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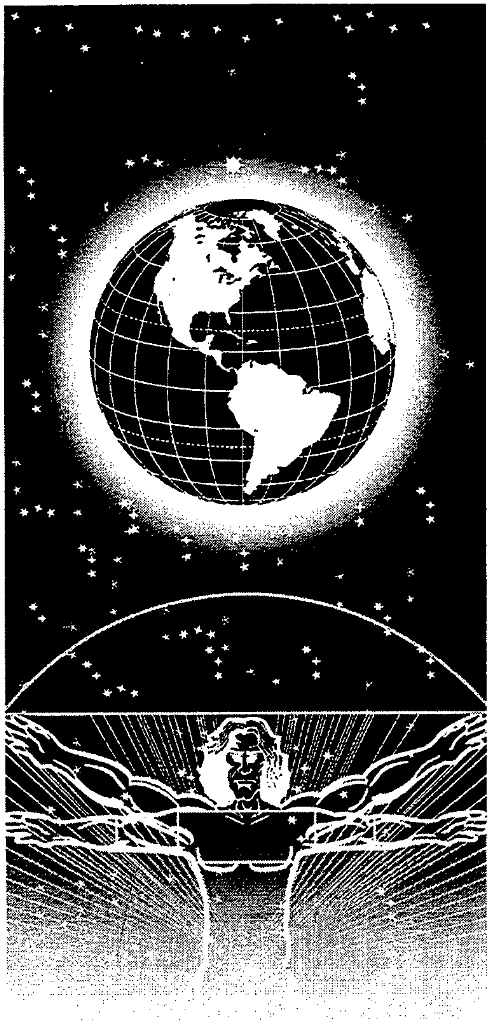

UNITED STATES AIR FORCE RESEARCH LABORATORY

VISUAL EFFECTS ASSESSMENT OF THE GREEN LASER-BATON ILLUMINATOR (GLBI)

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14. ABSTRACT
The Green Laser-Baton Illuminator (GLBI) was developed by LE Systems Inc. of Glastonbury, CT and is the first non-lethal technology (NLT) laser illuminator to incorporate a green (532 nm) laser. Green laser light is attractive because it is 8.27 times more sensitive to the eye during the day than red (650 nm) light. The GLBI has an eye hazard zone of 1.4 m and then becomes very eye safe because of a large beam divergence. AFRL/HEDO was employed by the National Institute of Justice (NIJ) to measure the GLBI laser beam characteristics and to write a human use protocol to collect GLBI effectiveness data. Effectiveness tests included: daytime visibility thresholds, glare source effects on a vehicle operator, flashblindness determination, and the effect of GLBI on night vision goggle (NVG) wear. The GLBI did not perform well as a daytime tagging device but worked well as a nighttime glare source. Although visible to NVG, the GLBI is much more covert to NVG than red illuminators. The most essential improvements to GLBI would be to miniaturize the device with a laser diode design and to homogenize the beam profile.

15. SUBJECT TERMS
Non-Lethal Technology; Laser Illuminator; Glare; Flashblindness; Night Vision Goggles; Maximum Permissible Exposure; National Institute of Justice

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VISUAL EFFECTS ASSESSMENT OF THE GREEN LASER-BATON ILLUMINATOR (GLBI)

INTRODUCTION

Civilian law enforcement agencies are continually searching for effective non-lethal technology (NLT) devices that could enhance their capability to deal with prison and arrest scenarios without using deadly force. The Green Laser-Baton Illuminator (GLBI) prototype (Fig. 1) was developed through a SBIR contract (DAAE30-96-C-0070, US Army ARDEC) to LE Systems Inc.[*] of Glastonbury, CT. The contract was funded by the Defense Advanced Research Projects Agency (DARPA) and the National Institute of Justice (NIJ)[#] through the Joint Program Steering Group (US Department on Justice and US Department of Defense). The Laser Systems Branch of the Air Force Research Laboratory (AFRL/DELS)[+] at Kirtland AFB, NM has monitored the contract, and the ten prototypes from this technology demonstration program were delivered to AFRL/DELS in April 1998. The principal customer for the GLBI is the NIJ who funded the eye safety certification[1] and the field visual effectiveness testing. The GLBI is designed to be hand held (Fig. 2) in a flashlight type design. The original GLBI prototype had an extensive eye hazard zone and was not safe for human testing at near distances. Therefore, AFRL/DELS modified the optical train decreasing the eye hazard zone to 1.4 m[1]. The modified GLBI is a low powered (43 mW at the aperture), diode pumped, solid state, green laser (532 nm) that becomes very eye-safe outside the hazard zone because of a large beam divergence [39.12 mrad (1/e)] and long pulse duration (12.4 ms)[1].

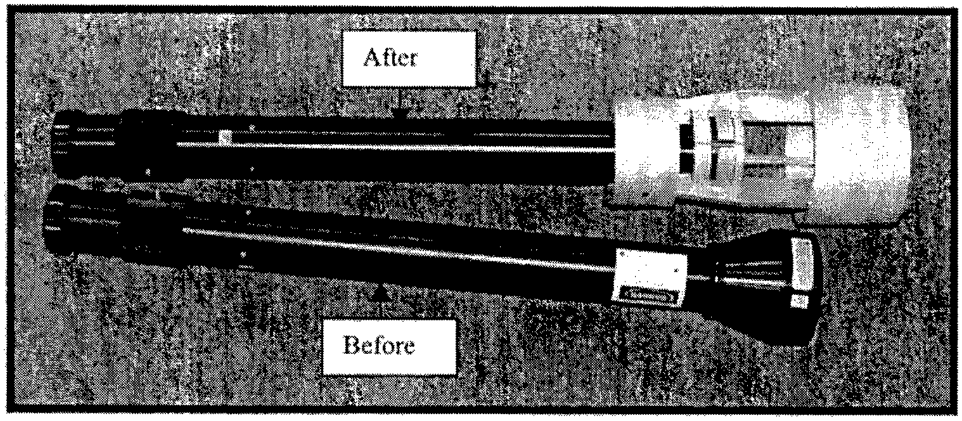

Figure 1 Green Laser Baton-Illuminator (GLBI) Before and After Modification

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[#] National Institute of Justice, 810 Seventh Street, NW, Washington DC 20531
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The GLBI is the first NLT laser illuminator to incorporate a green (532 nm) laser. The first red laser illuminator was powered by a red (650 nm) diode laser as are the follow-on red illuminators. The red laser illuminators were originally manufactured with a red (670 nm) diode with the expectation that they would be retrofitted with a red (632 nm) diode in the future. The illuminators used the red diode because that was the technology available at the time, and red is the international symbol for stop. The interest in a shorter length red wavelength (632 nm) and a green wavelength (532 nm) originated because of the increased visual efficiency of these wavelengths (Table 1 and Figure 3). Green is especially attractive since it is 8.27 times more efficient during the day (photopic) than 650 nm (Table 2) and should appear significantly brighter to the eye with equal energy exposure. The shift between scotopic (night) and photopic (day) peak sensitivities is called the Purkinjie shift[2] and is illustrated in Figure 3. When viewing a bright laser illuminator, the eye responds in the photopic region, even at night.

Figure 2 The Laser-Baton is Hand Held

Like the red illuminators, the GLBI will not cause a permanent eye injury unless it is abused by staring at the beam at very short ranges. It is designed to induce glare and perhaps some flashblindness, both of which are temporary effects. Glare can be defined as a relatively bright light in the visual field that degrades vision and may cause discomfort as long as the light is in the visual field[3]. With flashblindness, the light is bright enough to cause a significant effect on the retinal adaptation level so that there is a period of a loss of visual sensitivity after the light source has been removed[4, 5].

Table 1 CIE Spectral Luminosity Efficiency Function for Photopic Vision[6]

λ	$V(\lambda)$
532	.88496
632	.24488
650	.10700
670	.03200

Table 2 Photopic Efficiency Comparisons for Laser Diode Wavelengths

λ	V(λ)	# Times Efficient
532/632	.88496/.24488	3.61 X
532/650	.88496/.10700	8.27 X
532/670	.88496/.03200	27.66 X
632/650	.24488/.10700	2.29 X
632/670	.24488/.03200	7.65 X
650/670	.10700/.03200	3.34 X

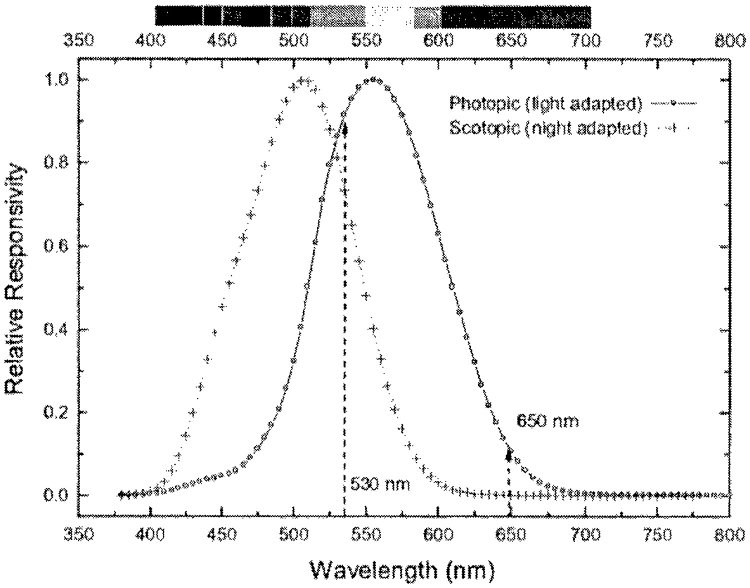


Figure 3 The Photopic and Scotopic Responses of the Eye (Purkinjie Shift)

Retinal damage from lasers usually occurs from three different mechanisms: mechanical, thermal, and photochemical[7]. Mechanical damage arises from sonic transients normally induced by short laser pulses with high energy. The red laser illuminators are all continuous wave (cw) and will not cause mechanical damage. Although pulsed, the GLBI will not cause mechanical damage because the energy emitted is too low and the pulses too long. Thermal damage is primarily created by longer (> 580 nm) visible and near infrared (700-1400 nm) wavelengths[7]. There is less concern for retinal cumulative effects from multiple exposures with the thermal mechanism because injury to tissue requires sufficient heat energy at threshold level to cause tissue coagulation and cell death. Subthreshold heat exposure will be conducted away by the surrounding tissue[8]. Photochemical damage, typically caused by shorter visible wavelengths (400-580 nm), is more of a concern for cumulative retinal damage. Ham et al.[7] found damage in the retina from shorter wavelengths at power levels too low to produce appreciable temperature rises. Because of the increased concern of damage to the retina from the cumulative effects of shorter wavelengths, the ANSI Standard[9] is more stringent for 532 nm than 650 nm for exposures of 20 s or more (Table 3). Cumulative effects are taken into consideration in the medical risk analysis section of this report.

AFRL/HEDO was responsible for assuring that the GLBI was eye safe when used within the perimeters of the human use protocol (#F-BR-2000-0015-H). AFRL/HEDO has already measured the beam profiles of many red (Figure 4) laser illuminators and has developed an expertise in beam evaluation and an extensive database. Unlike the current red laser illuminator beam profile that is uniform and has a "top-hat" profile, the GLBI beam profile contains several hot spots and is very irregular (Figure 4). The complete GLBI beam measurements and hazard analysis are available in a separate report[1].

Table 3 ANSI Standard Maximum Permissible Exposure

	650 nm	532 nm
0.25 s	2.6 mW/cm^2	2.6 mW/cm^2
10 s	1.0 mW/cm^2	1.0 mW/cm^2
20 s	851 μW/cm^2	500 μW/cm^2
30 s	769 μW/cm^2	333 μW/cm^2
40 s	716 μW/cm^2	250 μW/cm^2
50 s	677 μW/cm^2	200 μW/cm^2
100 s	569 μW/cm^2	100 μW/cm^2
1000 s	320 μW/cm^2	10 μW/cm^2

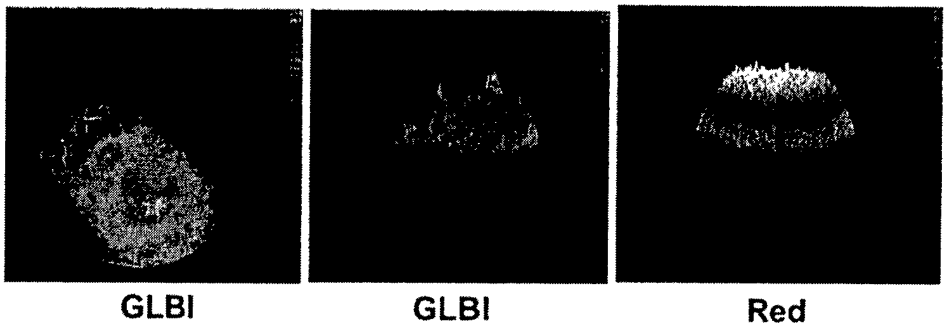

GLBI GLBI Red

Figure 4 The Laser Beam Profiles of the GLBI and Red Laser Illuminators

METHODS

Test Facilities and Subjects: All testing was held on Brooks AFB, TX near the Directed Energy compound. The Security Forces Squadron at Brooks AFB was informed of any testing activities prior to the event. A laser safety officer (LSO) was present at all testing events. Five subjects from the Brooks AFB community volunteered for the field study. All subjects had a laser eye examination, including a dilated retinal evaluation, on record with the Ophthalmology Branch of the USAF School of Aerospace Medicine prior to testing. The voluntary, fully informed consent of the subjects used in this research was obtained as required by AFI 40-403. The subjects were given a comprehensive eye safety briefing on the GLBI prior to signing their informed consent documents. Participants reporting a history of eye disease, hypersensitivity to light, or currently taking photosensitizing drugs were not accepted. Since GLBI is a pulsed laser system (pulse repetition frequency = 25.7 Hz), participants were questioned about any previous or family history of a convulsive response to flashing light. No candidate with any history of this problem was allowed to participate. Epilepsy is present in about one percent of the population, and collectively, about 30% of those with primary generalized epilepsies have a photoparoxysmal response, i.e., an EEG abnormality which is produced by flashing light which persists after the light is turned off[10]. The estimated proportion of the population of epileptics that is susceptible to photic induced epilepsy is about seven percent[10].

Field Irradiance Measurements: Although the GLBI laser beam was measured in the laboratory, it was important to compare the measured laser exposure at the proposed test distances in the protocol to the previously modeled laser exposure. The methods and results of these measurements are delineated in a 24 January 2000 report by WE Mitchell (Appendix 1).

Daytime Visibility Threshold Determination: Due to the requirement to keep the GLBI eye-safe as near the aperture as possible, the beam diverges rapidly after leaving the aperture. The GLBI does not have the capability like the current red illuminator to position a small circle of focused laser light on an intruder at any significant distance. Therefore, GLBI was not expected to be used as a tagging device because of a probable limited daytime visibility threshold. The daytime visibility measurements were held on a bright sunny April day with a temperature of 77° and a relative humidity (RH) of 52%. Test runs were taken throughout the day but were clustered during the evening hours as the sun was setting (1200, 1500, 1700, 1900, 1930, 2000 hrs). There were two target backgrounds with the target subject wearing either a military camouflaged shirt or a white T-shirt. A target luminance measurement was taken on each target background with a Minolta model #LS-110 photometer before runs during a timeframe. The target subject walked slowly away from the observer who shone the beam on the back of the target subject. Because of its weight, GLBI was mounted on a tripod to insure beam stability. There were two observers and each threshold was the mean of two runs. The observer had the target subject stop when the green laser light was no longer visible to the observer, and that distance was measured. The target subject walked in the direction away from the setting sun on all runs.

Effect on a Vehicle Operator: Since it is possible that an incidental exposure to a laser illuminator could act as a glare source for a passing motorist or an aircraft pilot, the effect of GLBI and a current red illuminator as a glare source was measured through the windshield of a static vehicle. Another rationale for this test is that law enforcement could use a hand held laser illuminator to purposefully disrupt a vehicle operator's visual capability by flashing the beam in their eyes. Any scratches or divots in the vehicle's windshield should scatter the beam and would most likely exacerbate the effect of the glare source. A standard high contrast Bailey-Lovie visual acuity chart was positioned 20 ft in front of the vehicle during a nighttime data session (2100 hr) and was illuminated by the vehicle's headlights. Bailey and Lovie incorporate a logarithmic progression of letter size, same number of letters per row, and equal between letter spacing into their charts[11]. The GLBI and the red illuminator (diverged position) were positioned on tripods 82 ft (25 m) from the vehicle in a direct line with the acuity chart and the vehicle operator and then 5-8° to the left of a direct line. The illuminators were positioned so that the beam shone directly above the visual acuity chart and into the subjects' eyes. The approximate red illuminator irradiance in the diverged position at 25 m is 14 μW/cm^2 while the approximate GLBI irradiance at that distance is 3 μW/cm^2. Binocular visual acuity measurements were taken with no glare source as a baseline and then with the GLBI and red illuminator as a glare source at a direct and 5-8° offset views. Mean binocular visual acuity was calculated using the geometric mean[12], which is easily obtained from the Bailey-Lovie chart because of the geometric progression between lines. Significant loss of visual acuity for this experiment was defined as a decrease of two or more lines of acuity.

Flashblindness Determination: Because the extent of flashblindness is highly dependent on retinal adaptation level and is more easily ascertained at night, subjects were tested at night only. This test was started at 1945 hr with subjects sitting in a chair viewing the GLBI, which was stabilized on a tripod at a test distance of 25 m (irradiance ~ 3 μW/cm^2). A low contrast (10%) Bailey-Lovie chart was positioned at 5 ft to the right of the subject and was solely illuminated by an approximate ¾ moon (~ luminance readings with the Minolta Photometer were background .06 cd/m^2 and letters .02 cd/m^2). A baseline binocular visual acuity with the Bailey-Lovie chart was measured first, and then the subject looked into the beam for 10 s. After the 10 s GLBI exposure, the subject tried to read the line of acuity that was their baseline on the Bailey-Lovie chart. The time between exposure and when the subject was again able to read their baseline visual acuity was timed with a stopwatch and was considered the period of flashblindness. Flashblindness for this study was defined and explained to the subjects as a temporary vision impairment (similar to that experienced from flash photography) that interferes with the ability to detect or resolve a visual target following exposure to a bright light. Subjects were also questioned on whether they experienced an afterimage and if so, what color, shape, and size was the afterimage.

Effect on Night Vision Goggles (NVG): Since a NVG is not a direct view optic device, there is no increased hazard when directly viewing a laser with a NVG. NVG amplify existing light and provide a virtual image on a green phosphor display[13]. The observers for this experiment were wearing either a F4949G or a new ANVIS-7 NVG, all equipped with 3rd generation Image Intensifier (I^2) tubes. Most SF members will be using the ANVIS-7 that has two oculars and a single 3rd generation I^2 tube. The ambient light level was judged as approximate ¾ moon illumination. The NVG test was videotaped with a special video camera also equipped with a 3rd generation I^2 tube. The 3rd generation I^2 tube is very sensitive to the red wavelength (650 nm) with a relative spectral sensitivity response of .40 compared to a 1.0 peak at 760 nm. However, the 3rd generation I^2 tube has only a relative spectral sensitivity of less than .00005 to the GLBI's green wavelength (532 nm). The video camera directly viewed the beams of the GLBI and red illuminator (in the focused and diverged positions) beginning at 100 m to determine whether the energy at that distance would cause the NVG to shut down (bloom). An automatic brightness control protects the I^2 tube from damage from excessively bright light sources[13]. If the camera did not bloom when exposed to each illuminator at that distance, it was moved closer by 25 m until the blooming distance for that illuminator and condition was determined. Additionally, a subdued American flag uniform patch (black with olive green stars and stripes), which was designed by Night Vision Equipment Co. (NVEC) for night use where low visibility is desired, was used to examine the reflective visibility characteristics through NVG of the illuminator beams. The NVEC patch provides long-range reflection of infrared light that can be seen only through night vision devices. Both the GLBI and red illuminator beams illuminated the patch directly and at various angles at a range of approximately 25 m. The results of this test were captured with the NVG video camera.

MEDICAL RISK ANALYSIS

The GLBI Laser System has output parameters that classify it as a Class 3b laser according to the ANSI Z136.1-1993 American National Standard for Safe Use of Lasers[1]. There is no skin hazard associated with exposure to this laser. The laser does not exceed the ANSI Z136.1-1993 maximum permissible exposure (MPE) for skin during an accidental 10-second exposure. The MPE is defined as "the level of laser radiation to which a person may be exposed without hazardous effect or adverse biological changes in the eye or skin"[9]. There is an eye hazard associated with the GLBI device under normal operational conditions with both unaided and aided viewing. The nominal ocular hazard distance (NOHD) for a ¼ s unaided intrabeam exposure is 1.4 m and is 13 m with a typical 7 x 50 binocular. The ocular hazard MPE for the GLBI (532 nm) can be calculated from Table 5 in the ANSI standard from the following equation:

$$\mathrm{MPE} = 1.8t^{3/4} \times 10^{-3}\ \mathrm{J/cm^2}$$

The ¼ s blink/aversion response MPE for the GLBI can be calculated from this equation to a value of .64 $\mathrm{mJ/cm^2}$. For repetitive pulses, this value is multiplied by the correction factor $C_p = n^{-1/4}$ where n is the number of pulses during the exposure time. The resultant MPE per pulse value for GLBI is .042 $\mathrm{mJ/cm^2}$.

Table 4 (GLBI Percentage of MPE) was used by AFRL/HEDO to guide the investigators in determining the number of allowable exposures per day for each subject. Cumulative exposures in a 24-hr period were treated as a single continuous exposure. The more conservative limit for cumulative exposures given within a 24-hr period and prescribed by AFRL/HEDO is 40% of the MPE. All exposures during the test were timed and entered on a cumulative log for each subject. The laser safety officer from AFRL/HEDO reviewed the logs daily to ensure that exposure levels were consistent with this medical risk analysis. Human testing was only done with GLBI in the light mode (PRF = 25.7 Hz) because the pulse characterization is predictable, and the laser safety analysis was accomplished for this mode. The GLBI was not used for human testing in the flash mode (Approximate PRF = 16 Hz) because the pulse characterization is random and an adequate laser hazard analysis could not be accomplished for this mode. Although the flash mode could not be measured for a hazard analysis, it is inherently much safer than the light mode because with the lower PRF, fewer pulses enter the eye during a prescribed time interval. Therefore, an accidental exposure with the flash mode is not an eye safety hazard.

Table 4 GLBI Percentage of MPE (Hyperbolic Beam Expansion)

	Exposure Time	¼ s	1 s	5 s	10 s	20 s	Irradiance (μW/cm^2)
Test Distance	10 m	3.3%	4.6%	6.9%	8.2%	9.8%	17
	25 m	0.5%	0.8%	1.1%	1.3%	1.6%	3
	50 m	0.1%	0.2%	0.3%	0.3%	0.4%	1
	100 m	.03%	.05%	.07%	.08%	0.1%	-

The following laser safety procedures were briefed to all participating subjects prior to participation in this study:

1. Allow only authorized and trained personnel to fire the GLBI.
2. Never intentionally fire the laser unit at anyone with the exception of the "intruder" under strict constraints of times and distances listed in this protocol.
3. No simulated intruder should purposefully view the GLBI laser beam at any distance for longer than 10 s.

4. Personnel observing the GLBI testing should maintain a distance of 20 m from the GLBI operator.
5. Laser safety observers and subjects serving as laser targets during non-visual testing will always wear the laser eye protection (LEP) provided.
6. Discontinue testing if any personnel other than the intruder are accidentally exposed.
7. For any accidental exposure of personnel to the GLBI within a range of 10 m, report the exposure immediately to the Laser Safety Officer.
8. Remove the batteries from the GLBI when not in use for testing.
9. Do not allow the use of binoculars or any other aided viewing devices within the GLBI testing area.

RESULTS

<u>Daytime Visibility Threshold Determination</u>: The visibility threshold for the two observers and the luminance from the military camouflaged shirt target for the designated time frames are plotted in Figure 5. The visibility thresholds of the two observers are in excellent agreement with minimal disparity at the 2000 hr data point when the illumination was rapidly changing with the setting sun. The thresholds ranged from 1.07 m during the brightest time of the day (1500 hr) to 16.15 m at sunset (2000 hr). Thresholds were not near the minimal 25 m daytime visible threshold that the AF SF designated for the red laser illuminator programs. None of the red illuminators met the daytime threshold requirement of 25 m either.

The visibility threshold for the two observers and the luminance from the white shirt target for the designated time frames are plotted in Figure 6. Visibility thresholds are in even better agreement with the two observers with the white shirt as the target. Even though the white shirt target was much more reflective than the fatigue shirt target, the visibility thresholds were very similar. Thresholds ranged from 1.37 m (1700 hr) to 16.46 m (2000 hr). The nighttime visibility threshold was estimated to be just over 150 m., and because the beam is so divergent, the GLBI performed more as an area illuminator rather than as a tagging device. The large GLBI footprint made it fairly easy to locate a target within the 150 m range at night.

<u>Effect on a Vehicle Operator</u>: The mean baseline binocular visual acuity (BVA) measured in the logarithm of the minimum angle of resolution (LogMAR) was .03 or 20/21.5. Mean BVA with the GLBI beam shining directly at the subject in the vehicle was 20/51.3 (LogMAR 0.41) and 20/50 (LogMAR 0.40) with the current red illuminator in the diverged position. As both of these measurements were a decrease of more than two lines of visual acuity, they met the criteria to be significant for this experiment. When the beams were directed at the subject in the vehicle from 5-8° from the direct line of sight, the mean BVA was 20/20.5 (LogMAR 0.01) with both the GLBI and diverged red illuminator conditions. These measurements were actually an improvement from

baseline, and two subjects did indicate during testing that the letters became clearer with the laser on at the 5-8° offset. This was most likely due to a decreased pupil diameter with the increased illumination. When subjectively comparing the GLBI glare cone to the red illuminator's glare cone in the diverged position, all five subjects agreed that the green appeared brighter, but the red cone was more irritating and disconcerting. Obviously, the GLBI and red illuminator footprints are not the same at the 25 m test distance. The GLBI beam is more divergent and, therefore, the footprint is larger. The red Illuminator has a uniform beam so the irradiance should be fairly equal throughout the beam, while the GLBI beam is a myriad of hot and cold spots making it difficult to ascertain the irradiance of the glare source for each subject. Both the size and quality of the footprints could confound this data.

Flashblindness Determination: Using a low contrast Bailey-Lovie visual acuity chart with no illumination other than moonlight was utilized to increase the test sensitivity for determining the amount of flashblindness created by exposure to the GLBI. Previous flashblindness testing with the red illuminators demonstrated minimal flashblindness using a high contrast near vision chart and low contrast Amsler Grid (both with external illumination), even though the irradiances were much higher. Mean baseline binocular visual acuity at night for the subjects with the low contrast Bailey-Lovie chart was 20/370 (LogMAR 1.85), which equates to between the 20/50 and 20/63 lines at the chart distance of five feet. The mean time between exposure and when the subject was able to read their baseline BVA was 14.6 s with a range between 5 and 35 s. This time of visual interruption was considered the period of flashblindness. All subjects reported a green afterimage following exposure that varied in shape and size.

Effect on Night Vision Goggles: The NVG camera bloomed when directed at the red illuminator beam from 100 m in both the focused and unfocused positions. This was not surprising noting the 3rd generation NVG I^2 tube's relative spectral sensitivity to 650 nm. However, the camera did not bloom when directed at the GLBI until it was moved up to 25 m. This was also not surprising considering how insensitive the 3rd generation NVG I^2 tube is to 532 nm. Although you can see the GLBI beam easily wearing NVG, the red beam overwhelms the green GLBI in side-by-side comparison through NVG. The red illuminator beam in the focused position is visible from the side through NVG emanating from the aperture. Neither the red illuminator divergent beam nor the GLBI beam is visible through NVG from the side. Predictably, the NVEC subdued uniform flag patch appeared as a bright circle of light through the NVG when illuminated by the red beam. In fact, the NVG was so sensitive to the red reflected light from the patch that no details of the flag were visible to the viewer. The patch appeared as a bright circle of light from several distances and off-axis angles. Any reflected GLBI light from the NVEC patch was not seen through the NVG.

Figure 5 Visibility Threshold (Camouflaged Shirt)

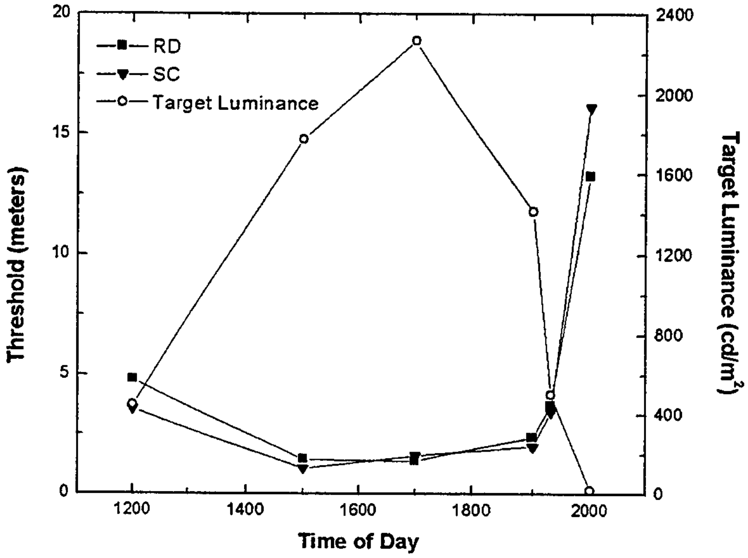
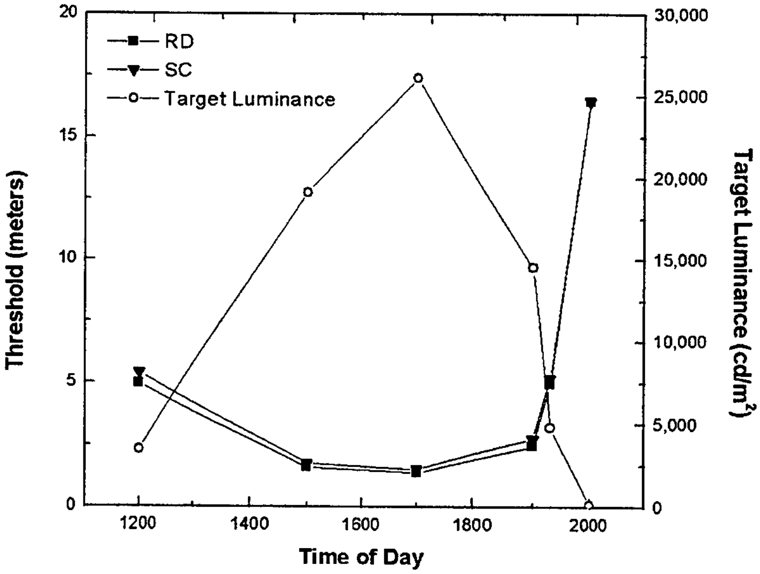


Figure 6 Visibility Threshold (White Shirt)



DISCUSSION

AFRL/HEDO determined that the GLBI laser system has output parameters that classify it as a Class 3b laser according to the ANSI Z136.1-1993[1]. When the LSO determines that there is a reasonable probability of accidental viewing with direct view optics, the laser beam is measured through a 50 mm aperture (e.g., 7 x 50 binoculars) rather than the standard 7 mm (maximum pupil diameter). The position of AFRL/HEDO is that all laser illuminators will have a reasonable chance of an accidental viewing through direct view optics and thus, the 3b classification. As with any other laser system, there is an increased eye hazard when viewing GLBI through direct view optics such as binoculars or a telescope. Viewing a laser through these direct view optics devices will increase the retinal irradiance by as much as the square of the magnifying power of the optical system, substantially increasing the eye hazard. ANSI Z136.1-1993 requires a medical surveillance program for users of a Class 3b laser system. An eye examination that includes a medical history, monocular visual acuities, monocular Amsler grid examinations, and monocular color vision tests is completed when the individual begins training with GLBI, to determine a baseline, and following a suspected injury. There is no requirement for periodic vision or dilated retinal examinations.

Current eye-safe* laser illuminators, including GLBI, have been a disappointment during daytime testing as psychological tagging and glare source devices and have been operationally effective only at nighttime. They appear to have some limited capability at dawn, dusk and on cloudy days. The GLBI beam is too diverged (to reduce the eye hazard zone to 1.4 m) to be effective as a daytime tagging or glare source device. Yet, green (532 nm) is 8.27 times more efficient to the light adapted eye than red (650 nm). If an eye-safe green illuminator with similar irradiance and focusing abilities as the current red illuminators was developed, the daytime effectiveness of the device would no doubt increase beyond the red illuminators. However, it still would be questionable if that enhancement of performance would equate to a significant improvement in daytime operational capability. AFRL/HEDO did compare the GLBI and red illuminator during these tests even though the devices are very dissimilar, and this may have been somewhat unfair. A more ideal comparison would be to contrast red and green laser illuminators with equal power laser diodes, the same optical train, and red and green sources matched for equal photopic luminance.

Green does have some other advantages over red which merit continued consideration for future development of this technology. Since the eye is so much more receptive to green than red, green laser light has more potential as a flashblindness and glare source when the corneal irradiances of both are the same. Green should also be able to elicit equal visual interruption with less energy than red. However, both the red and green laser illuminators have been evaluated as an excellent nighttime glare source during operational testing. Differences between the red and green illuminators may be difficult to discern at night at operational ranges because they both are most likely bright enough to overwhelm the retinal photoreceptors. Since NVG 3rd generation I^2 tubes are not very sensitive to green (532 nm), a green laser illuminator can be used more covertly

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* i.e., equal to or less than the MPE at test distances (preferably, at the laser aperture).

than a red illuminator. That's not to say that the GLBI is invisible to a NVG wearer. The GLBI is just much less visible to the NVG wearer than the red illuminators.

There could be several improvements made to the GLBI that would make it more marketable to law enforcement. Obviously, the GLBI needs to be made more compact and lighter (< 5 lbs.) to be utilized as a flashlight illuminator. The optical train needs to be miniaturized preferably with a laser diode when available rather than a laser solid-state design. Current green laser diodes are expensive and are not manufactured in high enough powers for use in laser illuminators (100-250 mW). At this time, there is no commercial application for green diodes other than low power diodes for laser pointers. Red diodes are being used extensively in the medical field while blue diodes are currently being developed for data storage and other commercial applications. An improved GLBI should be eye-safe at the aperture with a uniform "top hat" beam profile rather than the irregular beam with many hot spots that it now has. Since the cost of each illuminator will be fairly significant, the final product design needs to be hardened and drop test survivable. The current GLBI battery pack is unacceptable, and a reliable battery pack using standard batteries should be incorporated. To be effective for both psychological tagging and as a glare source, all illuminators should have an adjustable focus similar to the contemporary red laser illuminators. The small focused beam that is required for tagging an intruder at long distance is difficult to place into the eyes of a moving intruder. Conversely, a diverged beam that is ideal for use as a glare source at short ranges will not tag an intruder effectively at long distances.

OBSERVATIONS AND PROGRAM RECOMMENDATIONS

1. The GLBI did not perform well as a daytime tagging device primarily due to the highly divergent beam. However, the red laser illuminators previously tested also rated poorly as a daytime tagging device (See item 6, below).

2. The GLBI worked well as a nighttime glare source when shown directly at a vehicle operator and elicited some flashblindness at the test distance and under the conditions in this report.

3. Although visible to NVG, the GLBI is much more covert to NVG than the red laser illuminators.

4. The GLBI requires some significant improvements to make it marketable to law enforcement.

5. The red laser illuminators are tested and have proved effective as nighttime glare sources.

However;

6. Since the light adapted eye is 8.27 times more sensitive to green (532 nm) than red (650 nm), a green laser illuminator with a focused beam similar to the current red laser illuminator would most likely buy some increased daytime tagging capability.

7. Green laser light has more potential than red as a flashblindness and glare source when the corneal irradiances are the same.

8. The most essential improvement to GLBI would be to miniaturize the device with a laser diode design rather than its current solid-state design.

9. At this time, there are no green laser diodes manufactured in high enough powers (100-250 mW) to be used in a laser illuminator.

10. When higher power, green laser diodes become available, this technology should be further explored as an alternative or supplement to the red laser illuminators.

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APPENDIX 1

DEPARTMENT OF THE AIR FORCE
AIR FORCE RESEARCH LABORATORY (AFMC)

FROM: Wallace E. Mitchell, Litton-TASC

24 January 2000

SUBJECT: GLBI Irradiance Measurements

TO: Richard J. Dennis, AFRL/HEDO (Karta Technology, Inc.)

1. Purpose: This memo documents the results of measurements performed to compare measured laser exposure at various distances to previously modeled laser exposure.

2. Background: The GLBI prototype (Fig. 1) was developed through a small business innovative research (SBIR) contract (DAAE30-96-C-0070, US ARMY ARDEC) to LE Systems, Inc. of Glastonbury, CT. The contract was funded by the Defense Advanced Research Projects Agency (DARPA) and the National Institute of Justice (NIJ) through the Joint Program Steering Group (US Department on Justice and US Department of Defense). The Laser Systems Branch of the Air Force Research Laboratory (AFRL/DELS) at Kirtland AFB, NM has monitored the contract, and the ten prototypes from this technology demonstration program were delivered to AFRL/DELS in April 1998. The principal customer for the GLBI is the NIJ who is funding the eye safety certification and the field testing in this protocol. The original, unmodified prototype had a battery powered (3 amp Duracel, size 4/3A-nickel metal rechargeable) green laser diode [532 nm, 260 mW (180 mW at the aperture)]. The prototype device had a four-inch diameter output aperture, a divergence of 20 mrad, and a beam that was continually chopped at 8-18 Hz with a 50% duty cycle. This prototype was then reevaluated and modified by AFRL/DELS to improve the optical train. The Optical Radiation Branch (AFRL/HEDO) at Brooks AFB TX characterized the modified device and also performed hazard analysis. Results are presented in the Consultative Letter, AFRL-HE-BR-CL-1999-0025, Laser Hazard Assessment of the LE Systems Green Laser-Baton Illuminator (GLBI). The modified device was used in our measurements and the results are reflected in this memo.

3. Scope: Measurements were performed on 15 December 1999 in Bldg. 175E, Brooks AFB TX. Activities that took place included measuring the irradiance of the GLBI device at various distances (10 m, 25 m, 40 m), calculating irradiance through a 7 mm aperture (measured exposure), and comparing this irradiance to previously modeled exposure values.

4. Evaluation Personnel: Wallace Mitchell, Richard Dennis

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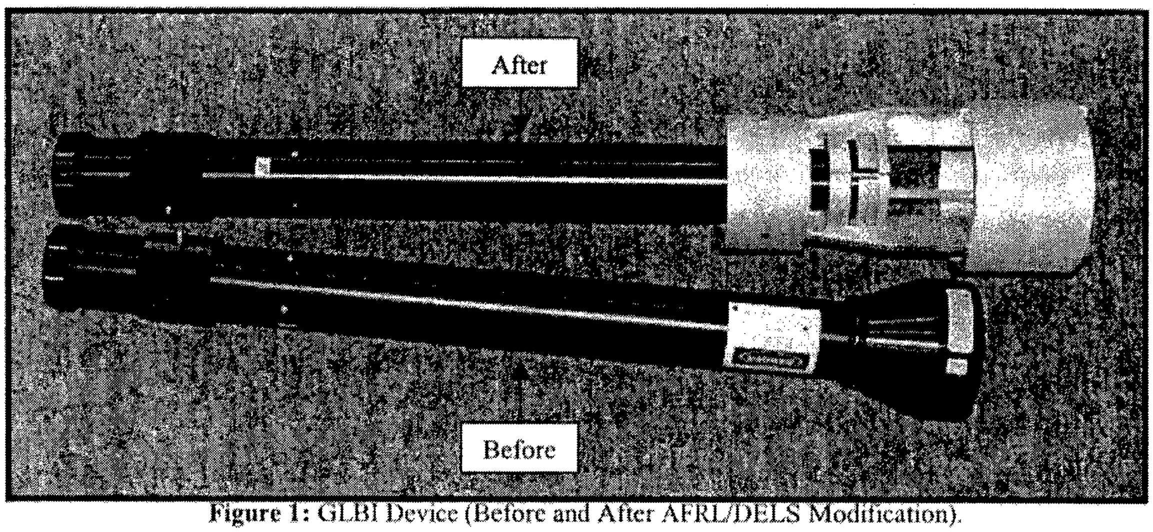

Figure 1: GLBI Device (Before and After AFRL/DELS Modification).

5. Laser Measurement and Techniques

a. Measurement Equipment: Laser measurement equipment and personnel were provided by AFRL/HEDO. All equipment is regularly calibrated and maintained according to manufacturer recommended schedule. Table 1 lists the equipment used in the GLBI measurements.

Description/Model Number	Serial No.	Date Calibrated
Laser Probe Model 6600 Radiometer	9109-0269	8/16/99
Laser Precision Model RKP-576 Probe	9107-0044	6/1/99
GLBI	06	N/A

Table 1: Equipment for GLBI Measurements

b. Irradiance Measurement: With the laser beam off, the background radiation was first corrected using the measurement features of the RM6600 radiometer. The irradiance was measured by placing the RKP-576 detector (area = 1 cm^2) directly in the path of the laser beam at one of the three measurement distances. Figure 2 illustrates the measurement setup. The beam was centered on the input aperture of the detector probe and then carefully moved to other positions so as to find the "hottest" portion of the beam. The highest value was then recorded. This was performed five times for each of the measurement distances. Results are shown in Table 2.

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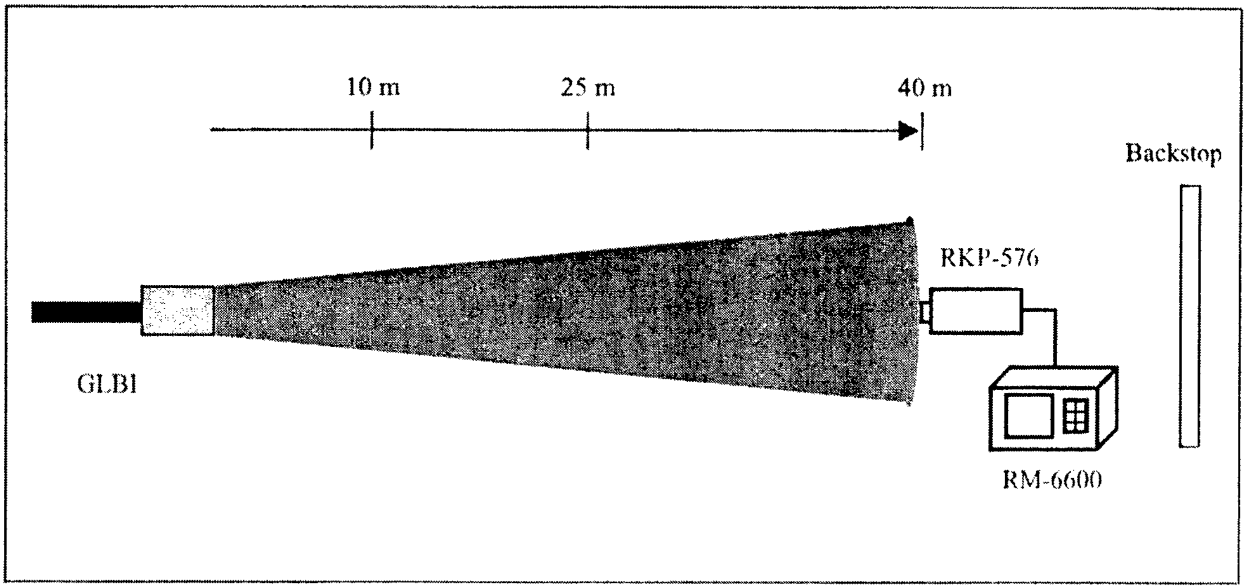

Figure 2: Irradiance Measurement Setup

Measurement #	Irradiance (uW/cm^2) @ 10 m	Irradiance (uW/cm^2) @ 25 m	Irradiance (uW/cm^2) @ 40 m
1	16.60	2.91	1.20
2	15.63	2.92	1.17
3	18.91	3.01	1.22
4	19.14	3.33	1.23
5	16.89	2.95	1.14
Average	**17.43 ± 0.87**	**3.02 ± 0.15**	**1.19 ± 0.06**

Table 2: Irradiance Measurement Summary

c. Irradiance through a 7 mm Aperture: The irradiance, E_{7mm} (uJ/cm^2) is given as

$$E_{7mm} = (E_{total}) * (\pi r^2) * (t) \qquad (1)$$

Where:

E_{total} is the average irradiance (uW/cm^2) from Table 2
r is the radius (cm) of the 7 mm aperture
t is the time of exposure (0.25 sec)

The results are given in Table 3.

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Irradiance (uJ/cm^2) thru 7 mm Aperture @ 10 m	Irradiance (uJ/cm^2) thru 7 mm Aperture @ 25 m	Irradiance (uJ/cm^2) thru 7 mm Aperture @ 40 m
1.68 ± 0.08	0.29 ± 0.01	0.11 ± 0.01

Table 3. Irradiance thru 7 mm Aperture Summary

d. Measured Exposure vs. Modeled Exposure: The modeled exposure was previously given in the Consultative Letter, AFRL-HE-BR-CL-1999-0025, Laser Hazard Assessment of the LE Systems Green Laser-Baton Illuminator (GLBI). Comparison of the measured exposure (E_{7mm}) to the modeled exposure is given in Table 4.

Measurement Distance (m)	Measured Exposure (uJ/cm^2)	Modeled Exposure (uJ/cm^2)	% Difference
10	1.68	1.38	18
25	0.29	0.22	24
40	0.11	0.09	18

Table 3. Comparison of Measured and Modeled Exposures

6. Conclusions: The measured exposure was, on average, 20% higher than the modeled exposure. Considering the low irradiance values that were measured, 20% is an acceptable value and the modeled exposure is therefore validated. Even with the higher measured values, the exposure is still just a small fraction of the MPE.

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