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The Long Range Reconnaissance and Observation System (LORROS) with the Kollsman, Inc. Model LH-40, Infrared (Erbium) Laser Rangefinder Hazard Analysis and Safety Assessment

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The Long Range Reconnaissance and Observation System (LORROS) with the Kollsman, Inc. Model LH-40, Infrared (Erbium) Laser Rangefinder Hazard Analysis and Safety Assessment

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Abstract

A laser hazard analysis and safety assessment was performed for the LH-40 IR Laser Rangefinder based on the 2000 version of the American National Standard Institute's Standard Z136.1, *for the Safe Use of Lasers* and Z136.6, *for the Safe Use of Lasers Outdoors*. The LH-40 IR Laser is central to the Long Range Reconnaissance and Observation System (LORROS). The LORROS is being evaluated by the Department 4149 Group to determine its capability as a long-range assessment tool. The manufacture lists the laser rangefinder as "eye safe" (Class 1 laser classified under the CDRH Compliance Guide for Laser Products and 21 CFR 1040 Laser Product Performance Standard). It was necessary that SNL validate this prior to its use involving the general public. A formal laser hazard analysis is presented for the typical mode of operation.

Summary

The laser hazard analysis and safety assessment of the Kollsman, Inc. Model LH-40 Laser Rangefinder, used in the Long Range Reconnaissance and Observation System (LORROS), confirms that the operation of this system presents a **Class 1 Laser Hazard** (under ANSI Std. Z136.1, for the Safe Use of Lasers as well as under the CDRH Compliance Guide for Laser Products and 21 CFR 1040 Laser Product Performance Standard) and should be considered "**eye safe**" for both aided (7x50 binocular) as well as unaided intrabeam viewing and may be **used without restrictions**. The LH-40 Erbium Laser Rangefinder is not intended to operate in navigable air space (ground level surveillance). The radiant wavelength is outside the visible range (as defined in the various standards: *ANSI Standard Z136.1-2000*, *ANSI Standard Z136.6-2000* and *FAA Order 7400.2E-Chapter 29* and does not pose a startle, dazzle, flashblindness or glare concerns to air crews and has a NOHD of zero in the normal flight zone.

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I. Introduction

The Kollsman Inc, Model LH-40, Erbium Laser Rangefinder was designed as an eye safe (Class 1 Laser) system intended to be used without restrictions. The LH-40 Erbium Laser Rangefinder was classified as a Class 1 laser system under the Center for Device and Radiological Health (CDRH) Compliance Guide for Laser Products and 21 CFR 1040 Laser Product Performance Standard. Under current Department of Energy (DOE) contract Sandia National Laboratories is required that Class 1 lasers meet the classification criteria of *ANSI Standard Z136.1-2000* for the Safe Use of Lasers. It was desired to validate that the LH-40 Erbium Laser Rangefinder met the Class 1 criteria under the ANSI standard through a formal laser hazard analysis and safety evaluation prior to its operation in the LORROS being evaluated by Sandia National Laboratories, Department 4149, in area surveillance applications.

II. Laser Parameters

Kollsman, Inc.

Model:	LH-40
Type:	Erbium (Er^+)
Wavelength:	1540 nm
Pulse Energy Output:	8 mj
Pulse duration:	25 ns $\pm$ 10 ns
Pulse Repetition Rate (PRF):	1 sample (pulse) every 6 seconds
Exit beam diameter:	25 mm
Beam Divergence:	1 milliradians

III. Hazard Analysis

Maximum Permissible Exposure

The **maximum permissible exposure** (MPE) for a multiple pulse exposure is always the smallest of the MPE derived through the evaluation of ANSI Rule 1 through ANSI Rule 3 [*ANSI Std. Z136.1-2000 (8.2.3.2)*].

$$MPE = \min\ \left[MPE_{rule1},\ MPE_{rule2},\ MPE_{rule3}\right]$$

Rule 1 (Single Pulse)

The MPE is given in *Table 5a* of the *ANSI Std. Z136.1-2000*:

$$MPE = 1.0 \quad {}^{J}\!/_{cm^2} \qquad 1500\ nm < \lambda < 1800\ nm$$

$$1\times10^{-9}\ \sec \le t \le 10\sec$$

The single pulse MPE is:

$$MPE_{Rule1} = 1.0 \quad {}^{J}\!/_{cm^2} \qquad \textit{ANSI Std. Z136.1-2000 (8.2.3-Rule 1)}$$

Rule 2 (Average Power MPE)

$$MPE_{Rule2} = \frac{MPE_{CW}}{PRF} \qquad \textit{ANSI Std. Z136.1-2000 (8.2.3-Rule 2)}$$

The standard exposure time is given as 10 second [*ANSI Std. Z136.1-2000 (Table 4a)*]. In any 10-second exposure window, at most only two pulse events would occur (worst case).

The maximum PRF would be:

$$PRF = \frac{2\ \ pulses}{10\ \ \sec} = 0.2\ \ \sec^{-1}$$

$$MPE_{Rule2} = \frac{0.1 \ \ {watts}/{cm^2}}{0.2 \ \ \sec^{-1}}$$

$$MPE_{Rule2} = 500 \times 10^{-3} \ \ {J}/{cm^2}$$

Rule 3 (Multiple Pulse)

The ANSI Rule 3 MPE is the product of the ANSI Rule 1 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** (C_p) is given in *Table 6* of the *ANSI Std. Z136.1-2000*.

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

Where "n" is the number of pulses in the exposure (T).

$$n = PRF \cdot T$$

The standard exposure time is given as: 10 seconds [*ANSI Std.Z136.1-2000 (Table 4a)*]. As in the rule 2 evaluation the maximum PRF is used.

$$n = \left(0.2 \ \ \sec^{-1}\right) \cdot \left(10 \ \ \sec\right)$$

$$n = 2 \ \ pulses$$

The multiple-pulse correction factor is:

$$C_p = \left(2\right)^{-0.25}$$

$$C_p = 0.841$$

The rule 3 MPE is:

$$MPE_{Rule3} = (0.841)\cdot\left(1.0 \quad {}^{J}\!/_{cm^2}\right)$$

$$MPE_{Rule3} = 841\times10^{-3} \quad {}^{J}\!/_{cm^2}$$

Table 1

Appropriate MPE

ANSI Rule	MPE $\left({}^{J}\!/_{cm^2}\right)$	Comments
1	1.0	*
2	500×10^{-3}	Appropriate
3	841×10^{-3}	

* For the wavelength range: 1.5   m<   <1.8   m, only ANSI Rule 2 & 3 apply [*ANSI Std. Z136.1-2000 (8.2.3.3-NOTE)*]; although ANSI Rule 1 is needed in the determination of ANSI Rule 3

The Allowable Emission Limit

The class **Allowable Emission Limit** (AEL) is the highest emission a laser may have and still be considered to be a member of a particular laser hazard class. From the prospective of an observer the AEL may be considered an Allowable Exposure Limit. The Laser Hazard Class 1 AEL is defined as the product of the appropriate MPE and the area associated with the limiting aperture [*ANSI Std. Z136.1-2000 (3.2.3.4.1-(2))*] and is simply referred to as "AEL".

$$Class\ 1\ AEL \equiv MPE \times A_{\lim}$$

$$AEL = MPE \times \frac{\pi}{4}(d_{\lim})^2$$

The limiting aperture for this wavelength is listed as 3.5 mm (0.35 cm) [*ANSI Std. Z136.1-2000 (Table 8)*].

$$AEL = \left(500 \times 10^{-3}\ J/cm^2\right) \times \frac{\pi}{4}(0.35\ \ cm)^2$$

$$AEL = \left(500 \times 10^{-3}\ J/cm^2\right) \cdot \left(0.0962\ \ cm^2\right)$$

The Class 1 AEL is:

$$AEL = 48.1 \times 10^{-3}\ \ J$$

The aperture for laser classification at this wavelength is given as 25 mm for the time 10 seconds to 30,000 seconds [*ANSI Std. Z136.1-2000 (Table 9)*].

Class 1 Laser

A Class 1 laser has an output emission that is equal to or less than the Class 1 AEL [*ANSI Std. Z136.1-2000 (3.3.1.1)*].

$$Q_{LH-40} < AEL$$

$$8\ \ mJ < 48.1\ \ mJ$$

The LH-40 Erbium Laser Rangefinder radiant output energy was given in the owner's manual as: 8 mJ in a 25 mm diameter beam, which is less than the appropriate Class 1 AEL.

Class 1 laser operations are exempt from all control measures and other forms of surveillance [*ANSI Std. Z136.1-2000 (3.3.1.1)*].

The LH-40 Erbium Laser Rangefinder is an eye safe laser and can be used in the general public area without restrictions.

Eye Protection

Laser Safety Eyewear

Class 1 lasers are "eye safe" and laser safety **eyewear is not required** [*ANSI Std. Z136.1-2000 (3.3.1.1)*].

Nominal Ocular Hazard Distance

The **Nominal Ocular Hazard Distance** (NOHD) is the range (R_{NOHD}) to the Safe Eye Exposure Distance (SEED). This can also be considered the distance from the laser to the boundary of the **Nominal Hazard Zone** (NHZ) where the ocular threat is equal or greater than the skin damage threat. The NOHD is calculated using the formula presented in the appendix of *ANSI Std. Z136.1-2000*.

The NOHD of a Class 1 laser is: 0 cm.

The NOHD for the LH-40 Erbium Laser Rangefinder was evaluated to confirm a nominal hazard zone of zero centimeters.

$$R_{NOHD} = \frac{1}{\theta}\sqrt{\frac{4Q_o}{\pi\ MPE} - d^2}$$

Where:

- R_{NOHD} Nominal Ocular Hazard Distance, SEED = NHZ, in centimeters.
- θ Beam divergence, in radians.
- Q_o Radiance (Average Pulse Energy), in Joules.
- MPE Applicable per pulse Maximum Permissible Exposure-intrabeam viewing, in J/cm^2.
- d Beam diameter at the exit of the laser, in centimeters.

For the LH-40 Laser Rangefinder:

$$R_{NOHD} = \frac{1}{10^{-3}} \sqrt{\frac{4\left(8 \times 10^{-3}\, J\right)}{\pi \left(500 \times 10^{-3}\, J \big/ cm^2\right)} - \left(2.5\ cm\right)^2}$$

$$R_{NOHD} = \frac{1}{10^{-3}} \sqrt{\frac{32 \times 10^{-3} cm^2}{\pi \left(500 \times 10^{-3}\right)} - 6.25\ cm^2}$$

$$R_{NOHD} = \frac{1}{10^{-3}} \sqrt{0.0204\ cm^2 - 6.25\ cm^2}$$

Since then argument of the square root is:

$$0.0204\ cm^2 - 6.25\ cm < 0 \quad \Rightarrow \quad R_{NOHD} = 0.00\ cm$$

The argument of the radical (square root) is negative confirming that the NOHD is zero and the LH-40 laser rangefinder presents a Class 1 Laser Operation Hazard (eye safe) at the laser exit.

Extended Ocular Hazard Distance

The **extended ocular hazard distance** (*EOHD*) is similar to the *NOHD* but applies to intrabeam aided-viewing. The possibility of aided viewing by security personnel (with 7x50 binoculars) requires that the EOHD specific to the LH-40 Erbium Laser Rangefinder be evaluated to confirm that it presents a Class 1 Laser Hazard under aided viewing.

IV. 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)*].

Effective Gain

The **effective optical gain** (G_{eff}) is usually used when considering intrabeam aided viewing of laser sources at closer distances, where the collecting aperture is not necessarily the same as the diameter of the objective optic, generally in the retinal hazard region; however, "the effective gain is useful for calculating the hazards for lasers with **wavelengths outside the retinal hazard region** (302 nm $\leq \lambda_{UV} < 400$ nm and 1.4 μm $\leq \lambda <$ 2.8 μm)" [*ANSI Std. Z136.1–2000 (B6.4.3.2)*]. The limiting aperture (diameter) in these wavelength regions (like the LH-40 Erbium Laser Rangefinder) is 3.5 mm for exposures of ten seconds or longer.

For laser wavelengths in these regions (1.4 μm $\leq \lambda_{IR} <$ 2.8 μm) the hazard is to the cornea of the eye instead of to the retina.

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

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

Where;

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

Collecting Aperture

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

$$D_c = \min\left(D_o, P \cdot D_f\right)$$ (*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-Table 8*)

Evaluation for 7x50 Binoculars

LH-40 Erbium $(1.54\mu m)$ Laser Rangefinder:

The radiant output is in the corneal hazard region $(1.4\mu m \le \lambda_{1.54\mu m} < 2.8\mu m)$.

<u>Given</u>:

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

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

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

$$= \min(50mm,\ 24.5mm)$$

$$D_c = 24.5\ \ mm$$

The effective optical gain (G_{eff}) for intrabeam aided viewing of the LH-40 Erbium Laser Rangefinder using a pair of 7x50 binoculars can be determined as follows:

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

<u>Where;</u>

G_{eff}:	Effective optical gain
D_c:	24.5 mm (calculated above)
D_L:	Diameter of laser beam at the collecting optic
D_f:	3.5 mm [*ANSI Std. Z136.1-2000 (Table 8)*]
:	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.

$$D_L = d_o + \quad R$$

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

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

$$D_L = D_C = d_o + \theta R_C$$

$$R_c = \frac{(D_c - d_o)}{\theta}$$

$$R_c = \frac{(24.5\ mm - 25.0\ mm)}{10^{-3}}$$

$$R_c \approx 0\ mm$$

Evaluation of the Effective Gain

The collecting aperture (24.5 mm) is the appropriate aperture to use for evaluating the aided viewing of the LH-40 Erbium laser rangefinder.

For intrabeam aided viewing of the LH-40 Erbium laser rangefinder 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 viewing the LH-40 Erbium laser rangefinder can be calculated as follows:

Given the following parameters:

D_f:	3.5 mm [*ANSI Std. Z136.1–2000 (Table 8*)]
D_c:	24.5 mm (Calculated previously for 7x50 binoculars)
τ_λ:	0.7 [*ANSI Std. Z136.1–2000 (Table 9*)]
G_{eff}:	Effective gain

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

$$G_{eff} = 34.3 \qquad\qquad 1.4\mu m \leq \lambda \leq 2.8\mu m$$

Evaluation of the Extended Ocular Hazard Distance

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

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

The *EOHD* can be calculated as follows:

$$EOHD = \frac{1}{\theta}\sqrt{\frac{4 \cdot Q_o}{\pi\left(\dfrac{MPE}{G_{eff}}\right)} - d_{out}^2} \quad cm$$

Simplified as;

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

$$EOHD = \frac{1}{10^{-3}}\sqrt{\frac{(4)\cdot(34.3)\cdot\left(8\times10^{-3}\ J\right)}{\pi\cdot\left(500\times10^{-3}\ J/cm^2\right)} - (2.5\ cm)^2}$$

$$EOHD = \frac{1}{10^{-3}}\sqrt{0.699\ cm^2 - 6.25\ cm^2}$$

The argument of the radical is negative indicating that the EOHD is zero.

$$EOHD = 0\ cm$$

Class 1 lasers are considered to be incapable of producing hazardous conditions to the eyes or skin under unaided and optically aided conditions [*ANSI Std. **Z136.6-** 2000 (3.2.1)*].

The **LH-40 Laser Rangefinder is a Class 1 Laser Operation Hazard** (eye safe) for intrabeam aided viewing with 7x50 binoculars as well as for unaided viewing.

Use in Navigable Air Space

The radiant output wavelength of the LH-40 Erbium Laser Rangefinder is outside the visible spectrum as defined by *ANSI Std. Z136.1-2000**, *ANSI Std. Z136.6-2000*†, and *FAA Order 7400.2E Chapter 29** and **does no**t 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.

*Visible: 400 nm ≤ ≤ 700 nm

†Visible: 380 nm ≤ ≤ 780 nm

The NOHD for invisible as well as visible laser light applies in Normal Flight Zone (NFZ). The NOHD for the LH-40 Erbium Laser Rangefinder was shown to be zero (page 12). The LH-40 Erbium Laser Rangefinder is not intended to be used in navigable air space; although, it would be safe to do so

Conclusion

The radiant output energy, of the LH-40 Erbium Laser Rangefinder (central to the LORROS) at the maximum Pulse Repetition Frequency, distributed over the limiting aperture is less than the appropriate Class 1 Allowable Emission Limit and is therefore a Class 1 Laser Hazard and may be considered "eye safe". The LH-40 Erbium Laser Rangefinder was shown to be "eye safe" for both aided (7x50 binocular) as well as unaided intrabeam viewing and can be used without restrictions in operations involving the general public as well as security personnel. The LH-40 Erbium Laser Rangefinder is not intended to be operated in navigable air space; although, it would be safe to do so because it does not pose a startle, dazzle, flashblindness or glare concerns to air crews and the NOHD (applicable to normal flight zone) is zero.

Symbols and Abbreviations

A	Area (in cm^2).
A_{lim}	Area of the limiting aperture.
ANSI	American National Standard Institute.
C_A	Wavelength correction factor.
C_p	Multiple pulse correction factor
CZ	Critical Zone
D, d	Diameter.
D_c	Diameter of the collecting optic.
D_e	Diameter of the exit pupil.
D_f	Diameter of the limiting aperture.
D_L	Diameter of the laser beam.
d_{lim}	Limiting aperture *ANSI Z136.1 Table 8*.
d_o	Exit diameter of the laser.
D_o	Diameter of the objective optic.
EOHD	Extended optical hazard distance associated with aided viewing.
FHD	Flight Hazard Distance.
G	Optical gain.
G_{eff}	Effective optical gain.
LFZ	Laser Free Zone
min	Minimum value.
MPE	Maximum permissible exposure (J/cm^2 or w/cm^2).
$MPE_{appropriate}$	The appropriate maximum permissible exposure.
MPE_{rule1}	Maximum permissible exposure derived from ANSI Rule 1.
MPE_{rule2}	Maximum permissible exposure derived from ANSI Rule 2.
MPE_{rule3}	Maximum permissible exposure derived from ANSI Rule 3.
MPE_T	The maximum permissible exposure for the exposed duration T.
$MPE_{thermal}$	The MPE derived from the thermal limit.
n	Number of pulses.
NFZ	Normal Flight Zone.
NOHD	Nominal ocular hazard zone.
P	Magnification power.
PRF	Pulse repetition frequency.

Q	Radiant energy (in joules).
Q_o	Output radiant energy.
R	Range, distance from the laser
R_c	Distance from the laser where the beam diameter is equaled to the collecting aperture.
SZ	Sensitive Zone
T	Time (in seconds).
t	Duration (in seconds).
t_{min}	The maximum exposure time for the MPE equaled to that of 1 ns.
	Radiant power (in watts).
	Transmission.
	Transmission as a function of wavelength.
	Wavelength.

References

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

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

FAA Order 7400.2E Chapter 29: Outdoor Laser Operations

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