# *SHOALS Public Laser Safety*

The SHOALS program is designed around the safe operation of the airborne laser system. All aspects of the laser operation fall under the American National Standards Institute (ANSI) Z136.1-1993. Prior to field trials and operation in 1994, The U.S. Army Environmental Hygiene Agency at Aberdeen Proving Ground, Maryland validated and published the attached report (#25-42-D776-93 ) identifying SHOALS' ability to perform the required assignments without endangering the public.

*In-place safety practices have provided 6 years of accident free operation and are continuously monitored.*

*A Laser Safety Officer is assigned to the field team.*

*All field personnel are required to complete initial baseline eye examinations prior to field assignments.* Medical surveillance programs include annual eye re-examinations.

*Safety briefing and training for all active field personnel prior to laser operations, both airborne and ground based testing.*

*A Pilot Pause Switch in the front cockpit for temporarily disabling the laser. The switch is designed to allow the pilots to utilize their forward-looking ability to assess and minimize risks to the public.*

*The SHOALS airborne software is equipped with built-in "switched" that predetermine the lowest altitude for operating the laser based on the flightplanned altitude vs. beam divergence. The software disables the laser if the platform goes below the pre-determined altitude.*

*Recent hardware upgrades have not changed the safety margins designed into the airborne system.*

*System operational parameters are continually monitored and re-evaluated to ensure continued safe operations.*

SHOALS Laser Specifications

| Property | Value |
|---|---|
| Wavelength | 532 & 1064 nm |
| Pulse Freq | 400 Hz |
| Pulse Energy | >5 mJ Total (532 + 1064 nm) |
| | <6 mJ Green (532 nm stand alone) |
| Type | ND:Yag |

Laser Hazards - Eye & Skin

Class 4 laser WILL cause eye damage if viewed directly or indirectly from close up. Minimal safe distances during firing is >50 meters

# SHOALS LASER SAFETY

- **Definition**
  - **Light Amplification by Stimulated Emission of Radiation**
  - **A device that produces and amplifies light**
  - **SHOALS Bathymeter Laser**
    - **Hazard classification:**
      - **The ability of the primary laser beam or reflected primary laser beam to cause biological damage to the eye or skin during intended use.**
    - **Class IV category**
      - **High power**
      - **Biological damage**
      - **Potential for fire**
      - **Potential for laser generated air contaminants**
    - **ND:Yag – Solid State**
      - **NeoDymium Doped Crystal Yttrium Aluminum Garnet**
    - **KTP**
      - **Potassium Titanyl Phosphate (KTiPO$P_4$ or KTP)**
      - **Used in ND:Yag systems for frequency doubling**
      - **1064 nm to 532 nm**
    - **Old Big Sky Laser: 20 mjules / 5 watt potential**
      - **200 Hz or 200 pulses per second**
    - **Newer CEO Laser: 10 mjules / 2.5 watt optimal**
      - **400 Hz or 400 pulses per second**
- **Most outstanding aspects of solid state lasers**
  - **Output is not continuous – increased output power vs. initial power**
    - **Pulsed energy / pulse width = 625 kWatts Green Peak Power**
    - **Pulsed energy / pulse repetition = 2 Watts Green Average Power**
- **Laser hazards**
  - **Intra-Beam: Direct eye exposure to the beam**
    - **Avoid walking in the beam path**
    - **Wear goggles at all times**
  - **Diffuse: In-direct exposure to the beam (reflected off of objects in the beam path)**
    - **Keep beam path clear of objects reflecting the beam**
    - **Wear goggles at all times**
- **Nominal Hazard Zone (NHZ)**
  - **Intra-Beam**
    - **6 mrad = 337 meters**
    - **8 mrad = 225 meters**
    - **12 mrad = 169 meters**
  - **Diffuse**
    - **6 mrad = 1 meter**
    - **8 mrad = 1 meter**
    - **12 mrad = 1 meter**
- **Laser protection**

- **Safety protocols**
    - **Ground based operations**
        - **Keep people at least 50 feet away during the day**
        - **Keep people at least 75-100 feet away at night**
        - **During hard target testing; keep path to target and area 45$^{o}$ to either side clear**
        - **Use curtain for energy measurements**
        - **Man pause switch during entire process**
            - **Clear unobstructed view of area**
            - **No other duties**
        - **Big Red button on front panel of LEU for quick termination of laser activity**
    - **Airborne operations**
        - **Software monitoring of altitude vs. beam divergence**
            - **Smaller beam divergence requires higher altitudes**
        - **Pilots pause switch, their forward looking position allows better anticipation of hazards.**
        - **No overflies of heavily populated areas**
        - **Big Red button on front panel of LEU for quick termination of laser activity**
- **Non-Beam Hazards**
    - **High Voltage**
    - **Glycol**
    - **Methynol**
    - **Acetone**
    - **NO2**
- **Laser Accident Summaries**
    - **Past decade:**
        - **28% due to Alignment**
        - **16% due to improper eye wear or eye wear failure**
        - **16% due to high voltage**

- **Closure**
    - **Primary tool for safe operations is and always will be attention to the process, environment and people**.

- **Goggles**
  - **Full protection**
  - **Alignment**
- **Pause switch**
  - **Push to pause, easy motion**
  - **Pull to make, thought required**
  - **Curtains**

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | **Wavelegnth:** | **Pulse Energy:** | **Pulse Duration** | **Average Laser Power (J*hz)** | **Pulse Rep Rate** | **Initial Beam Diameter** | **Nominal Operational Divergance** | **Nominal Operational Altitude** | **Exposure Duration** | **MPE: Ocular Exposure (Table 5.)** | **NOHD: Nominal Ocular Hazard Distance** | **Diffuse Reflection NHD** | | | | |
| 2 | *(nanometers, nm)* | *(Joules, J)* | *(Seconds, s)* | *(Watts, W)* | *(hertz, hz)* | *(meters, m)* | *(Radians, rad)* | *(meters, m)* | *(seconds, s)* | *(J/cm-2)* | *(meters, m)* | *(meters, m)* | | | | |
| 3 | 532 | 4.00E-03 | 6.50E-09 | 1.60 | 400 | 2.31E-03 | 6.00E-03 | 400 | 6.50E-09 | 5.00E-07 | 336.42 | 0.73 | | | | |
| 4 | 1064 | 6.00E-03 | 1.21E-08 | 2.40 | 400 | 2.31E-03 | 6.00E-03 | 400 | 1.21E-08 | 5.00E-06 | 130.29 | 0.28 | | | | |
| 5 | 532 | 4.00E-03 | 6.50E-09 | 1.60 | 400 | 2.54E-03 | 9.00E-03 | 300 | 6.50E-09 | 5.00E-07 | 224.28 | 0.73 | | | | |
| 6 | 1064 | 6.00E-03 | 1.21E-08 | 2.40 | 400 | 2.54E-03 | 9.00E-03 | 300 | 1.21E-08 | 5.00E-06 | 86.86 | 0.28 | | | | |
| 7 | 532 | 4.00E-03 | 6.50E-09 | 1.60 | 400 | 2.77E-03 | 1.20E-02 | 200 | 6.50E-09 | 5.00E-07 | 168.21 | 0.73 | | | | |
| 8 | 1064 | 6.00E-03 | 1.21E-08 | 2.40 | 400 | 2.77E-03 | 1.20E-02 | 200 | 1.21E-08 | 5.00E-06 | 65.15 | 0.28 | | | | |
| 9 | 532+1064 | 1.00E-02 | 1.21E-08 | 4.00 | 400 | 2.77E-03 | 1.20E-02 | 200 | 1.21E-08 | 1.09E-06 | 180.38 | 0.78 | | | | |
| 10 | | | | | | | | | | | | | | | | |
| 11 | | | | | | | **Big Sky Laser** | | | | | | | | | |
| 12 | 532 | 5.00E-03 | 6.00E-09 | 1.00 | 200 | 2.77E-03 | 1.20E-02 | 200 | 5.00E-09 | 5.00E-07 | 132.98 | 0.58 | | | | |
| 13 | 1064 | 1.50E-02 | 9.00E-09 | 3.00 | 200 | 2.77E-03 | 1.20E-02 | 200 | 5.00E-09 | 5.00E-06 | 72.84 | 0.32 | | | | |
| 14 | 532+1064 | 2.00E-02 | 6.00E-09 | 4.00 | 200 | 2.77E-03 | 1.20E-02 | 200 | 5.00E-09 | 1.54E-06 | 151.62 | 0.66 | | | | |
| 15 | **scan patern #** | **altitude** | **swath width** | **lateral spacing** | **forward spacing** | **beam divergance** | **planned speed** | **scanner frequency** | | **ANSI Z136.1 Table 5 Maximum Permissible Exposure (MPE) for Ocular Exposure** | | | **MPE: Skin Exposure** | **ANSI Z136.1 Table 7** | | |
| 16 | | *(meters, m)* | *(meters, m)* | *(meters, m)* | *(meters, m)* | *(milliradians, mrad)* | *(meters/second, m/s)* | *(hertz, hz)* | | Wavelength (um) | Exposure Duration | MPE | *(J/cm-2)* | Wavelength (um) | Exposure Duration | MPE |
| 17 | 2 | 300 | 110 | 4 | 4 | 9 | 53.4976 | 6.71 | | 0.532 | $10^{-9}$ to 18E-6 | 5.00E-07 | **2.00E-02** | 0.532 | $10^{-9}$ to $10^{-7}$ | 0.02 |
| 18 | 3 | 400 | 220 | 6 | 6 | 6 | 74.588 | 4.66 | | 0.532 | 18E-6 to 10 | 1.30E-09 | **1.00E-01** | 0.532 | $10^{-7}$ to 10 | $1.1C_A*t^{0.25}$ |
| 19 | 4 | 400 | 110 | 4 | 4 | 6 | 54.5264 | 6.85 | | 0.532 | 10 to $10^4$ | 1.00E-02 | **2.00E-02** | 0.532 | 10 to 3E4 | 0.20 |
| 20 | 5 | 400 | 220 | 7 | 7 | 6 | 86.9336 | 5.44 | | 1.064 | $10^{-9}$ to 50E-6 | 5.00E-06 | **1.00E-01** | 1.064 | $10^{-9}$ to $10^{-7}$ | 0.10 |
| 21 | 6 | 200 | 110 | 3 | 3 | 12 | 37.0368 | 4.66 | | 1.064 | 50E-6 to $10^3$ | 3.99E-27 | **2.00E-02** | 1.064 | $10^{-7}$ to 10 | $1.1C_A*t^{0.25}$ |
| 22 | 7 | 300 | 82 | 3 | 3 | 9 | 48.3536 | 6.85 | | | | | **1.00E-01** | 1.064 | 10 to 3E4 | 1.00 |
| 23 | | | | | | | | | | | | | **4.17E-02** | 532+1064 | | |
| 24 | Beam divergance scale | | | | | | | | | | | | | | | |
| 25 | *mrad* | *meters* | | | | | | | | | | | | | | |
| 26 | 1.50E-02 | 3.00E-03 | | | | | | | | | | | | | | |
| 27 | 1.40E-02 | 2.92E-03 | | | | | | | | | | | | | | |
| 28 | 1.30E-02 | 2.85E-03 | | | | | | | | | | | | | | |
| 29 | 1.20E-02 | 2.77E-03 | | | | | | | | | | | | | | |
| 30 | 1.10E-02 | 2.69E-03 | | | | | | | | | | | | | | |
| 31 | 1.00E-02 | 2.62E-03 | | | | | | | | | | | | | | |
| 32 | 9.00E-03 | 2.54E-03 | | | | | | | | | | | | | | |
| 33 | 8.00E-03 | 2.46E-03 | | | | | | | | | | | | | | |
| 34 | 7.00E-03 | 2.38E-03 | | | | | | | | | | | | | | |
| 35 | 6.00E-03 | 2.31E-03 | | | | | | | | | | | | | | |
| 36 | 5.00E-03 | 2.23E-03 | | | | | | | | | | | | | | |
| 37 | 4.00E-03 | 2.15E-03 | | | | | | | | | | | | | | |
| 38 | 3.00E-03 | 2.08E-03 | | | | | | | | | | | | | | |
| 39 | 2.00E-03 | 2.00E-03 | | | | | | | | | | | | | | |
| 40 | | | | | | | | | | | | | | | | |
| 41 | | | | | | | | | | | | | | | | |

**Formula for column D**

$$\Phi_{av} = Q_p * PRF$$

**Formula for Column L**

$$\sqrt{\left(\frac{s*\Phi_{av}*Cos(0^0)}{p*MPE}\right)}$$

**Formula for column K**

$$\frac{1}{f}\sqrt{\left(\left(\frac{4*\Phi}{p*MPE}\right)-a^2\right)}$$

$Q_p$ = Column B

$\Phi_{av}$ =Column D

$f$ =Column G

**a** = Column F

$s$ = reflectivity of viewed surface (expressed as 1 if not known)

DEPARTMENT OF THE ARMY
U. S. ARMY ENVIRONMENTAL HYGIENE AGENCY
ABERDEEN PROVING GROUND, MARYLAND 21010-5422

REPLY TO
ATTENTION OF

HSHB-MR-LL (40)

MEMORANDUM FOR Commander, Waterways Experiment Station, Corps of Engineers, Coastal Engineering Research Center, ATTN: CEWES-CD-SE (Mr. Jeff Lillycrop), 3909 Halls Ferry Road, Vicksburg, MS 39180-6199

SUBJECT: Preliminary Nonionizing Radiation Protection Study No. 25-42-D776-93, Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) System, 10-12 May 1993

1. Reference memorandum, Waterways Experiment Station, Corps of Engineers, CEWES-CD-SE, 23 August 1991, subject: Request for Technical Assistance, and endorsement thereto.

2. As requested in paragraph 1, a study of the optical radiation hazards associated with the use of SHOALS was conducted at Optec, Inc., during 10-12 May 1993. The laser tested was not a SHOALS laser, but one with an increased output in the green (532 nm). Other pertinent characteristics, i.e., beam divergence and radiant energy output in the infrared (1064 nm), were representative of the SHOALS laser.

3. The effective beam divergence with the SHOALS set to 12 mrad was calculated based upon average irradiance measurements as a function of distance. The effective divergence was 8 mrad at 532 nm and 12 mrad at 1064 nm. The beam divergence with the SHOALS set to 2 mrad was determined using a 4-meter focal length lens. The beam divergence was 0.75 mrad at 532 nm and 1.5 mrad at 1064 nm. These measurements were made with 63 percent (1/e) of the total power passing through the measurement aperture.

4. The radiant energy was 7.6 mJ at 532 nm and 15.8 mJ at 1064 nm. The specified values for the SHOALS were 5 mJ at 532 nm and 15 mJ at 1064 nm.

5. The effective maximum permissible exposure is based upon the radiant exposure as a function of distance, not only radiant energy as described in TB MED 524. The correct MPE for simultaneous exposure at both wavelengths to the SHOALS laser transmitter is 0.88 uJ/cm$^2$ per pulse. This exposure limit assumes that an accidental exposure will consist of exposure to a single pulse because of the beam spacing on the water surface.

6. The calculated nominal ocular hazard distance (NOHD) for unaided viewing based on measured parameters and the above exposure limit is 180 m. The NOHD using a radiant energy of 5 mJ at 532 nm and 15 mJ at 1064 nm (SHOALS specifications) is 162 m. This distance is increased when viewing through magnifying optics. However, even when viewing through 7 X 50 binoculars at a distance of 200 m, the exposure level is below that known to cause injury in experimental animals.

7. The optical density (OD) for laser eye protectors to protect against a 50-pulse exposure is 4.8 at 532 nm and 4.3 at 1064 nm. Personnel who could only be exposed to a single pulse require an OD of 4.4 at 532 nm and an OD of 3.9 at 1064 nm.

8. It is recommended that further measurements be made on a laser transmitter with the SHOALS design specifications at a distance of 200 m through appropriate apertures to establish a data base at the operating distance.

9. The point of contact for this study is Mr. James K. Franks, Laser Branch (DSN 584-5064/3932).

FOR THE COMMANDER:

David H. Sliney

DAVID H. SLINEY
Chief, Laser Branch

(410) 671-3002 (Sliney)
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671-2331 (Jim Franks) (Laser optical program)

SHOALS EYE SAFETY PROBABILITY CALCULATIONS October 16/91

There are two ways to evaluate the safety measure of a laser system in terms of the eye safety. The first one is to use a deterministic model to calculate the nominal ocular hazard distance (NOHD) from an established eye safety standard (e.g. ANSI # Z136.1-1986). The second way is to employ a statistical model to calculate the probability of eye injury at the nominal operational distance (r) of the laser system.

Table 1 lists the nominal operational specifications for the SHOALS bathymeter. According to the ANSI # Z136.1-1986 standard, the NOHD values for the SHOALS system with a two meters diameter laser spot size (10 milliradians at 200 meters altitude) for a single laser shot is 117 meters for unaided eyes and 826 meters for eyes viewing with a 7 x 50 binocular (7 times magnification and 50 mm input aperture). The NOHD calculations are treated as single shot calculations here even though the laser will be firing at a 200 Hz pulse repetition frequency (PRF). This is justified by the non overlapping scanning pattern intended to be used in the hydrographic surveys. From these ANSI standard NOHD calculations, the 200 meters nominal operational altitude is eye safe only when the laser observer is viewing the laser shot with unaided eyes. However, viewing the laser shot with the regular 5 x 70 binocular is clearly not eye safe according to the ANSI standard. Similar NOHD values have also been confirmed according to the TB MED 524 document.

Table 1 Nominal Operational Specifications For SHOALS Bathymeter

| | |
|---|---|
| Pulse Energy | 5 mJ at 532 nm |
| | 5 mJ at 1064 nm |
| Pulse Duration | 5 nsec |
| Beam Divergence | 10 milliradians |
| Initial Beam Diameter | 1.5 cm |
| Pulse Repetition Frequency | 200 Hz |
| Scanner Frequency | <5 Hz |
| Nominal Altitude | 200 meters |

In what follows, we will present a statistical model to calculate the probability of eye injury in a year's normal operation of the SHOALS system. From that calculation, we will show that the probability of eye injury can still be kept to a reasonably low value despite the high NOHD value (826 meters for 7 x 50 binocular viewing) required by both the ANSI and TB MED 524 standards. In order to calculate the probability of eye injury, we have evaluated separately the probability of someone in a boat being illuminated by the laser, the probability of that someone in a boat looking at the helicopter when the laser is firing at him, and the probability of eye damage when laser light is collected in the eye.

Probability of eye injury in one year of operation ($P_{yi}$) =

1) Probability of someone in a boat being illuminated by the laser per unit area (P[illegible]) x

2) Probability of someone in a boat looking at the helicopter ($P_e$) x

3) Probability of eye damage when that person sees the laser light ($P_d$) x

4) Total area covered in one year ($A_T$)

1) The probability of someone in a boat being hit by the laser/unit area ($P_{bh}$) =

The probability of the first pilot not observing the boat (not disabling the laser) ($P_{p1}$) x

The probability of the second pilot not observing the boat ($P_{p2}$) x

Fraction of area covered by the laser foot print ($F_A$) x

Number of boats per unit area ($N_B$) x

Number of people per boat ($N_p$)

We assumed $P_{p1} = 1/1000$ because one pilot will have primary task to watch out for boats in order to shut down the laser when necessary. $P_{p2} = 1/10$ because the second pilot will be primarily concerned with flying the aircraft and only secondarily with watching out for boats

The fractional area of the laser foot print is given by (see figure 1):

$$F_A = \pi/4 \ d_s^2 \ / \ (a_f \times a_l)$$

where $d_s$ is the diameter of the laser spot on water surface

$a_f$ is the forward spot spacing

$a_l$ is the lateral spot spacing we usually use.

if we set $a_f = a_l = a$

then $F_A = \pi \ d_s^2 \ / \ 4a^2$

and for $a = 3$ meters, $d_s = 2$ meters, $F_A = 0.35$

we also assumethat $N_B = 10$ boats/Km$^2$

$N_p = 1$ person/boat

Thus, the probability of someone in a boat being illuminated by the laser, $P_{bh}$ is calculated to be $3.5 \times 10^{-4}$ Km$^{-2}$

2) Probability of someone in a boat being hit by the laser shot is also looking at the laser shot through a binocular ($P_e$) =

Probability of someone in a boat being illuminated by a laser shot and also looking at the helicopter ($P_{e1}$) x

probability of that same person using binoculars ($P_{e2}$)

we assume $P_{e1} = 0.5$

$P_{e2} = 0.5$

thus, $P_e = 0.25$

(Note: a separate calculation for the probability of a yearly eye injury for observers not using binoculars will be demonstrated later. However, the probability will be orders of magnitude down from the probability of yearly eye injury for observers using binoculars. This is why we describe the case with binoculars as our main calculation.)

3) Probability of eye damage ($P_d$) when a person sees the laser shot with binoculars

$$P_d = \int_0^{\infty} P_k(k_2)\, P_L(k_2T)\, dk_2$$ [1]

where $P_k(k_2)$ is the probability density function for the scintillation factor $k_2$, and $P_L(k_2T)$ is the probability distribution factor for the occurrence of an opthalmascopically visible lesion when $k_2T$ energy is focused onto the retina. T is the energy collected by the pupil (assume certain pupil size) with no scintillation factor.

$P_d$ can be calculated using an analytical solution [1]

$$P_d = Q(w(r))$$

where Q is the complement of the cumulative normal distribution

$$Q(b) = 1 - 1/\sqrt{2\pi} \int_{-\infty}^{b} \exp(-t^2/2)\, dt$$

and $w(r) = ( \ln( ED_{50} / T(r) ) + 0.5\, \sigma_{max}^2 ) / ( (\ln S)^2 + \sigma_{max}^2 )^{1/2}$

where $ED_{50}$ is the dose which would cause lesions in 50% cases.

$\sigma_{max}$ is the measured maximum standard deviation of the scintillation factor probability density function.

S is the slope of the dose response curve ($S = ED_{84} / ED_{50}$ or $ED_{50} / ED_{16}$)

$T(r) = 4\, E_o \exp(-\sigma r)/( (d_o + r\theta)^2 )\, G \;\; \pi/4\, d_e^2$

where $E_0$ is the laser pulse energy (Joules)

$d_0$ is the initial beam diameter (cm)

r is the helicopter nominal altitude (cm)

$\theta$ is the beam divergence (radian)

G is the optical gain of the binocular

$d_e$ is the diameter of the pupil opening (cm)

$\sigma$ is the atmospheric attenuation coefficient.

For SHOALS transmitter, $E_0 = 5$ mJ, $d_o = (0.5 + \theta/10)$ cm, r = 200 m, $\theta = 10$ mrad and we use $\sigma = 0.1\ km^{-1}$, therefore $\exp(-\sigma r) = 1$

where $G = D_o^2/d_e^2$ when $d_e >= D_e$

$G = D_o^2/D_e^2$ when $d_e <= D_e$

(from ANSI Z136.1-1986 & TB MED524)

$D_o$ is the diameter of binocular object lens,

$D_e$ is the diameter of binocular exit lens,

P is the power or magnification of the binocular

We use a 7 x 50 binocular in our calculation because that is the most commonly used. As for the diameter of the pupil opening, we use $d_e$ = 3 mm for daytime and $d_e$ = 7mm for night time calculation (see Fig. 2). (Note: the proper choice of pupil opening will diameter will affect the end result tremendously.) We have adopted values of $ED_{50}$, S, $\sigma_{max}$ from D. R. Brighton's paper [1] to calculate W(r)

| Parameter | Lambda1 = 1064 nm | Lambda2 = 532nm |
|---|---|---|
| $\sigma_{max}$ | 0.813 | 1.08 |
| $ED_{50}$ | 135 µJ | 10 µJ |
| S | 1.85 | 1.4 |

It is important to recognize that the above listed values of $\sigma_{max}$ for Lambda1 & Lambda2 were obtained during day light for a near-ground, horizontal propagation path. If we want to do a proper air to ground scintillation calculation, Ref. 2 is needed.

We have also used a polynomial approximation to calculate Q[w(r)]

where $P(x) = 1 - 1/2\,(1 + d_1x + d_2x^2 + d_3x^3 + d_4x^4 + d_5x^5 + d_6x^6) + \varepsilon(x)$

$\varepsilon(x) < 1.5 \times 10^{-7}$

$d_1 = 0.0498673470$ $\quad d_4 = 0.0000380036$

$d_2 = 0.0211410061$ $\quad d_5 = 0.0000488906$

$d_3 = 0.0032776263$ $\quad d_6 = 0.0000053830$

and P(x) is the cumulative normal distribution

$$P(x) = 1/\sqrt{2\pi} \int_{-\infty}^{x} \exp(-t^2/2)\, dt$$

$$P(x) + Q(x) = 1$$

therefore $Q(x) = 1 - P(x)$

Thus, if someone sees a laser pulse directly with binoculars, the probability of eye damage is:

$$P_d = 6 \times 10^{-4} \quad \text{for 532 nm}$$

$$P_d = 3 \times 10^{-9} \quad \text{for 1064 nm}$$

4) As for the total area covered in one year, $A_T$, we have used a scenario based on a total system operation time of 150 hours per year. The total area covered in a year, $A_T$ can be calculated by Ra x 150 (Ra is rate of area coverage). Ra is calculated to be 4.3 $Km^2/hr$ for a spot spacing of 3 meters, a swath width of 100 meters and a flight speed of 12 m/sec. This gives the $A_T$ = 649 $Km^2$/year.

Finally then, we can calculate the probability of eye injury in one year of operation, $P_{yi} = P_{bh} \times P_e \times P_d \times A_T$. The probability of yearly eye injury, $P_{yi}$ is $4 \times 10^{-5}$ and $2 \times 10^{-10}$ for 532 nm and 1064 nm respectively. The most sensitive parameter that affects the probability of yearly injury ($P_{yi}$) result is the total amount of energy collected onto the retina. This parameter is determined by the laser spot size on the water surface and the diameter of the pupil opening. The laser spot size is determined by the altitude of the helicopter and the beam divergence of the output beam. The pupil opening diameter is determined by the intensity of sky light. In SHOALS scenario, day light operation is assumed, hence the diameter of the pupil opening is limited to 3 mm. Fig. 3 & 4 shows the effect of laser spot diameter & pupil opening diameter on the probability of eye damage per laser shot and the probability of yearly eye injury (note that the graph values on the vertical axis is the $\log_{10}$ of the probability). As we can see, the green (532 nm) wavelength has a much higher probability of eye damage than the IR (1064 nm) wavelength. For example, when a 3 meter laser spot spacing with 2 meter spot diameter is used during day time (3 mm pupil opening), the probability of eye injury per year is less than $4 \times 10^{-5}$ and $2 \times 10^{-10}$ for 532 nm and 1064 nm respectively.

For the sake of comparison, the yearly probability of eye injury if no binoculars are assumed will become $10^{-12}$ and $10^{-20}$ for green and IR respectively. It is also important to recognize that without binoculars, 200 m altitude is beyond the eye safe range required by the ANSI Z136.1-1986 and TB Med 524 standards. (<117 m for 10 mrad beam divergence).

Ref


1. David R Brighton, "The consequences of using uncorrected NOHD values in laser safety calculations", Radiation Protection in Australia (1988), vol 6., No. 3, pg. ?.

2. W.F. Dabberdt, "An investigation of atmospheric effects on laser propagation and the impact on eye safety", Stanford Research Institute Project 1341 Contract F41609-71-C-0029 NTIS AD 755 405, 1972.

3. M. Abramowitz & I.A. Stegun, "Handbook of Mathematical Functions", Dover Publications Inc., N.Y., 1965, pg. 931-932.

Figure 1 Scanning Laser Spot Pattern on Water Surface

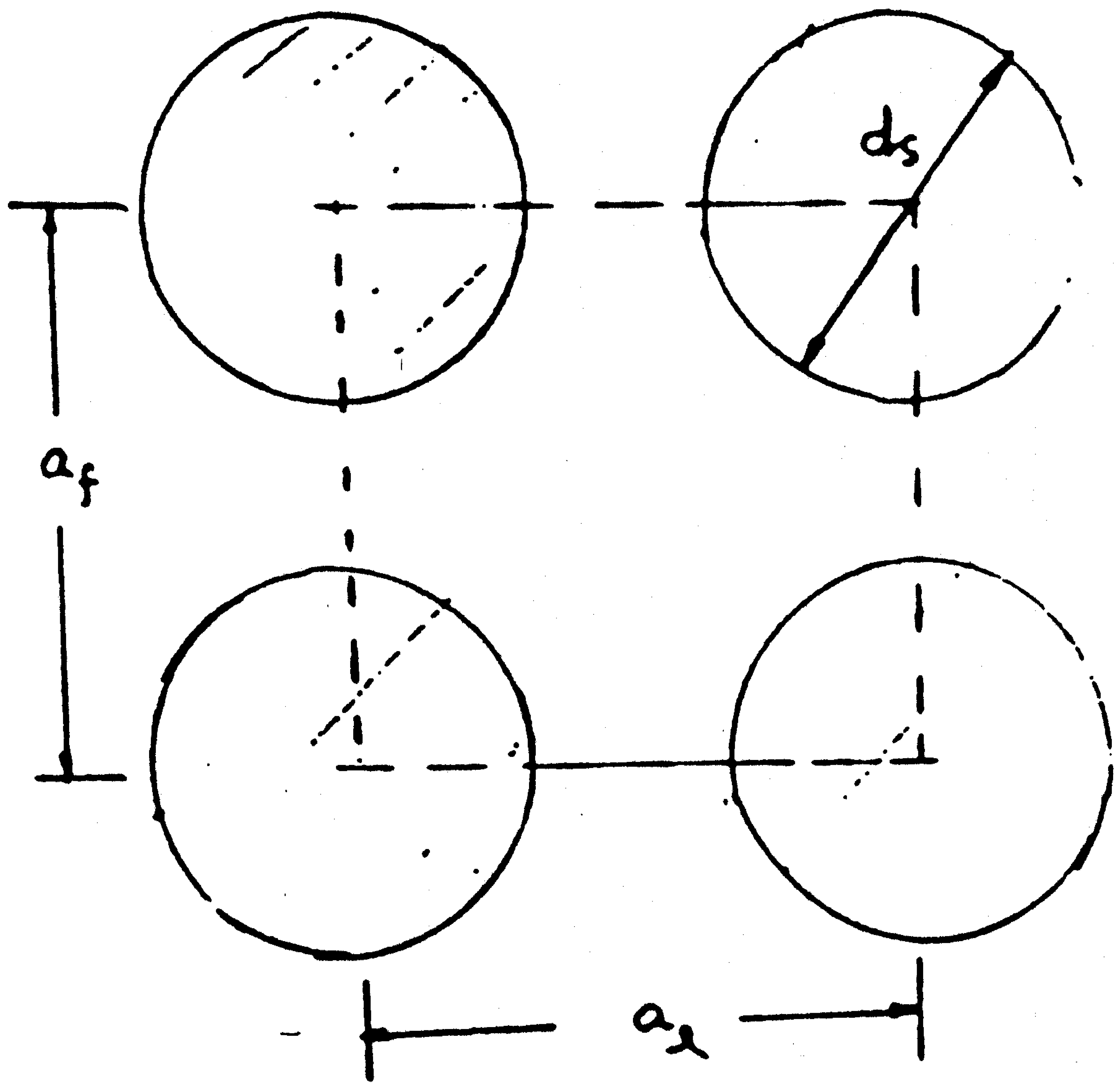

Figure 2 Eye Characteristics (Pupil Size Vs Illumination)

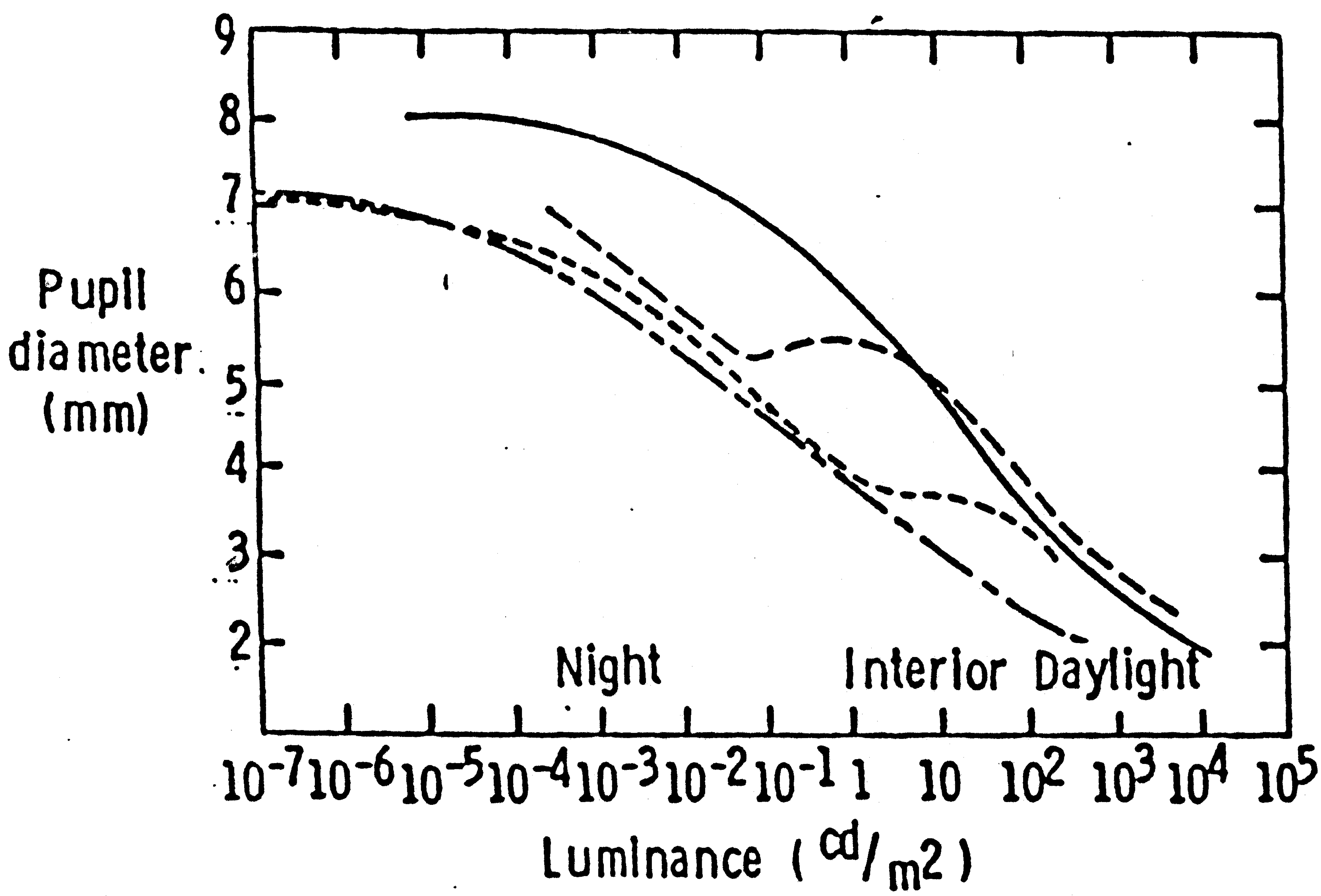

Figure 3 Probability of Yearly Eye Injury Vs Pupil Diameter

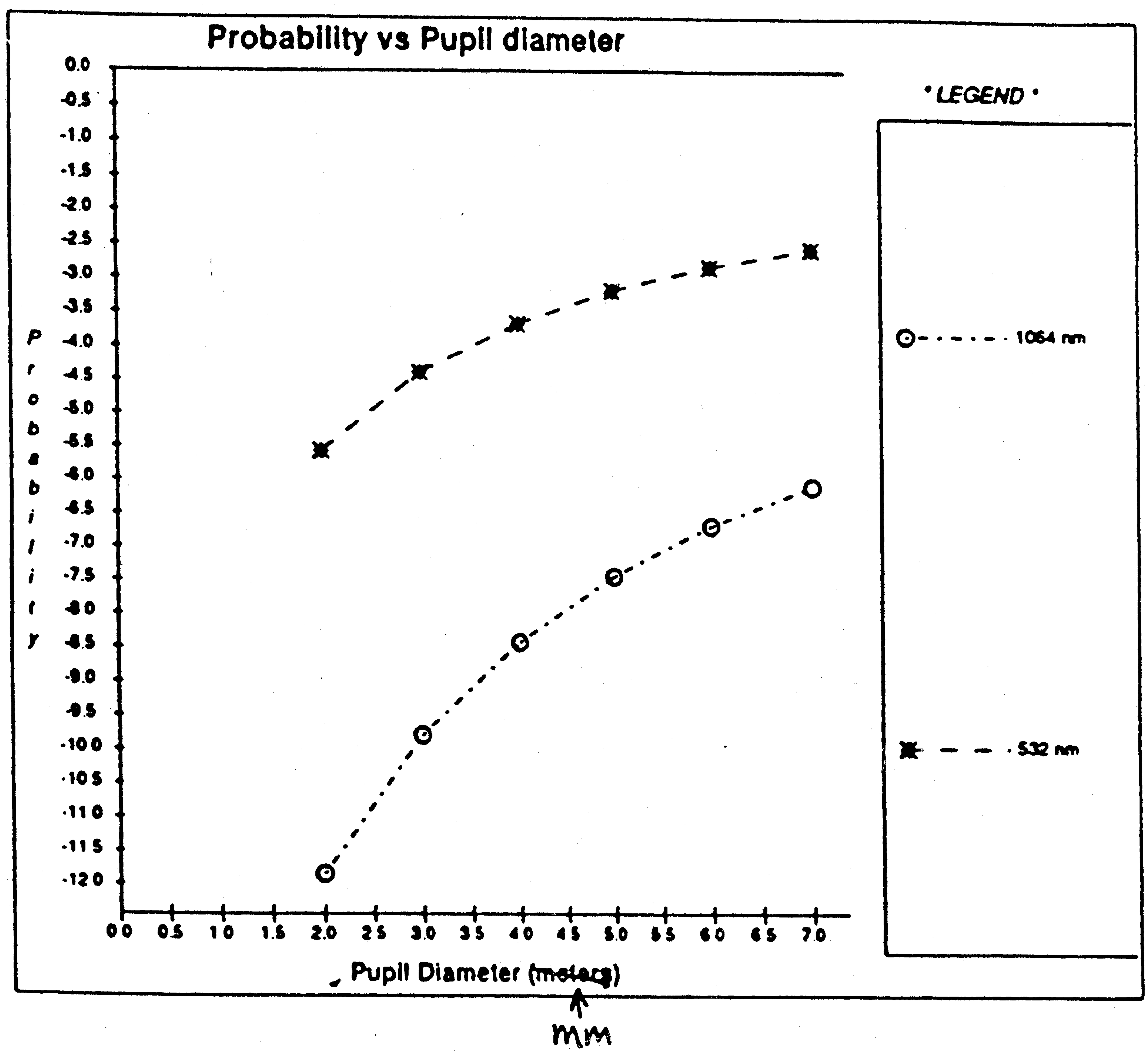

Figure 4 Probability of Yearly Eye Injury Vs Laser Spot Diameter