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Technical Report: NAVTRADEVCEN IH-154

GAS LASERS IN WEAPON FIRING SIMULATORS

D. Breglia
Physical Sciences Laboratory

November 1968

DoD Distribution Statement

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NAVAL TRAINING DEVICE CENTER
ORLANDO, FLORIDA

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ABSTRACT

This report summarizes an in-house effort to optimize a laser source in a weapon firing simulator. Preliminary findings indicate that a 1-mW He-Ne gas laser is the most suitable, monochromatic display. This conclusion was reached after an analysis of the following parameters: spectral output and eye response, power or energy output and laser safety, beam divergence and desired display, beam diameter, mode of operation, reliability, and weight and size.

Naval Training Device Center, Orlando, Fla.

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Laser
Simulator
Display
Laser Hazard

Naval Training Device Center
Breglia, D.

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Approved:

George Derderian
Head, Physical Sciences Laboratory

Dr. H. H. Wolff
Technical Director

NAVAL TRAINING DEVICE CENTER

ORLANDO, FLORIDA

FOREWORD

In the past year small gas lasers were used extensively in the commercial market. These lasers are presently being used for applications such as surveying, optical alignment, and tooling. This report demonstrates a military training application of the gas laser.

DENIS R. BREGLIA
Physicist

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SECTION I

INTRODUCTION

The pulsed ruby laser being used in a contractor-developed laser simulator is inefficient and borders on being dangerous for human viewing. These characteristics were known in 1964 when the ruby laser was chosen, but it was difficult to use any other type.

Since 1964 several lasers, which do not have these undesirable characteristics, have been developed to fill commercial needs. These same lasers possess a great potential for use in training devices and weapon simulators. Therefore, some investigations and evaluations have been made by the Naval Training Device Center in these areas. This report summarizes efforts in these areas which led to the in-house development of a laser weapon firing simulator.

SECTION II

STATEMENT OF THE PROBLEM

A. LASER PARAMETERS

Of prime concern in choosing a laser for a specific system simulator or display is whether it is the optimum element for the situation and, if it is, whether there need be human viewing. The following factors should be considered:

1. SPECTRAL OUTPUT

Lasers are currently available in configurations suitable for weapon firing simulator/hit indicators with the following spectral lines:

488 nm Argon
515 nm Argon
530 nm 2nd Harmonic Nd Doped Glass
633 nm He-Ne
694 nm Ruby

The above lasers all have visible light outputs and are available as production items from a large number of sources.

2. POWER OR ENERGY OUTPUTS

The lasers listed in 1 above are available in the power or energy ranges shown in table 1.

TABLE 1. POWER OR ENERGY OF CERTAIN LASERS

LASER	POWER OR ENERGY
Argon	1 mw - 5 w
ND Doped Glass	1 mw - 300 mw
He-Ne	5 mw - 100 mw
Ruby	10 mj - 10 j

When a laser is used in a specific situation, the energy or power will be limited by safety considerations.

3. BEAM DIVERGENCE

The minimum beam divergences shown in table 2 are commercially available from the types of lasers shown in table 1.

TABLE 2. BEAM DIVERGENCE OF CERTAIN LASERS

LASER	MINIMUM BEAM DIVERGENCE
Argon	.5 mr
Nd Doped Glass	3-4 mr
He-Ne	.5 mr
Ruby	3-4 mr

4. BEAM DIAMETER

The initial diameter of the beam is approximately 2 mm for the low power gas lasers (Argon and He-Ne) and approximately 6 mm for the low energy ruby and Nd doped glass lasers.

5. MODE OF OPERATION

The lasers may be operated in pulse or cw modes. In the cases of the Nd doped glass and ruby, the cw is a quasi-cw in that cw operation is actually achieved by rapid pulsing.

6. WEIGHT AND SIZE

All of the above lasers when low powers are desired can be made with suitable size and weight. This will be discussed in a later section.

B. HUMAN OBSERVER PARAMETERS

1. EYE RESPONSE

The human eye is a luminous flux detector with a fairly well known spectral response. The eye "sees" or responds to wavelengths within a certain band of the electro-magnetic spectrum with varying degrees of response. As can be seen in figure 1, the laser spectral linesof interest have the following relative luminous efficiency based on an efficiency of 100% at 555 nm[1*].

TABLE 3. LUMINOUS EFFICIENCY OF LASER LINES

COLOR	WAVELENGTH	RELATIVE LUMINOUS EFFICIENCY
Blue	488 nm	19.3%
Blue-Green	515 nm	60.8%
Green	530 nm	86.2%
Red	633 nm	24.7%
Deep Red	694 nm	0.6%

*The superscript numbers refer to reference numbers.

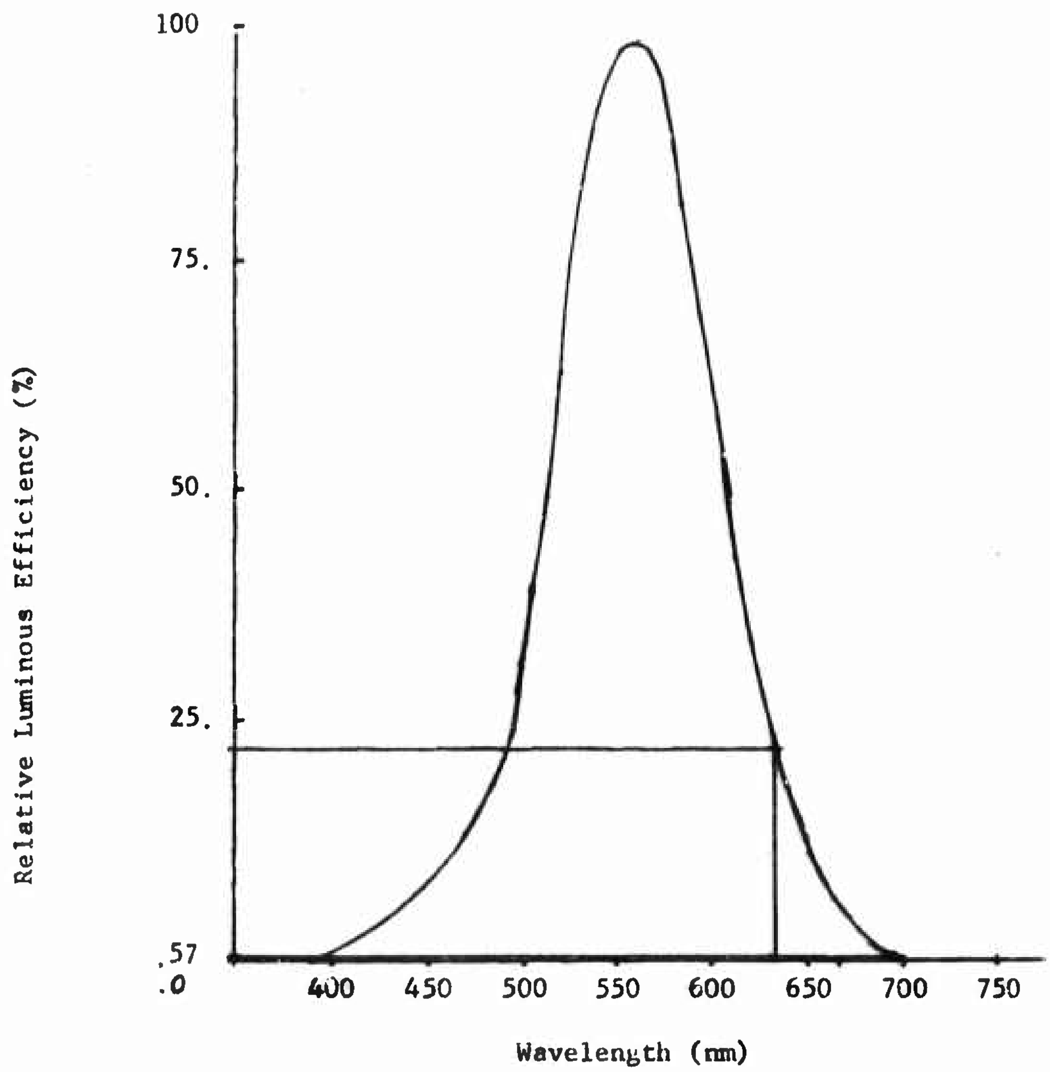

Figure 1. Relative Luminous Efficiency of the normal human eye as a function of wavelength

The physical meaning of table 3 may be illustrated in the following statement. It would take approximately one hundred times as much energy at 694 nm to elicit an equal eye response at 515 nm. (This assumes bright lights and correspondingly day-adapted or photopic vision.) Therefore, in terms of efficiency, the optimum laser for a monochromatic display is one which requires the least amount of energy to elicit the same response (i.e., visual sensation of brightness.) The lasers which would fall into this category at the present time are the Argon Ion Gas Laser, the Neodymium-doped - 2nd-harmonic Laser, and the He-Ne Laser. The Ruby Laser, however, is almost invisible by comparison and is a poor choice for human viewing.

Another important factor is that the eye has a persistence of approximately 0.1 second. This leads to the conclusion that a pulse of shorter duration would cause the same visual sensation as a pulse of equal energy over 0.1 second. This is known as Bloch's Law[2].

2. POWER OR ENERGY CONSIDERATIONS

The limitations on the Power/Energy output of a laser utilized in a human viewing situation are:

a. Irradiance and radiant exposure at the eye of a human observer are not to exceed damage thresholds.

b. Power/energy combined with eye response should be sufficient to give the desired value of luminance.

3. LASER SAFETY GUIDELINES

The safety numbers for lasers operating in the visual region presently accepted are:

a. For non-Q-spoiled pulse lasers the corneal radiant exposure is not to exceed $\sim 10^{-7}$ j/cm^2.

b. For continuous wave lasers the corneal irradiance is not to exceed $\sim 10^{-6}$ w/cm^2.

These numbers are based on both theoretical and experimental data from many sources[3]. Another important safety consideration when comparing pulse and cw lasers is that the energy per pulse can vary considerably (as much as 50%, even with the same ruby), from pulse to pulse. A cw laser power output however, will not vary measurably over hours of continuous use.

SECTION III

METHOD OF PROCEDURE

A. INTRODUCTION

The present laser weapon firing simulator consists of a pulse ruby laser, a focusing lens system, and a retro-reflective target. A trainee, immediately adjacent to the laser, fires the laser (a single pulse) at the retro-reflective target, the lens system focuses the diverging beam to a 1-cm spot on the retro-reflective target located 60 m from the trainee. The trainee observes the spot and corrects his fire. The laser characteristics as measured at "US Army Environmental Hygiene Agency"[4] are:

Mode of Operation; Single Pulse

Energy Output per Pulse; 0.005 to 0.07 j

Length of Pulse 150 microsec

Natural Beam Divergence of Ruby 3 to 4 mrad

Diameter of Ruby Rod 0.25 in.

Spectral Line Output 694.3 nm

Spot Diameter 60 m from Lens System is 1 cm

Maximum Radiant Exposure at Trainee's position 4.4×10^{-8} j/cm^2

B. CHOOSING THE HE-NE CW LASER

After a judicious review of product literature, a rugged 1-mw He-Ne laser was purchased as a possible substitute for the ruby. The reasons for choosing the He-Ne laser were:

1. It is used fairly extensively in commercial applications such as surveying, machine and tool alignment, optical alignment, and range finders.

2. Although the spectral line emission is not at the peak of the eye response function at 633 nm, it is approximately 40 times the eye response at 694.3 nm.

3. Lasers with better spectral outputs were not available as off-the-shelf items in the size and power range required.

C. CHARACTERISTICS AND ADVANTAGES OF THE HE-NE LASER

1. Mode of Operation - Continuous Wave

This enables the instructor to boresight the simulator without constantly firing and subsequently adjusting position until "on target". The advantages gained in safety of a continuous wave laser have been explained above. These may be summarized as:

a. The damage threshold is higher (more energy required to produce lesion).

b. No inherent output variations.

2. Power Output - 1 mw

The basic advantage is that less energy is received by the eye over a short period of time. A 1-mw laser would take 40 seconds to deliver the same amount of energy as that in a 40-mj pulse.

3. Spectral Output - 633 nm

As indicated above, the eye response to 633 nm light is approximately 40 times greater than that at 694.3 nm.

4. Length of Pulse

As the cw laser would be operating continuously, the length of pulse (or length of fire burst) could be controlled to many values over a great range depending on the training situation (See "Mode of Operation" above).

5. Beam Divergence - 0.8 mrad

A beam divergence of 0.8 mrad gives a spot size of 2 in. in diameter at 60 m with no optics required.

D. <u>MODIFICATIONS REQUIRED</u>

The simulator laser,besides having specified power and divergence,had to conform to certain dimensions and general specifications. These were:

1. Laser head should be in cylindrical package no more than 2½ in. in diameter and 18 in. long.

2. The laser should be rugged and usable in the field and not confined to laboratory operation.

3. The laser power supply should be ruggedized and capable of 12 or 24 vdc or 110 vac power input.

4. The simulator should be sealed and require no adjustment by the instructor or trainee.

5. It would be desirable not to require forced air cooling of the simulator.

6. The simulator should be capable of being fired in bursts or continuously.

7. The simulator should be capable of being mounted in an M-73 machine gun mount.

E. <u>CHOICE OF LASER MANUFACTURER</u>

1. Requirements 1, 2, 3, 4, and 5 in D above were satisfied by proper choice of manufacturer based on manufacturer's specifications. The laser chosen conformed to power, spectral line and divergence specifications as well as having the following characteristics:

a. Laser Head Dimensions - Cylinder 2 in. in diameter

b. Ruggedized for Field Use

c. Power Requirement - 12 vdc
- 110 vac
- 35 w

d. Sealed Laser Head

e. No Cooling Required

F. CHOICE OF SHUTTER

Requirement 6 of D above was satisfied by proper choice of solenoid operated shutter. A circuit was designed to operate a solenoid mounted on the laser. The solenoid is spring loaded and attached to a small aluminum flag which shutters the laser. When connected to the tank trigger circuit, the shutter may be opened in either of two modes. The first mode opens the shutter for 1/10 second when the tank trigger is depressed. The second mode allows the shutter to remain in the open position for as long as the trigger is depressed.

G. MOUNTING ADAPTER

Requirement 7 of D above was satisfied by designing and fabricating a mounting adapter to fit into the M-73 machine gun mount.

SECTION IV

RESULTS

A. INTRODUCTION

The gas laser simulator has been demonstrated to many interested groups (see appendix B). The initial reactions, prior to testing and evaluation, were extremely good. The personnel attending the demonstrations were most favorably impressed by the small size, simplicity of operation, potential low maintenance, and low cost.

B. SAFETY ANALYSIS

The prototype simulator has been analyzed from the standpoint of safety of the human observer. The calculations and results for both the direct exposure and reflected radiation are given below.

1. Direct Exposure

Considering a cw laser having the following characteristics:

Power Output 1 mw;
Beam Divergence 0.8 mrad;
Beam Diameter at Laser Output 2 mm;

The hazard of on-axis viewing of the direct beam may be calculated as follows:

If the 2-mm aperture of the laser subtends less than 1 minute of arc, the laser may be considered as a point source and the concept of intensity may be used. Making this assumption, the intensity of the laser is given by:

a. $J = \frac{P}{W}$ w/sterad where P = Radiant Power (watts)

W = Solid Angle (sterad)

J = Radiant Intensity (watts/sterad)

The solid angle is related to the divergence angle in the following way:

b. $W = 2\pi\,(1-\cos \phi/2)$ sterad

where ϕ = divergence angle

where ϕ is small, this reduces to

c. $W = \frac{\pi\phi^2}{4}$ sterad

from a. and c.

d. $J = \frac{4P}{\pi\phi^2}$ w/sterad

Substituting the known values

e. $J = 2 \times 10^3$ w/sterad

The irradiance on the eye at a range r from the laser will be:

f. $H_E = \frac{J}{r^2}$

Since the threshold irradiance (H_{EL}) has been set for safety reasons at

$$H_{EL} = 10^{-6} \text{ w/cm}^2$$

The minimum distance for direct beam viewing is determined to be:

g. $r_m = \sqrt{\frac{J}{H_E}}$

h. $r_m = 4.5 \times 10^4$ cm = 450 m

Therefore, direct on-axis viewing is hazardous up to 450 m for a 1-mw He-Ne Laser. This is a direct result of the laser power being concentrated in a very small solid angle. The danger of reflections from objects such as metal cans and wet leaves is low because such reflections do not preserve the small solid angle[4].

2. Reflection from a Diffuse Screen

The spot size on the target located 60 m from the laser will be $\sim$ 5 cm in diameter. Since this is small in comparison to the distance to the trainee (60 m), equation "a" may again be employed to determine the irradiance on the trainee's eyes.

Reflection from a diffuse screen does not preserve the small solid angle of the incident direct beam. The reflected light varies with angle of view with a distribution which varies according to the screen properties. Since the viewing angle and screen material are known, the reflected intensity can be calculated.

For the screen material used, the characteristic reflective property is that the screen has a retro-reflective "gain" of 115 over that of a "Lambertian" surface, when the screen is viewed from the same direction from which the laser was incident. This is the case (i.e., the trainee is immediately adjacent to the laser).

Assuming that the screen has an albedo = 1 (i.e., no absorption) the radiant power of the target (P_T) will be equal to the radiant power of the laser.

$$P_T = P$$

For a "Lambertian" surface, the radiant intensity is defined as:

i. $J_L = \frac{P_T}{\pi}$ w/sterad

This is calculated to be $J_L = 3.2 \times 10^{-4}$ w/sterad.

Since the target screen has a "gain" of 115 over Lambertian, the target spot intensity will be: $J_T = 115\ J_L$

$$J_T = 3.7 \times 10^{-2} \text{ w/sterad}$$

Calculating the irradiance, from equation f., at the eye located 6.0×10^3 cm from the screen.

$$H_E = \frac{J_T}{(6 \times 10^3)^2}$$

j. $H_E = 6 \times 10^{-9}$ w/cm^2

The irradiance due to a 1-mw laser used in the way described is thus more than two orders of magnitude safe.

Of course consideration has not been made of image size on the retina. This is covered in appendix A.

SECTION V

CONCLUSIONS

The investigations have led to the development of a prototype weapon firing simulator. The simulator consisting of a 1-mw He-Ne gas laser, a solenoid shutter mechanism, and a mounting adapter is capable of replacing the ruby laser simulator currently in use.

SECTION VI

RECOMMENDATIONS

1. For this specific application the recommendations are:

   a. Environmental testing of the simulator assembly.

   b. Determination of specification for production model.

2. Further applications of gas laser simulators to weapon firing simulation include:

   a. Other flat trajectory weapon training.

   b. With some modifications, ballistic trajectory may be simulated.

3. Other training situations which might employ simulators such as this are:

   a. Monochromatic displays.

   b. Aiming and tracking trainers.

REFERENCES

1 Judd, Deane B.

"The 1931 I.C.I. Standard Observer and Coordinate System for Colorimetry" Journal of the Optical Society of America, Volume 23 (1933) pg. 359.

2 Graham, C. H. et al: Vision and Visual Perception John Wiley (1965) pg. 76.

3 "Proceedings of the Laser Safety Workshop" January 1968 University of Cincinnati.

4 Laser Hazards Special Study No. 42-24-68, "Laser Training Device 3A102B" US Army Environmental Hygiene Agency, Edgewood Arsenal.

APPENDIX A

MEANS OF DETERMINING SAFETY NUMBERS.

As determined by the Office of the Surgeon General, the safety numbers are values of irradiance or radiant exposure measured at the cornea. Unfortunately, these numbers are, by nature, conservative when the irradiance or radiant exposure is considered for the near field case (the source subtends greater than 1 minute of arc).

The reason for using a cornea number is that it is impossible to monitor or measure a retinal number. However, the retinal irradiance or radiant exposure determines the damage threshold so a worst case is assumed (wide pupil and minimum image size) and corneal numbers are extrapolated.

For a point source the eye will concentrate the laser to a focus on a single cone on the retina. By taking the ratio of the area of the pupil to the area of a single cone, the "concentration" factor can be obtained.

Area of Cone = $36 \times 10^{-6} mm^2$

Area of Pupil = $12\ mm^2$

"Concentration" = $\sim 10^6$ times

Since the functional damage threshold is $\sim 1\ w/cm^2$ at the retinal level (for cw Lasers) the corresponding corneal damage threshold will be $10^{-6}\ w/cm^2$. The corneal criteria for a non-point source however is conservative. The corneal irradiance will not change appreciably with source size for equal source power until the source diameter is greater than 1/10 the distance to the source. The retinal irradiance however does change. Consider the following situation. A laser is used to illuminate a spot on a target of 50 m from an observer. At 50 m the laser spot will be far-field to the observer only if it is less than 2 cm in diameter. Consider that the laser uses optics to focus the spot to any size from 1 cm to 5 meters in diameter.

The radiant power of the target spot is equal to the radiant power of the laser and therefore the irradiance at the observer's cornea will be constant (within 1%) as the spot is varied from 1 cm to 5m in diameter.

The irradiance at the retina, however, will be inversely proportional to the area of the laser spot. This means that a 10-cm spot will give 100 times less retinal irradiance than a 1-cm spot for equal source power but the same corneal irradiance. Therefore, for near-field conditions the specification on corneal irradiance is not practical.

APPENDIX B

DEMONSTRATIONS OF GAS LASER

The following demonstrations of the laser simulator were given:

16 April 1968 - On-Site demonstration to:

Technical Director

Commanding Officer A.P.G.

Associate Technical Director Code 50

Associate Technical Director Code 30

Deputy Associate Director A.P.G.

Laboratory Head, Code 51

Department Head, Code 37

24 April 1968 - Demonstration at Fort Knox, Kentucky. Representatives from the following organizations attended:

USA Armor School

USA Materiel Command

Frankford Arsenal NZZOO

USA Combat Development Command

15 May 1968 - Demonstration at Army Research Office, Washington, D.C. This demonstration was witnessed by representatives of the following organizations:

Dept of Army Research

Army Research Office

Army Materiel Command

16 May 1968 - Demonstration at DC SOPS, Hq CONARC, Ft. Monroe, Virginia

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Laser Simulator Display						