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FIELD TEST OF A LASER SIGNALLING DEVICE

by

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March 1972

U.S. ARMY MATERIEL COMMAND

HARRY DIAMOND LABORATORIES

WASHINGTON, D.C. [illegible]

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1. INTRODUCTION

Visible signalling devices of various types have been in use from the earliest days of mankind. A flag, or torch, or smoke from a fire provided instantaneous communications over line-of-sight paths for thousands of years before the invention of electrical or electronic devices such as the telegraph, telephone, and radio. In the last hundred years, however, these new and convenient methods of conveying information have almost totally supplanted visual signals in everyday-life, and for most of us the only visual signalling still in use is a vague hand wave or a flashed automobile headlamp.

The two major areas where visible signals are still in use are military and emergency situations. In emergencies the need for communications is pressing, the means may be limited, and the required vocabulary is small. The message is simple, "Here I am," in the case of flares, signalling mirrors, smoke, and flashlights; and "Get out of my way," in the case of flashing lights on emergency vehicles. In the military the message may be much more complex, but the level of training and discipline among military users allows more complex conventions. This combines with more extensive equipment to provide an expanded vocabulary. Thus red smoke may mean "This is your target," while green smoke means "This is a friendly position." Also, the military often has use for the simple emergency message such as "Here I am."

Most visual signals are insecure. The flare that says "Here I am," to a rescue helicopter also delivers the same message to hostile ground forces in the area. The smoke that says "This is a friendly position," to attacking aircraft also compromises the code (color) of the day and allows later "spoofing" by the enemy. The most obvious relatively secure optical signals are hooded searchlight beams and heliograph systems such as simple signalling mirrors. Both depend on an aimed beam of light which is visible only to the intended receiver. Various infrared signalling devices also offer security, but require apparatus of some sort at the receiver and thus reduce one of the major advantages of any visible signal, which is the fact that each and every individual is equipped with an extremely sensitive and versatile set of optical receivers.

Recent developments in laser technology, and in particular the development of a small, portable, battery-powered Helium-Neon laser at the Harry Diamond Laboratories, suggest that a laser signalling device may be practical for emergency and

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military use. Such a device, complete with batteries for a reasonable period of operation, might be approximately the size and weight of a flare pistol and have an output of about 1.5 milliwatts at 0.6328 μm. By making use of characteristics of standard light sources, it is shown in the appendix that a small laser should be nearly two orders of magnitude more effective as a visible signal than an electric light of similar size and input power.[1]

The laser signaller could have a narrow beam both to increase source brightness and to insure security. The standard specifications of beam size in a multimode laser is in terms of the beam divergence α of the output beam where α is the full apex angle (at the laser) of a cone that contains 90% of the beam power. The beam divergence of the laser can be designed to be any value from about one milliradian up to several tens of milliradians, and can be made adjustable by using a simple lens system at the source of the laser.

Unit cost of such devices in reasonable quantities should be quite low ($200 - $300) and there is no reason to anticipate any major difficulty in meeting military environmental specifications. A device of this type would be suited to emergency signalling applications such as downed-aircrew recovery and to simple surface-to-air signalling such as marking of friendly lines or landing zones. A simple communication or identification code in the form of manual or automatic on-off keying might be provided.

This report describes a series of field tests designed to determine the actual visibility of such a laser signaller under realistic conditions. In addition, it was hoped that the test would confirm the security of the signal (cut-off of visibility for observers outside the beam) and provide some data on the optimum beam divergence for such a device, taking into account the trade-off between the desire for high visibility (small α) and easy aiming of the beam (large α).

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[1]Electro-Optics Handbook, Radio Corp. of America, Defense Electronic Products, Aerospace Systems Division. (Burlington, Mass.) 1968.

2. EXPERIMENTAL PROCEDURES

The field test was carried out in two phases over a three-day period (6 - 8 July 1971). The first phase consisted of tests over a line-of-sight path from the roof of Building 92 of the Harry Diamond Laboratories (Washington, D. C.) to the roof of a high-rise building in Silver Spring, Maryland, over a range of 6.55 km (fig. 1). This phase was used to adjust the laser signaller, confirm the boresighting technique, measure the spot size over which the signal was visible, and try several values of laser beam divergence.

The second phase of the test was carried out at the Harry Diamond Laboratories Test Area (HDL/TA) located on the Potomac River near La Plata, Maryland. In this phase the laser signaller was located at the tree line on the bank of the river and a UH-1 helicopter from Davidson Field, Fort Belvoir, Virginia, flew a series of prearranged courses at ranges from 2 to 30 km from the laser and at altitudes from 1500 to 4500 feet (fig. 2). Observers on the helicopter noted the subjective visibility of the laser signaller at various known ranges, and both still and motion pictures were taken from the air.

During both phases of the test, radio communications between the laser-signaller position and the observer position permitted adjustment of beam divergence and aiming of the beam to provide maximum data.

It was originally intended that a prototype of the battery-powered laser signaller be used as the laser in this test. However, a fault in the power supply prevented it from operating for extended periods. A commercial Helium-Neon laser was substituted for the prototype. It had an output power of 1.5 milliwatts with a 1.5-milliradian beam divergence, closely matching the characteristics of the prototype signaller. A variable focus telescope was used to expand the laser beam to about 3 centimeters diameter and to recollimate it to give a beam divergence that could be varied continuously from 1 to 10 milliradians. The laser and telescope were mounted on a metal plate. A 5-power telescopic rifle sight was mounted to the same plate in such a way that its axis could be adjusted to be parallel to the laser beam. This

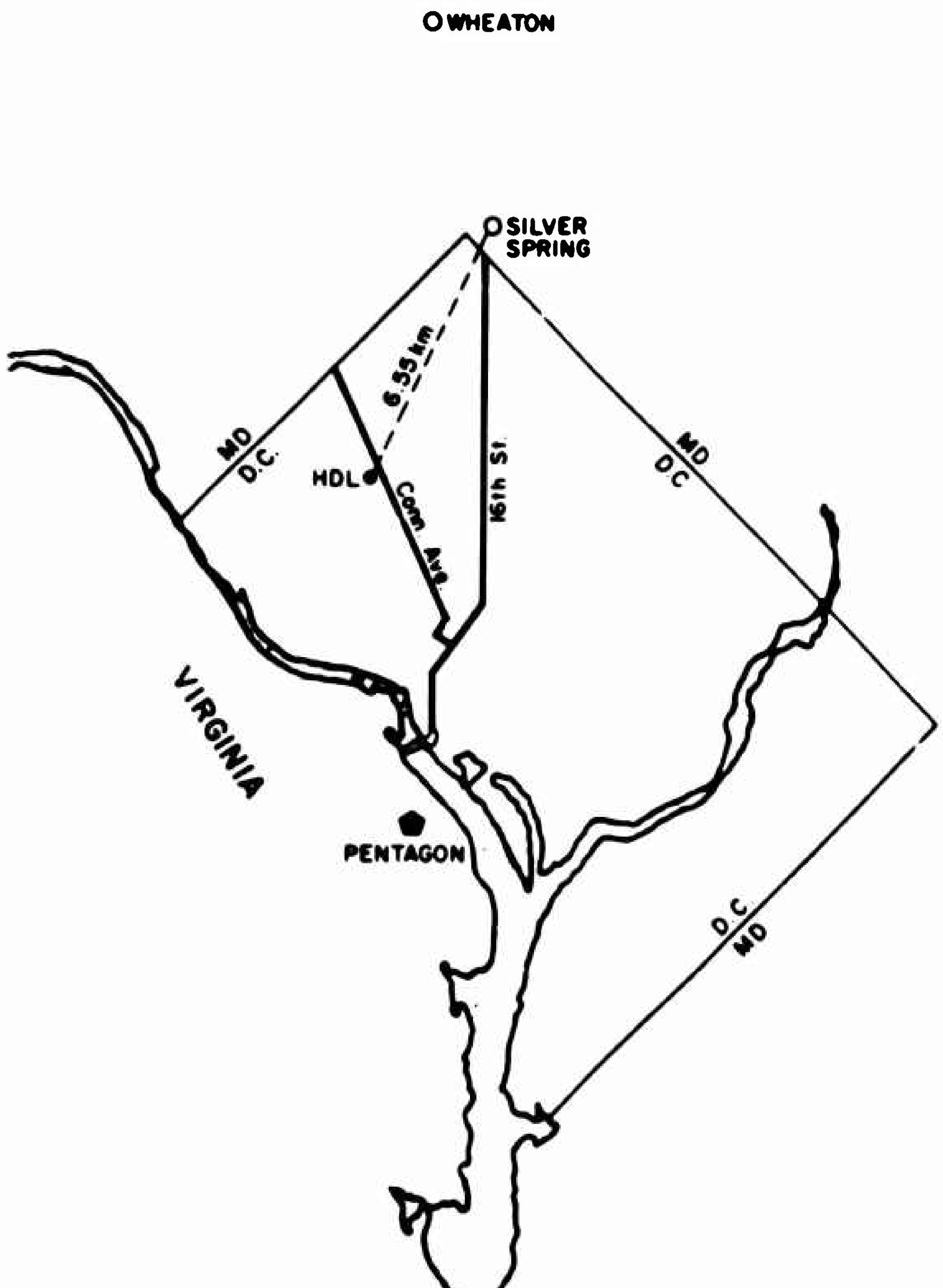

Figure 1. Map of the metropolitan Washington, D. C. area showing the end points of the roof-to-roof phase of the test

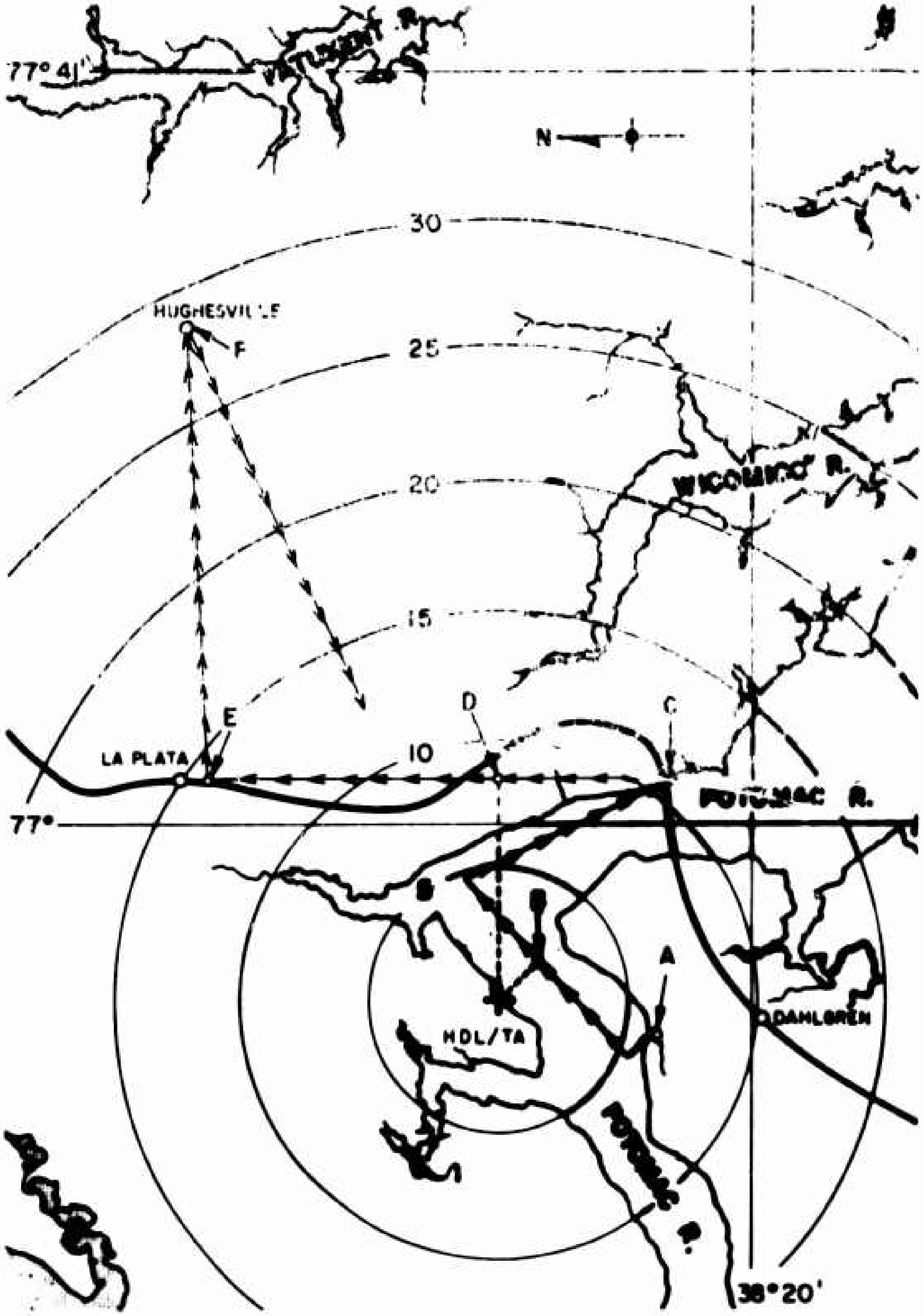

Figure 2. Map of the vicinity of the Harry Diamond Laboratories Test Area showing the laser position and the helicopter flight path. Circles give range in kilometers.

arrangement is shown schematically in figure 3. In use, the assembly was mounted on a heavy tripod which could be swept on two axes for tracking moving targets or locked in position on a stationary target.

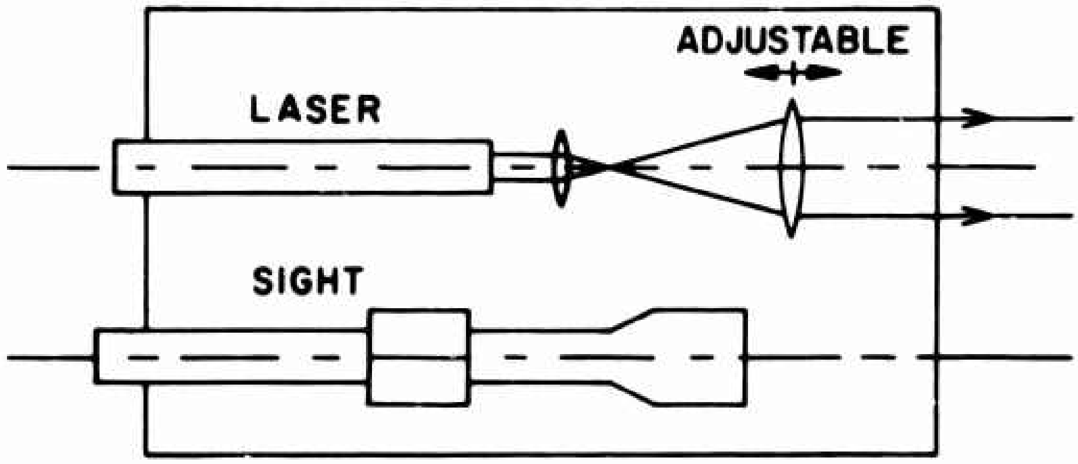

Figure 3. Diagram of the laser signalling arrangement used in the tests

Bore sighting of the rifle scope to the laser beam was accomplished by using a molded plastic reflector of the type used on the rear of motor vehicles. The laser beam was returned by this reflector in a relatively narrow beam (about 10 degrees full angle). The sighting telescope was adjusted by mounting the reflector 50 to 100 feet from the laser and aiming the laser at the reflector. The sight was then adjusted making proper allowance for parallax. In bright sunlight, the beam itself was completely invisible from the side or when striking diffuse reflectors and could not be seen even when a piece of white paper was held in its path.

When a laser device is proposed for field use, it is necessary to consider the eye hazard, if any, which that device introduces. The power level of the laser signaller is low enough that diffuse reflection presents no hazard, even when the reflector is only a few inches from the laser. The only possible hazard is from the direct beam or true specular reflections.

The irradiance, $H(R)$ in watts/cm^2, in the beam is given by the equation

$$H(R) = P_0 e^{-\sigma R} [\pi (r_0 + \frac{\alpha R}{2} 10^{3})^2]^{-1} \quad (1)$$

where P_0 is the radiant power output of the laser in watts, R is the range from the laser to the observer in kilometers, and σ is the atmospheric attenuation coefficient in km^{-1}. As a rough estimate, σ may be taken to be equal to 3.9/V where V is the meteorological visibility.[2] The term in brackets is the beam area, r_0 is the beam radius at the telescope output lens in centimeters, α is the full angle beam divergence, and R is again the range in km. This equation neglects losses in the telescope, which were about 16 percent in this experiment. From a safety standpoint the worst case is $\alpha = 2.0$ milliradian and $\sigma = 0$, then

$$H(R) \approx P_0 \left[\pi (r_0 + 10^2 R)^2\right]^{-1} \qquad (2)$$

H(R) is plotted versus R in figure 4, for $P_0 = 1.5 \times 10^{-3}$ watt and $r_0 = 0.5$ cm. For continuous-wave lasers, the currently established safe level of exposure is 10^{-6} watt/cm^2, with a recommended safety factor of 2 for field and training exercises.[3] The resulting level (5×10^{-7} watt/cm^2) is shown in figure 4, and it can be seen that H(R) is below this level for R greater than 0.3 km. For this test a safety range of 2 km was used and the laser was turned off whenever the helicopter came within that range.

The real threshold for eye damage (neglecting the factor-of-two safety margin), is at a range of 200 m (10^{-6} watts/cm^2). The spot diameter at 200 m is only about 36 cm which makes it very unlikely that the spot would inadvertently be directed into an observer's eye. Furthermore, the 10^{-6} watt/cm^2 level is a "safe" level of exposure, meaning that a higher exposure is required to give a high probability of detectable eye damage. Reasonable field practice would require that the 300 m safety range be observed, but occasional accidental exposures at much shorter ranges can be expected to carry only a relatively low statistical risk of eye damage. The exact level of risk is a matter of concern and should be established, but it is certainly many orders of magnitude less than the risk associated with pulsed lasers used in illuminators, designators, and range-finders. The laser signaller is certainly much safer than a flare pistol and probably as safe as a flare or smoke bomb.

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[2] Wolfe, W. L. (ed.), Handbook of Military Infrared Technology, Office of Naval Research, Department of the Navy (Washington, D. C.) 1965, p.203.

[3] TB MED 279 (NAVMED P-5052-350), Departments of the Army and the Navy, Washington, D. C. (24 Feb. 69) Paragraph 6(a).

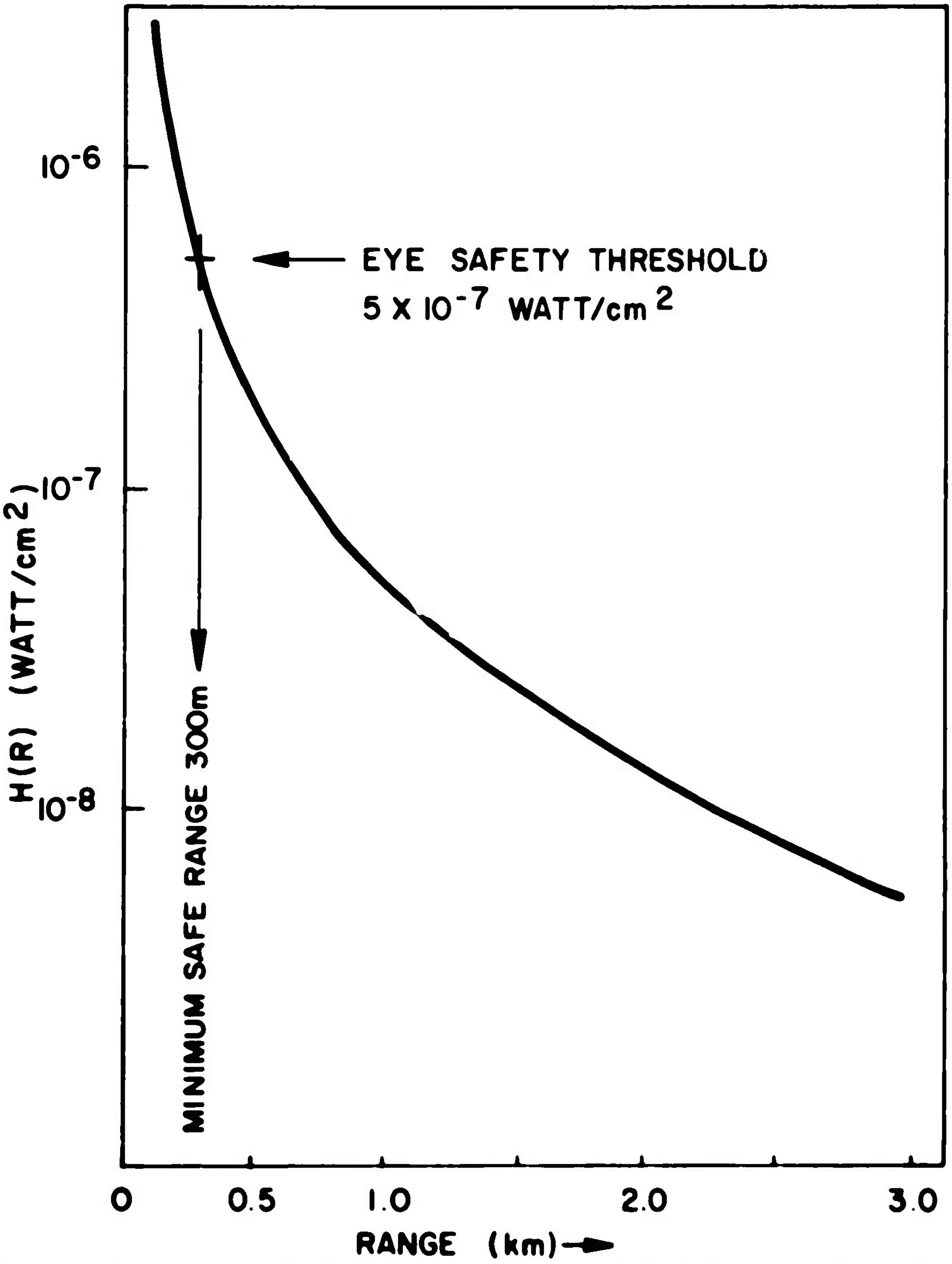

Figure 4. Graph of H(R) versus the range R for a He-Ne laser with 1.5 mW output and 2x10⁻' radian beam divergence. The eye safety threshold shown is the level suggested by TB MED 279 (Ref. 4)

Using equation 1 with $\alpha = 2 \times 10^{-3}$ rad, $P_0 = 1.5 \times 10^{-3}$ watt, $\sigma = 0.2\ km^{-1}$ (corresponding to a visibility of about 20 km) and R = 20 km gives $H(20\ km) = 2.2 \times 10^{-12}\ watt/cm^2$, which is a readily detectable signal with narrow band pass optical filtering and off-the-shelf detectors. This allows two possible somewhat more sophisticated systems to be considered. First, a search aircraft could be provided with a scanning detector system (or set of multiple detectors) that would automatically alert the aircraft crew when even a momentary flash of energy at the right wavelength was received from a laser signaller. This reduces the tracking steadiness required for the laser operator and enlarges the effective search area of the aircraft. The detector system could be made to provide directional information to the aircraft crew which could then follow up with visual sighting. Second, a modulation (amplitude or subcarrier frequency) might be imposed on the laser signal and, in applications where the tracking is sufficiently steady, a beamed communications channel can be created from a laser to an optical receiver. This channel is essentially immune to interception and jamming, although it is strictly limited to line-of-sight applications.

3. RESULTS

A. Phase I: Harry Diamond Laboratories to Silver Spring, Maryland.

Testing began on 6 July 1971 in the late afternoon. Meteorological visibility was estimated to be approximately 15 km. The sky was overcast. The observer-to-laser range was 6.5 km. The laser was clearly visible as a very bright red spot with apparent dimensions nearly equal to the platform on which the laser was mounted (about 3 m). Testing was terminated after about 30 minutes due to rain.

The second test period was at about noon on 7 July. Conditions were bright sunshine with light haze and visibility estimated at 20 to 25 km. After attempting to center the spot on the observer the spot diameter was measured for 2- and 4-mrad beam divergences. These numbers are compared with the calculated spot size [given by $2(r_0 + 10^5\alpha R/2)$] in table I.

The discrepancy in spot size is probably due to failure to center the spot vertically on the observers, so that a chord of the circular spot was measured instead of a diameter.

Table I. Measured Versus Calculated Spot Size

α(mrad)	Spot Diameter (cm)	
	Experimental	Calculated
2	880	1300
4	1940	2600

An errcr of about one third of a spot diameter in vertical positioning would account for these differences. The uncertainty in the measured values is about ±60 cm, which can account for some of the discrepancy. The beam was found to have a very well defined boundary. Movement of the observer over a distance of about 60 cm was sufficient to go from full visibility to full extinction. At the 2-mrad setting, the spot was extremely bright, and effects that are characteristic of coherent light could be clearly observed (speckle and grain in the light spot). At the 4-mrad setting, these effects were reduced but the spot was still very bright and immediately caught the eye even against a brightly sunlit cityscape. A test at 6 mrad indicated very noticeable reduction in spot brightness.

In the fringe of the beam, a flickering was observed, which was atributed to atmospheric effects. No such effects were visible elsewhere in the beam. The spot fringes were about 60 cm in extent, indicating about 0.1 mrad of random spot jitter over a 6.5-km path. This is an upper limit only, since part of the fringe thickness was probably due to the gradual fall-off of beam intensity.

B. Phase II: Surface-to-air at the HDL Test Area.

This phase of the test was carried out on 8 July 1971 under conditions of bright sunlight and scattered clouds. There was a bank of industrial haze originating at a power plant at point C (fig. 2) at the east end of the U.S. Route 301 bridge across the Potomac River and running southeastward to form a barrier at a range of about 10 km from the laser position at the test area. Meteorological visibility was estimated to be at least 20 km. The helicopter flight path was excluded from areas south of the HDL/TA (at ranges over about 5 km) by a restricted airspace over the U.S. Naval Weapons Laboratory at Dahlgren, Virginia.

Figure 2 shows the region around the HDL/TA and shows the helicopter flight path with 6 specific reference points (A through F). The flight path was not actually flown as one continuous flight, but was completed as shown in a series of disconnected segments. The helicopter altitude varied from 1500 to 4500 feet. The range on the ground from laser to helicopter varied from 2.5 km to 28 km. The slant range is not significantly different from the ground range.

The laser signaller was clearly visible from the air at all points along the flight path. In the vicinity of point B (R = 2.5 km), there was some difficulty in holding the spot on the helicopter with a 2-mrad beam, indicating that a larger or an adjustable beam divergence is desirable to reduce tracking problems at short ranges. A 4-mrad beam was tried at short ranges, and this eliminated the tracking problem. At all ranges over 5 km, a 2-mrad beam allowed adequate tracking of the target. The variation in tracking difficulty with range requires some comment since the angular size of the spot is the same at all ranges and the required tracking precision is thus independent of range. The explanation is presumably that the higher angular tracking rate at short range makes it more difficult to follow the target. It should be noted that a 2-mrad pointing accuracy is equivalent to hitting a 20-cm diameter target at 100 meters, which is not a particularly difficult feat of marksmanship. In the case of using the signaller for spotting purposes, it is only necessary to sweep the beam back and forth over the aircraft to provide a flashing light that can easily be located.

The apparent enlargement of the dimension of the laser source seen in the first phase of the test was again observed. The air-borne observers reported that the light spot appeared to be about the same size as a small truck parked near the laser position. Photographs taken at points along the flight path show this enlargement but do not reproduce the brilliance of the signal. Figure 5 is a photograph taken from near point A. All air-borne observers who have seen the photographs agree that the signal was orders of magnitude brighter than the spot seen on the prints. This effect is due to the limited dynamic range of photographic film as compared with the human eye. The spot on the film is saturated and all additional energy is simply lost.

At ranges of more than 5 km the ground crew could not hear the helicopter, and at ranges of the order of 10 km or greater there was great difficulty in tracking it visually. Once track was lost at these ranges it required careful searching with field glasses and some prompting by radio to

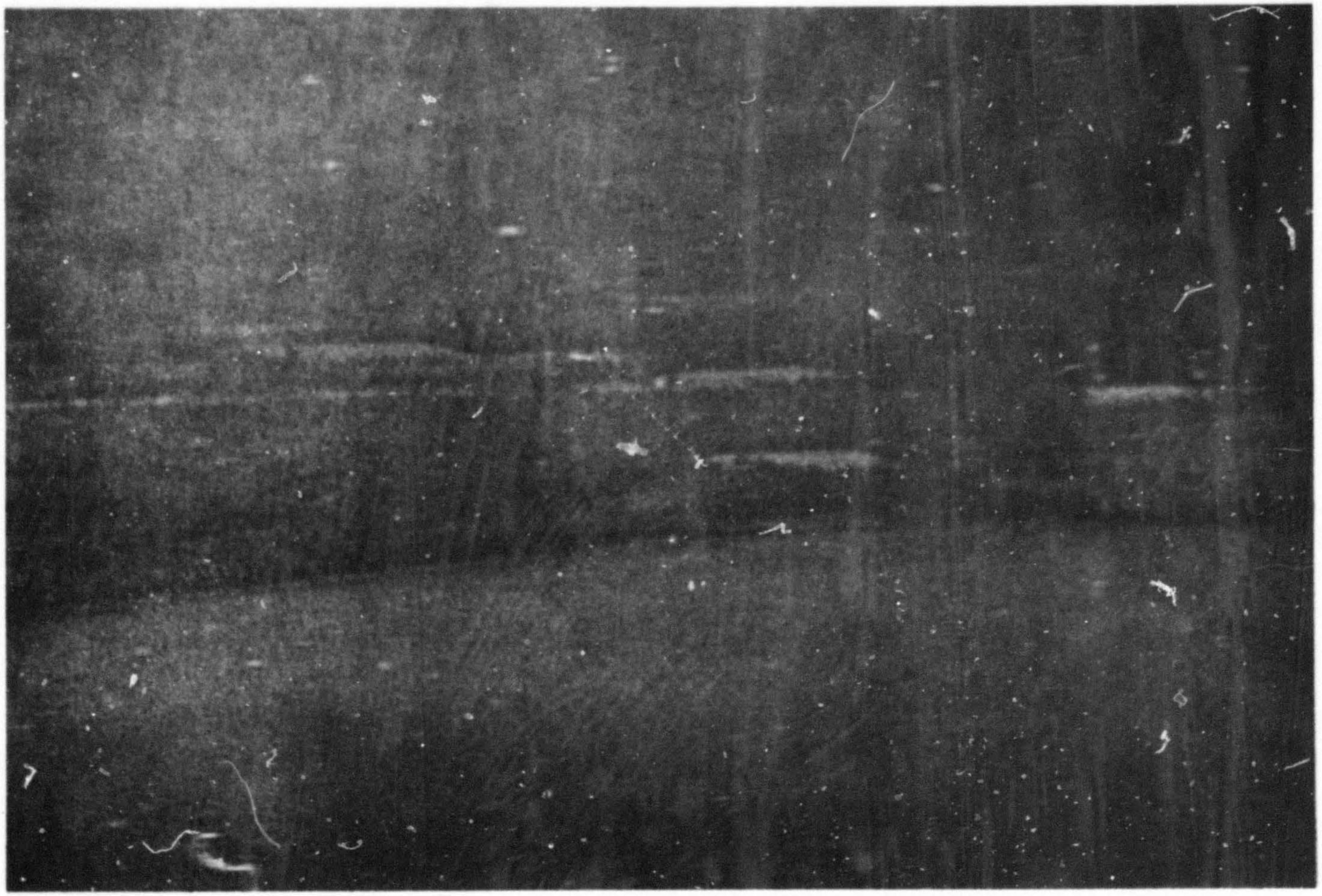

Figure 5. Photograph taken from helicopter at range of approximately 5 km. The laser appears as a saturated red spot with the film unable to respond to the full brightness of the signal as reported by observers

reacquire the helicopter. At these ranges the laser was still a brilliant and eye-catching signal. At the extreme range (point F, Hughesville) of 28 km, the helicopter was invisible to all observers on the ground except the laser operator who had continuously tracked it with his telescopic sight. The air-borne observers could still clearly see the laser, however, and reported that they would have immediately seen it at that range if they were making a search of the area. It should be noted that this range corresponds to the case of a search aircraft at 30,000 feet and a horizontal range of 26 km. In this case the aircraft might easily be visible due to its contrail or simply its larger size (this is demonstrated by common experience in watching a commercial airliner in flight).

In summary, the second phase of the test demonstrated that the laser signaller, operating at 1.5 milliwatts and 2 milliradians beam angle, was a clearly visible and eye-catching beacon at ranges out to at least 28 km. The operating environment was realistic, consisting of a marsh and forest background and a moving air-borne observer. The test also demonstrated that 2 milliradians is a reasonable compromise between source illuminance and tracking-precision requirements under somewhat idealized conditions (telescopic sight and scanning-tripod mount). All air-borne observers were very impressed by the immediate visibility of the signal at all ranges, particularly the Army aircrew who had no previous exposure to laser devices.

4. CONCLUSIONS

This field test demonstrates the feasibility of using very low-powered helium-neon lasers as secure, visual signalling devices. In particular, the availability of small battery-powered lasers weighing between two and three pounds and having forms somewhat like a flare pistol suggests that these devices are particularly well suited to emergency signalling applications such as downed-aircrew recovery and to beacon applications such as landing-zone designations or friendly-force marking. An elementary degree of protection against hostile "spoofing" of laser signals can be provided by using simple dot-dash recognition codes. The secure beam nature of the signal insures that these codes will not be compromised upon first usage. Other applications may immediately occur to potential users who become aware of the capabilities of these devices.

While this report was in preparation a prototype signaller was constructed at Harry Diamond Laboratories for testing by the U.S. Air Force. This prototype is shown in figure 6. Its dimensions and weight are about 20 percent greater than current state-of-the-art capabilities because of a severe time schedule on its construction which forced the use of some unoptimized off-the-shelf components. Never the less, it is only nine inches long and weighs about three pounds, complete with a battery-pack capable of providing one hour of continuous transmission or many hours of intermittent signalling. Tests conducted at Eglin AFB on 5 November 1971 confirmed its operating capabilities over surface-to-air ranges of up to 6.4 kilometers with a very wide beam (10 milliradians) which had been selected to simplify aiming.

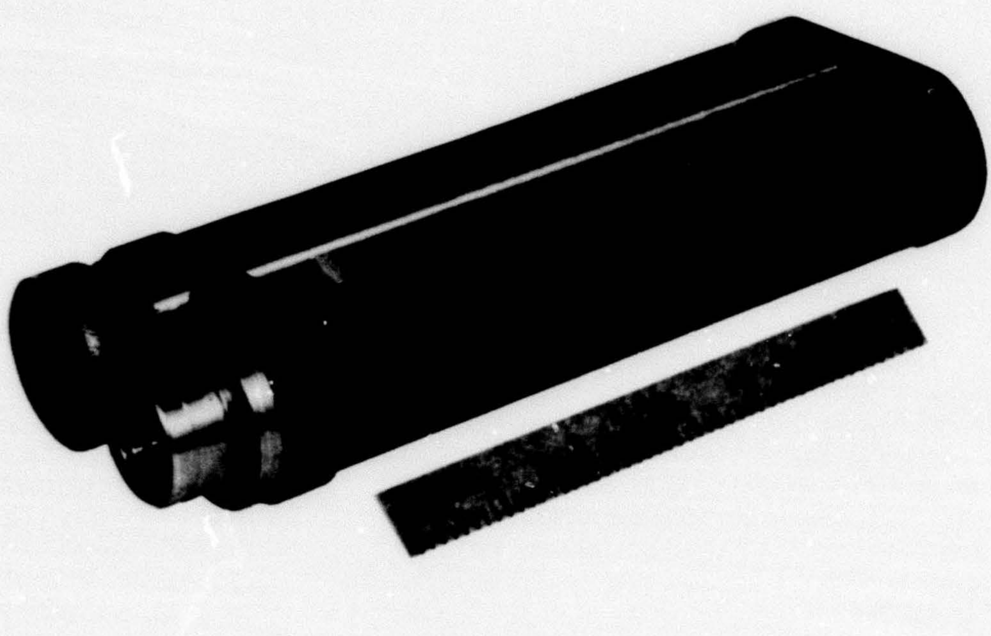

Figure 6. View of prototype laser signaller constructed at HDL for testing by the US Air Force

Appendix A. Comparison of a Laser to a Flashlight

A laser signaller with a 1.5×10^{-3} watt output at 632.8 nm and a 2.0×10^{-3} radian full-angle beam divergence is expected to require about 6 watts of electrical input power at about 800 volts. If an allowance for 50 percent losses in converting from a battery-pack voltage to 800 volts is made, it seems reasonable to compare such a laser to a "flashlight" that uses a 12-watt bulb.

The output of the laser and that of the flashlight must be expressed in lumens to compare properly their effectiveness in stimulating the human eye. For the laser this is accomplished by using the equation

$$F \text{ (lumens)} = K_\lambda P_\lambda \text{ (watts)},$$

where F is the luminous flux of the laser and P_λ is the radiant flux of the laser. The coefficient K_λ is the absolute luminosity of a monochromatic source at wavelength λ in lumens/watt. At λ = 632.8 nm, K_λ = 120 ℓm/W.[1] We then have

$$F_{laser} = 0.18 \ \ell m.$$

The flashlight is somewhat more complicated since for a broad-band source it is necessary to calculate the integral

$$F = \int_{\substack{\text{visible} \\ \lambda}} K_\lambda P_\lambda d\lambda .$$

Fortunately, it is possible to measure F directly, and it has been shown that for an input power near 10 watts a tungsten lamp yields 7.9 lumens per watt of electrical input power, so that $F_{flashlight}$ = 94.8 ℓm.[1]

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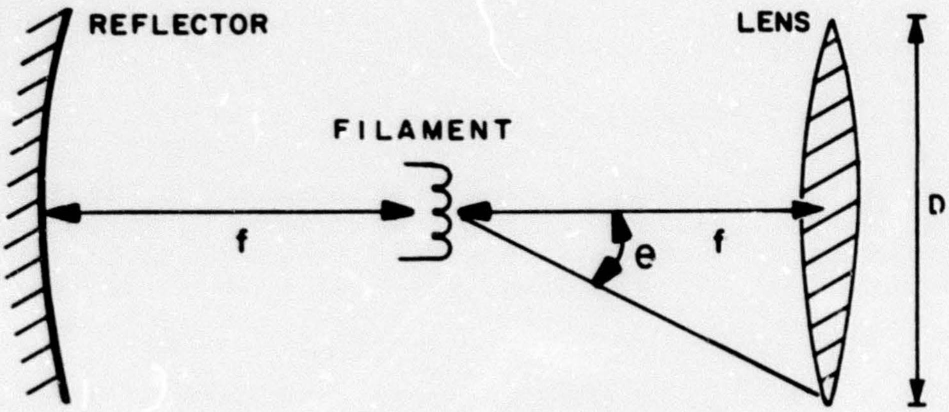
[1] Electro-Optics Handbook, Radio Corp. of America, Defense Electronic Products, Aerospace Systems Division. (Burlington, Mass.) 1968.

The laser emits all of its output flux into a cone with full apex angle (α) of 2×10^{-3} radians. The luminous intensity of the laser is thus

$$I_{laser} \simeq \frac{F}{\alpha^2} = 4.5 \times 10^4 \ \ell m/sr.$$

To get an equivalent number for the flashlight it is necessary to make several assumptions about the geometry of the optical system. The f/number of the system is defined as $\mathcal{F} = f/D$ where D is the diameter of the lens and



f is its focal length. With the filament located at the focal point, the lens subtends a solid angle $\Omega = 2\pi(1-\cos\theta)$ at the filament with $\cos\theta$ given by

$$\cos\theta = \frac{f}{\sqrt{(D/2)^2 + f^2}}$$

$$= f\{(D/2)^2 + \mathcal{F}^2 D^2\}^{-1/2}$$

$$= (f/D)\{(1/4) + \mathcal{F}^2\}^{-1/2}$$

$$\cos\theta = 2\mathcal{F}\{1 + 4\mathcal{F}^2\}^{-1/2}$$

An f/1 system ($\mathcal{F} = 1$) is a reasonable upper limit on the collecting power of the optics, in which case $\cos\theta = 2/\sqrt{5} = 0.894$ and $\Omega = 0.66$ sr. If the lens and the reflector each collect 0.66 sr of the total available 4π sr the fraction of light which is collected is $1.32/4\pi = 1.06 \times 10^{-1}$.

The beam divergence of a flashlight is determined by the filament dimensions and the focal length of the collimating optics. Using the fact that the angular magnification of a single lens is unity, we have $\alpha = x/f$, where x is the filament dimension and f is again the lens focal length. If the lens diameter is taken as 2 inches and $\mathcal{F} = 1$ we have f = 2 inches. Taking the filament as symmetrical with a dimension of 1/4 inch gives $\alpha = .25/2 = 125 \times 10^{-3}$ radians.

Combining the geometric collecting efficiency of 0.106 and the calculated value of α gives

$$I_{flashlight} = (0.106) \frac{94.8}{(125 \times 10^{-3})^2} = 6.43 \times 10^2 \; \ell m/sr,$$

so that

$$\frac{I_{laser}}{I_{flashlight}} \cong 70.$$

Since the detectability of a signal depends only on I (in the limit of point sources which applies in the case of hand held signallers) it follows that the laser will be as visible at a range of 7 km as the flashlight is at only 100 meters.