff} : Effective Optical Gain.
- D_c : Diameter of collecting aperture.
- D_L : Diameter of laser beam at the viewing range from the laser
- D_f : Diameter of limiting aperture (ANSI Std. Z136.1-Table 8)
- τ_{λ} : Transmission factor of the optical system (ANSI Std. Z136.1-Table 9)

Collecting Aperture

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

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

Where;

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

B. UV Output

The following evaluation is for the case of single pulse intrabeam aided viewing of the airborne AURA laser UV output (355-nanometer) with a pair of (7x50) binoculars.

Evaluation for 7x50 Binoculars

Given;

P: 7 (7 x 50 binoculars)

D_o: 50 mm (7 x **50** binoculars)

D_f: 1 mm (for T < 0.3 seconds – *ANSI Z136.1 Table 8*)

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

$$= \min(50mm, 7 \cdot 1 \text{ mm})$$

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

$$D_c = 7 \text{ mm}$$

The effective optical gain for intrabeam aided viewing of the airborne AURA laser UV output using a pair of 7x50 binoculars can be determined as follows:

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

Where;

D_c: 7 mm (calculated above).

D_L: Diameter of laser beam at the collecting optic.

D_f: 1 mm [*ANSI Std. Z136.1-2000 (Table 8)*].

τ_λ: Transmission coefficient: 0.7 [*ANSI Std. Z136.1-2000 (Table 9)*].

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

$$D_L = d_o + \theta R$$

Where:

- D_L : Diameter of the laser beam at range, R.
- d_o : Exit diameter of the laser beam.
- θ : Beam divergence at the 1/e points.
- R: Distance from the laser.

The diameter of the laser beam as a function of the distance from the laser is always larger than the diameter of the collecting aperture in this case.

$$D_L = 10 \text{ mm} + (500 \times 10^{-6}) \cdot R > D_C = 7 \text{ mm}$$

$$D_C < D_L$$

In this case, the collecting aperture is always smaller than the beam diameter for all distances (R) from the laser.

1. Evaluation of the Effective Gain

For intrabeam aided viewing of the SRSS airborne AURA laser UV output the effective optical gain can be calculated from.

$$G_{eff} = \tau_\lambda \frac{D_c^2}{D_f^2}$$

The effective gain for a 7x50 binocular intrabeam viewing the SRSS airborne AURA laser at a distance where the laser beam is larger than the collecting aperture can be calculated as follows:

Given the following parameters:

- D_f : 1 mm [*ANSI Std. Z136.1-2000 (Table 8)*]
- D_c : 7 mm (Calculated previously for 7x50 binoculars)
- τ_λ : 0.7 [*ANSI Std. Z136.1-2000 (Table 9)*]

$$G_{eff} = (0.7) \frac{(7 \text{ mm})^2}{(1 \text{ mm})^2}$$

$$G_{eff} = 34.3$$

2. Evaluation of Increased Hazard

The increase in the ocular hazard for intrabeam aided viewing the airborne AURA laser UV output using a pair of (7 x 50) binoculars for a single pulse exposure over similar unaided interviewing is as follows.

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

3. Extended Ocular Hazard Distance Determination

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

The formula for calculating the EOHD is derived from the formula for the NOHD given in the Appendix of the *ANSI Std. Z136.1-2000* as follows, where MPE is replaced by the increased ocular hazard term ($HAZ_{\uparrow}$):

Recall;

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

Where;

NOHD: Nominal Ocular Hazard Distance, in centimeters.

θ : Beam divergence, in radians at the 1/e points.

Q_o : Output radiant energy, in joules.

MPE: Maximum Permissible Exposure, in joules/cm².

d_{out} : Output beam diameter of the laser, in centimeters.

The EOHD can be calculated as follows:

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

Where;

EOHD: Extended Ocular Hazard Distance, in centimeters.

θ : Beam divergence, in radians at the 1/e points.

Q_o : Output radiant energy, in joules.

$HAZ_{\uparrow}$: Increased ocular hazard, in joules/cm².

d_{out} : Output beam diameter of the laser, in centimeters.

4. EOHD for the UV output of the airborne AURA – Single Pulse Exposure

$$HAZ_{\uparrow} = \frac{MPE}{G_{eff}}$$

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

Simplified as;

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

As applied to the intrabeam viewing of the airborne AURA laser UV output with a pair of 7x50 binoculars for a single pulse exposure.

The EOHD for the intrabeam aided (single-pulsed) viewing of the airborne AURA at typical UV Output (50 mJ) with 7x50 binoculars:

$$EOHD_{UV(50mJ)} = \frac{1}{(500 \times 10^{-6})} \sqrt{\frac{(4) \cdot (34.3) \cdot (50 \times 10^{-3} J)}{\pi \cdot (5.6 \times 10^{-3} J/cm^2)} - (1 cm)^2}$$

$$EOHD_{UV(50mJ)} = 39.4 \times 10^3 cm$$

$$EOHD_{UV(50mJ)} = 394 \text{ meters}$$

The EOHD for the intrabeam aided (single-pulsed) viewing of the airborne AURA at maximum UV Output (60 mJ) with 7x50 binoculars:

$$EOHD_{UV(60mJ)} = \frac{1}{(500 \times 10^{-6})} \sqrt{\frac{(4) \cdot (34.3) \cdot (60 \times 10^{-3} J)}{\pi \cdot (5.6 \times 10^{-3} J/cm^2)} - (1 cm)^2}$$

$$EOHD_{UV(60mJ)} = 43.2 \times 10^3 cm$$

$$EOHD_{UV(60mJ)} = 432 \text{ meters}$$

Table 3

Single-Pulsed EOHD -The Airborne AURA UV Outputs

(Observed Intrabeam Through 7x50 Binoculars)

Q_o (mJ)	MPE (J/cm²)	G_{eff}	EOHD (meters)
50	5.6x10 ⁻³	34.3	394
60	5.6x10 ⁻³	34.3	432

5. EOHD for the IR output of the airborne AURA – Single Pulse Exposure

For the retinal hazard region (400 nm < λ < 1400 nm) the actual gain of the optical aid is used in the determination of the EOHD.

Actual Gain

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

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

Where;

- G: Optical Gain
- D_o: Diameter of objective optic
- D_e: Diameter of exit pupil
- τ_λ: Transmission factor of the optical system

The actual gain of the 7x50 binoculars to the AURA IR output is calculated as follows.

$$G = (0.7) \left[\frac{50mm}{7mm} \right]^2$$

$$G = 35.7$$

The EOHD for the airborne AURA IR Outputs can be calculated from:

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

The single-pulsed EOHD for the airborne AURA at the typical IR out of 1.5 mJ observed intrabeam with a 7x50 binocular:

$$EOHD_{IR(1.5mJ)} = \frac{1}{(500 \times 10^{-6})} \sqrt{\frac{(4) \cdot (35.7) \cdot (1.5 \times 10^{-3} J)}{\pi \cdot (5.0 \times 10^{-6} J/cm^2)} - (1cm)^2}$$

$$EOHD_{IR(1.5mJ)} = 234 \times 10^3 \text{ cm}$$

$$EOHD_{IR(1.5mJ)} = 2.34 \text{ km}$$

The single-pulsed EOHD for the airborne AURA at the typical IR out of 2 mJ observed intrabeam with a 7x50 binocular:

$$EOHD_{IR(2mJ)} = \frac{1}{(500 \times 10^{-6})} \sqrt{\frac{(4) \cdot (35.7) \cdot (2 \times 10^{-3} \text{ J})}{\pi \cdot (5.0 \times 10^{-6} \text{ J/cm}^2)} - (1 \text{ cm})^2}$$

$$EOHD_{IR(2mJ)} = 270 \times 10^3 \text{ cm}$$

$$EOHD_{IR(2mJ)} = 2.70 \text{ km}$$

Table 4

The Single-Pulsed EOHD - The Airborne AURA IR Outputs

(Observed Intrabeam With 7x50 Binoculars)

Q_o (mJ)	MPE (J/cm²)	G	EOHD (km)
1.5	5.0x10 ⁻⁶	35.7	2.34
2.0	5.0x10 ⁻⁶	35.7	2.70

The single pulse IR output, of the airborne AURA laser is the, “most hazardous” of the two. The maximum EOHD for the airborne AURA is derived from this “most hazardous” output and was calculated to be 2.7 kilometers

Table 5

Proteus Flight Characteristics

Typical Ground Speed (Proteus)	90 Kn (46.3 m/sec)
Operational Altitude	1 km to 5 km
Angular Range (forward to aft)	$\pm 20^\circ$

C. Minimum Operational Altitude

The minimum operational altitude of the Proteus aircraft with the laser active and light emitted can be determined by the EOHD and the flight and operational characteristics of the system.

Figure 1

Typical emission configuration of the airborne AURA cruising to and from the “target” area with laser emitted at a forward angle.

The minimum operational altitude (Alt_{min}) of the Proteus with the AURA laser active and emitting IR light to provide for Class 1 (eye safe) exposure for aided intrabeam viewing can be determined by the *EOHD* (presented in Table 4) and the expected forward emission angle (θ) as depicted in figure 1. Worst case forward angle is during cloud search ($\theta = 20^\circ$).

$$\cos(\theta) = \frac{Alt_{min}}{EOHD}$$

$$Alt_{min} = EOHD \cdot \cos(\theta)$$

$$Alt_{min} = EOHD \cdot \cos(20^\circ)$$

Table 6

Minimum Operational Altitudes

Wavelength Range	Output (mJ)	EOHD (km)	Alt_{min} @ 20° (km)
UV	50	0.394	0.370
UV	60	0.432	0.406
IR	1.5	2.34	2.20
IR	2.0	2.70	2.54

D. Review of the Exclusion Zone of the Proteus Aircraft.

The radiant output wavelengths of the airborne AURA are outside the visible spectrum as defined by *ANSI Std. Z136.1-2000**, *ANSI Std. Z136.6-2000†*, and *FAA7400.2D Chapter 34** and do not pose a visual interference (distraction, disruption, or disorientation) concern for aircrews in navigable air space. Startle, dazzle, flashblindness and glare concerns apply only to visible light and do not apply to invisible laser beams. The critical zone exposure distances (CZED) and the sensitive zone exposure distance (SZED) do not apply.

The NOHD and the EHOD for invisible, as well as visible, laser light applies in Normal Flight Zone (NFZ).

The Proteus minimum “ground speed” is 90 knots (46.3 m/sec). At the typical PRF of 30 hertz for the AURA (Big Sky) laser, the spatial separation between pulses is more than 1.5 meters.

Pupil Size and the Limiting Aperture

The normal human pupil size is on the order of 3 mm (in 70 year olds) to 5 mm (in 20 year olds) in daylight and >3 mm (in 70 year olds) to >9 mm (in 20 year olds) at night depending upon the age of the individual and the ambient light conditions; whereas, the limiting apertures listed in *ANSI Table 8* are **normalization factors** and are **not actual physical sizes**.

Worst Case

Given relative motion between the laser (Proteus) and an unknown observer (either on the ground or in another aircraft) an accidental exposure would entail no more than **at most one laser pulse**. The probability of an individual with a viewing aid being co-aligned at the correct viewing angle, spatial location and intrabeam with the airborne AURA laser during a ten nanosecond laser “on” event while the Proteus is traveling at 90 knots is extremely unlikely. Although the probability of an exposure is extremely unlikely, an exclusion zone about the Proteus, of at least the single pulse EOHD is required.

The single pulse EOHD or SEED for both IR and UV emissions is given Table 6 for typical and maximum outputs.

The largest SEED is for the IR emission at the maximum output (2 mJ), 2.7 kilometers (~8,860 feet).

The airspace exclusion zone (single-pulse hazard zone) about the airborne AURA laser, while in normal flight (to and from the target area) extends from the aircraft to ~7,910 feet below the Proteus and out to ~4,040 feet forward and out to ~8,660 feet to either side of the aircraft.

*Visible: $400 \text{ nm} \leq \lambda \leq 700 \text{ nm}$,

†Visible: $380 \text{ nm} \leq \lambda \leq 780 \text{ nm}$

VII. Conclusion

Under worst case conditions, the airborne AURA IR Rangefinder Operating at maximum output, the minimum operational altitude of the Proteus aircraft is **2.54** kilometers AGL in order to present a Class 1 (eye-safe) Hazard to aided intrabeam viewing on the ground with a 7x50 binoculars.

VIII. References

- (1) SAND2004-0413, Laser Hazard Analysis for Airborne AURA (Big Sky Variant) Proteus Platform
- (2) ANSI Std. Z136.1-2000: for Safe Use of Lasers, Published by the Laser Institute of America.
- (3) ANSI Std. Z136.6-2000: for Safe Use of Lasers Outdoors, Published by the Laser Institute of America.
- (4) FAA 7400.2D Chapter 34, Outdoor Laser/High Intensity Light Demonstrations

IX. Abbreviations

AEL	Allowable Emission (Exposure) Limit
AF	Air Force
AFRL	Air Force Research Laboratory
A_{lim}	Area of limiting aperture
ANSI	American National Standard Institute.
C_p	Multiple pulse correction factor.
CW	Continuous wave.
CZED	Critical Zone Exposure Distance
d_{aid}	Entrance diameter of optical aid.
d_{exit}	Exit diameter of the telescope.
d_{lim}	Diameter of limiting aperture.
d_o	Output beam diameter.
E	Irradiance, in J/cm^2 .
E_o	Output Irradiance, in J/cm^2 .
EOHD	Extended Ocular Hazard Distance.
H_p	Irradiance of the beam over the limiting aperture.
Hz	Hertz, cycle per second, sec^{-1} .
J	Joules, unit of energy.
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.
$MPE_{/pulse}$	Per Pulse Maximum Permissible Exposure.
$MPE_{m.p.}$	Multiple Pulse Maximum Permissible Exposure.
$MPE_{s.p.}$	Single Pulse Maximum Permissible Exposure.
mw	Milliwatts, 10^{-3} watts
NFZ	Normal Flight Zone
nm	Nanometer, 10^{-9} meters.
NOHD	Nominal Ocular Hazard Distance.
ns	Nanosecond, 10^{-9} seconds.
NHZ	Nominal Hazard Zone.
OD	Optical Density of the laser safety eye ware.
OD_{min}	Minimum Optical Density required of laser safety eyewear.

PRF	Pulse Repetition Frequency.
Q	Radiant Energy, in Joules.
Q _o	Output Radiant Energy, in Joules.
SEED	Safe Eye Exposure Distance
SZED	Sensitive Zone Exposure Distance
t	Exposure duration, pulse duration
t _b	Boundary time between photochemical and thermal limits
t _d	Dwell time.
T	Exposure duration, in seconds.
T _x	Cross-over time between ANSI Rule 3 and ANSI Rule 2
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.

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