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Frequency Agile Laser Safety & Hazard Analysis for the Sandia Remote Sensing System LIDAR

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Abstract

A laser safety and hazard analysis was performed for the Raytheon Frequency Agile Laser (FAL) to be used with the Sandia Remote Sensing System (SRSS) B-70 Trailer based on the 2007 version of the American National Standards Institute's (ANSI) Standard Z136.**1**, *for Safe Use of Lasers* and the 2005 version of the ANSI Standard Z136.**6**, *for Safe Use of Lasers Outdoors*. The B-70 SRSS LIDAR system is a portable platform, which is used to perform *laser interaction* experiments and tests at various national test sites.

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Safety Summary

FAL CO2 LIDAR

Inside B-70 (before beam expanding telescope)	Outside (After Expansion to 4” diameter)
$OD_{\min} = 3.56 \ @ \ 9.2\mu m - 10.7\mu m$	“Eye Safe”

I. Introduction

The Hughes Aircraft Company Frequency Agile Laser (FAL) is a repetitively pulsed Class 4, closed cycle, TEA, carbon dioxide laser which is tunable from 9.2 microns to 10.7 microns, whose output is programmable to wavelength scan through specific selected wavelengths during laser runs.

II. Laser Parameters

Table 1

Laser Class	4
Wavelength	9.2 μm to 10.7 μm
Output Pulse Energy (maximum)	200 mJ
Pulse Width (Full Width at Half Power Points)	~200 ns*
Pulse Repetition Frequency (PRF)	20 Hz
Exit at the laser	~1 cm
Exit from telescope	10 cm
Beam Divergence ($1/e^2$ points) full angle	0.5 mR after beam expansion

* Measure at the "half-power' points.

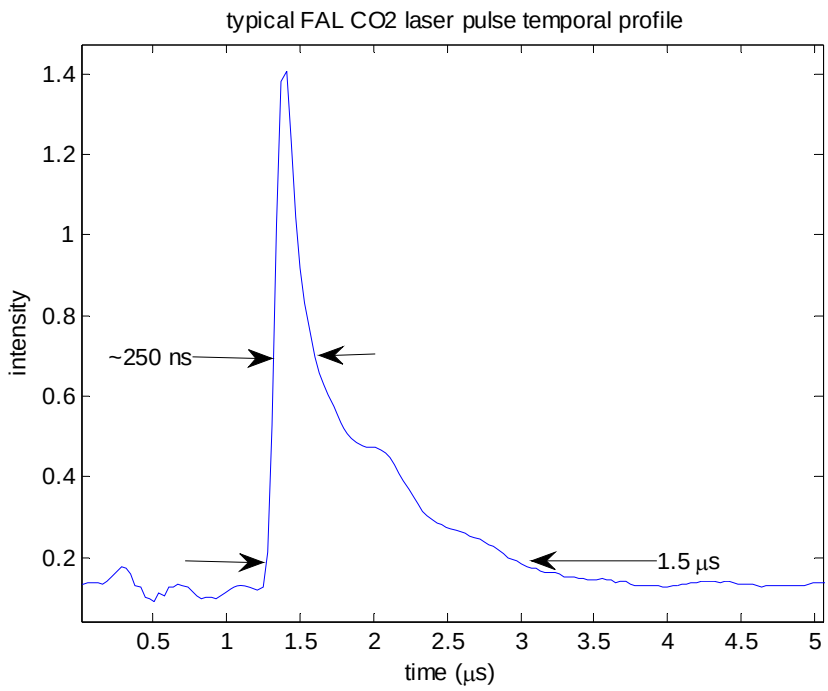

Figure 1

A typical FAL CO2 laser pulse temporal profile.

III. Hazard Analysis

The **Maximum Permissible Exposure** (MPE) for a multiple pulse exposure is always the smallest of the MPE determined by the application of ANSI Rule 1 through 3 [*ANSI Std. Z 136.1-2007 (8.2.3)*]. The MPE presented in *ANSI Std. Z136.1-2007 (Table 5a)* for 2.6 to 1000 micron laser exposures of 100 nanoseconds to 10 seconds is the **thermal limit** and is a function of the pulse duration.

$$MPE = 0.56 \cdot t^{0.25} \, J/cm^2$$

The temporal profile of the FAL pulse, Figure 1, is to a degree dominated by the "**gain switch spike**" (*GSP*) region. Using a planimeter to measure the "area under the curve" and then comparing the area under the gain switch region to the area of the entire pulse event it was found that ~45.3 % of the pulse energy was contained in the gain switch region.

For the purpose of laser hazard analysis the **pulse duration** (t) is defined at the "**half-power" points** [*ANSI Std. Z136.1-2007 (8.2.2)*]. With reference to Figure 2 the half-power points are within the gain switch region. The pulse duration for **Full Width at Half Maximum** (FWHM) was measured at the half of maximum intensity points and was on the order of 200 nanoseconds (~201 ns).

$$t = t_{FWHM} = 201 \times 10^{-9} \text{ sec}$$

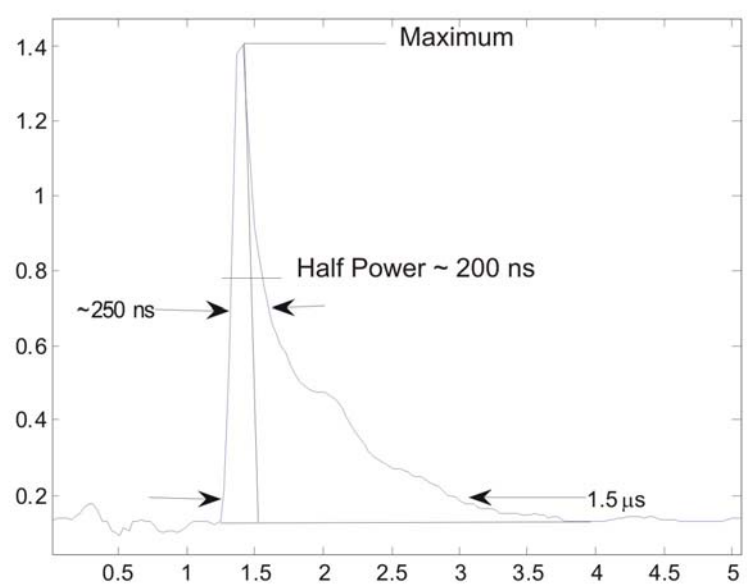

Figure 2

A typical FAL CO2 laser pulse temporal profile with 'half-power' points to determine the appropriate pulse duration for the laser hazard analysis.

Gain Switch Region

ANSI Rule 1 (Single Pulse)

No single pulse in a train of pulses can exceed the single pulse MPE [*ANSI Std. Z136.1-2007 (8.2.3 – Rule 1)*].

$$MPE_{Rule1} = 0.56 \cdot t^{0.25} \; J/cm^2$$

$$= 0.56 \cdot \left(201 \times 10^{-9}\right)^{0.25} \; J/cm^2$$

$$MPE_{Rule1} = 11.9 \times 10^{-3} \; J/cm^2$$

ANSI Rule 2 (Average Power Thermal)

The appropriate MPE for Rule 2 is the MPE for the limiting exposure distributed over the number of laser pulses produced during the limiting exposure [*ANSI Std. Z136.1-2007 (8.2.3 – Rule 2)*].

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

The appropriate **limiting exposure** (T) is given in *ANSI Std. Z136.1-2007 (Table 2)* as **10 seconds** for this wavelength region. The number of laser pulses produced in the limiting exposure is the product of the limiting exposure (T) and the **Pulse Repetition Frequency** (PRF).

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

$$= \frac{0.56 \cdot \left(10^{0.25}\right) \; J/cm^2}{\left(20 \;\; \sec^{-1}\right) \cdot \left(10 \;\; \sec\right)}$$

$$MPE_{Rule2} = 4.98 \times 10^{-3} \; J/cm^2$$

ANSI Rule 3 (Multiple Pulse – Thermal Hazard)

No single pulse in a pulse train can exceed the product of the single pulse MPE and the multiple-pulse correction factor $\left(C_p\right)$ [*ANSI Std. Z136.1-2007 (8.2.3 – Rule 3)*]. ANSI Rule 3 for multiple pulse exposures applies to the thermal limit only.

$$MPE_{Rule3} = C_p \cdot MPE_{Rule1}\left(thermal\right)$$

$$= \left(n^{-0.25}\right) \cdot 0.56 \cdot t^{0.25} \, J/cm^2$$

$$= \left(200^{-0.25}\right) \cdot 0.56 \cdot \left(201 \times 10^{-9}\right)^{0.25} \, J/cm^2$$

$$MPE_{Rule3} = 3.15 \times 10^{-3} \, J/cm^2$$

Appropriate MPE

Table 2

MPE – GSP

ANSI Rule	MPE $\left(J/cm^2\right)$	Comment
1	11.9×10^{-3}	
2	4.98×10^{-3}	
3	3.15×10^{-3}	smallest

Long Pulse

Whereas approximately 45 percent of the pulse energy is delivered in the gain switch region the entire pulse energy is delivered in approximately 1.5 microseconds.

ANSI Rule 1

$$\begin{aligned} MPE_{Rule1} &= 0.56 \cdot t^{0.25} \, J/cm^2 \\ &= 0.56 \cdot \left(1.5 \times 10^{-6}\right)^{0.25} \, J/cm^2 \\ MPE_{Rule1} &= 19.6 \times 10^{-3} \, J/cm^2 \end{aligned}$$

ANSI Rule 2

$$\begin{aligned} MPE_{Rule2} &= \frac{MPE(T)}{PRF \cdot T} \\ &= \frac{0.56 \cdot \left(10^{0.25}\right) J/cm^2}{\left(20 \ \sec^{-1}\right) \cdot \left(10 \ \sec\right)} \\ MPE_{Rule2} &= 4.98 \times 10^{-3} \, J/cm^2 \end{aligned}$$

ANSI Rule 3

$$\begin{aligned} MPE_{Rule3} &= C_p \cdot MPE_{Rule1}(thermal) \\ &= \left(n^{-0.25}\right) \cdot 0.56 \cdot t^{0.25} \, J/cm^2 \\ &= \left(200^{-0.25}\right) \cdot 0.56 \cdot \left(1.5 \times 10^{-6}\right)^{0.25} \, J/cm^2 \\ MPE_{Rule3} &= 5.21 \times 10^{-3} \, J/cm^2 \end{aligned}$$

Table 3

MPE – Long Pulse

ANSI Rule	MPE $\left(J/cm^2\right)$	Comment
1	19.6×10^{-3}	
2	4.98×10^{-3}	smallest
3	5.21×10^{-3}	

IV. Safety Calculations

Laser Safety Eyewear

The **minimum Optical Density** $(OD_{\min})$ required of the laser safety eyewear is derived from the *ANSI Std. Z136.1-2007 (Equation B98)*. The incident pulse energy is distributed of the limiting area derived from the limiting aperture (D_f).

$$OD_{\min} = \log\left[\frac{H_0}{MPE}\right] = \log\left[\frac{Q_o / A_{\lim}}{MPE}\right] = \log\left[\frac{Q_o}{A_{\lim} \cdot MPE}\right]$$

The appropriate limiting aperture is given in *ANSI Std. Z136.1-2007 (Table 8b)* for the limiting exposure of 1 to 300 nanoseconds (Rule 1 & 3) as: 1 mm.

The minimum OD for exposure to the **GSP region** is calculated for 45.3% of the pulse energy delivered over the GSP exposure.

$$OD_{\min}(GSP) = \log\left[\frac{(0.453)\cdot\left(200\times10^{-3}\,J\right)}{\left(\frac{\pi}{4}\right)\cdot(0.1\ cm)^2\cdot\left(3.15\times10^{-3}\ J/cm^2\right)}\right]$$

$$OD_{\min}(GSP) = 3.56$$

The appropriate limiting aperture for the **long pulse exposure** given in *ANSI Std. Z136.1-2007 (Table 8b)* for the limiting exposure of 10 seconds (Rule 2) as: 3.5 mm.

$$OD_{\min}(LP) = \log\left[\frac{\left(200\times10^{-3}\,J\right)}{\left(\frac{\pi}{4}\right)\cdot(0.35\ cm)^2\cdot\left(4.98\times10^{-3}\ J/cm^2\right)}\right]$$

$$OD_{\min}(LP) = 2.62$$

The minimum OD for the laser safety eyewear for full protection against the unexpanded laser output is driven by the gain switch region:

$$OD_{\min} = 3.56\ @\ 9.2\mu m - 10.7\mu m$$

Nominal Ocular Hazard Distance (Outdoor)

The beam is expanded to approximately 10 cm diameter with 500-microradian beam divergence by a beam expanding telescope prior to exiting the platform housing.

The Nominal Ocular Hazard Distance $(NOHD)$ from the laser can be calculated using the range equation [*ANSI Std. Z136.1-2007 (Equation 51)*].

$$r_{NOHD} = \left(\frac{1}{\theta}\right) \cdot \sqrt{\frac{4 \cdot Q_o}{\pi \cdot MPE} - a^2}$$

Gain Switch Region

$$r_{NOHD}(GSP) = \left(\frac{1}{500 \times 10^{-6}}\right) \cdot \sqrt{\frac{4 \cdot (0.453) \cdot \left(200 \times 10^{-3}\ J\right)}{\pi \cdot \left(3.15 \times 10^{-3}\ J/cm^2\right)} - (10\ \ cm)^2}$$

$$= \left(\frac{1}{500 \times 10^{-6}}\right) \cdot \sqrt{36.6\ \ cm^2 - 100\ \ cm^2}$$

$$= \left(2 \times 10^3\right) \cdot \sqrt{-63.4\ \ cm^2} \Rightarrow 0^*$$

$$r_{NOHD}(GSP) = 0.00$$

The FAL radiance exiting the beam expanding telescope is "**eye safe**" because the radiant exposure at the telescope exit is less than the MPE.

Long Pulse

$$r_{NOHD}(LP) = \left(\frac{1}{500 \times 10^{-6}}\right) \cdot \sqrt{\frac{4 \cdot \left(200 \times 10^{-3}\ J\right)}{\pi \cdot \left(4.98 \times 10^{-3}\ J/cm^2\right)} - (10\ \ cm)^2}$$

$$= \left(\frac{1}{500 \times 10^{-6}}\right) \cdot \sqrt{51.1\ \ cm^2 - 100\ \ cm^2}$$

$$= \left(2 \times 10^3\right) \cdot \sqrt{-48.9\ \ cm^2} \Rightarrow 0$$

$$r_{NOHD}(LP) = 0.00\ \ cm$$

The FAL exit beam is **eye safe** for the long pulse as well as the gain switch pulse region.

V. Conclusions

Whereas the FAL CO2 laser beam presents an ocular hazard to laser personnel inside the B-70 LIDAR platform, it does not present an ocular hazard (eye safe) to personnel outside the B-70 LIDAR platform after the beam has been expanded by the exit telescope.

Personnel inside the Laser Hazard Area (inside B-70) are required to don laser safety eyewear with:

$$OD_{\min} = 3.56 \ @ \ 9.2\mu m - 10.7\mu m$$

VI. References

1 ANSI Standard Z136.1–2007: for Safe Use of Lasers, Published by the Laser Institute of America.

2 ANSI Standard Z136.6–2005: for Safe Use of Lasers Outdoors, Published by the Laser Institute of America.

VII. Symbols and Abbreviations

a	Laser Diameter
A_{lim}	Area of limiting aperture
ANSI	American National Standards Institute
cm	Centimeter
C_p	Multiple-pulse correction factor
CW	Continuous wave
D_f	Diameter of limiting aperture
H	Radiant Exposure (J/cm^2)
Hz	Hertz, cycle per second, sec^{-1}
J	Joules, unit of energy
LIDAR	LIght Detection And Ranging
mJ	Millijoule, 10^{-3} Joules
MPE	Maximum Permissible Exposure
MPE_{Rule1}	MPE derived by ANSI Rule 1
$MPE_{Rule\ 2}$	MPE derived by ANSI Rule 2
$MPE_{Rule\ 3}$	MPE derived by ANSI Rule 3
n	Number of pulses
NHZ	Nominal Hazard Zone
nm	Nanometer, 10^{-9} meters
NOHD	Nominal Ocular Hazard Distance
ns	Nanosecond, 10^{-9} seconds
OD	Optical Density of the laser safety eyewear
OD_{min}	Minimum Optical Density required of laser safety eyewear
PRF	Pulse Repetition Frequency (sec^{-1})
Q	Radiant Energy, in Joules
t	Exposure duration, pulse duration or pulse-width
T	Limiting Exposure (seconds)
θ	Beam divergence

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