# **Laser Power Beaming Hazard Analysis for Unmanned Ground and Aerial Vehicles**

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# **Abstract**

Laser power beaming (LPB) is the wireless transmission of electrical power with the use of a laser source and a receiving device in the form of photovoltaic arrays. There is a recent increase in the desire for systems utilizing LPB to power unmanned aerial and ground vehicles limited by short operational time due to battery life. The required lasers for this application present serious hazards to the operators of the unmanned vehicle, as well as personnel in the surrounding area. Hazard analysis is critical for this application. This paper discusses topics in hazard analysis for 125 watt infrared lasers with continuous wavelengths ranging from 800nm to greater than 1400nm under the guidelines of the American Standard for the Safe Use of Lasers. The intention is to find an optimum wavelength range that reduces laser hazards and meets the application requirements to power small (about 0.5m) drones while operational. The major topics included for hazard analysis are maximum permissible exposures (MPE), evaluations of a Gaussian beam, direct beam exposures, reflected beam exposures, and optical density for eye protection. After the hazard analyses is completed, a method of enlarging beam diameters to reduce irradiance below harmful exposure levels is shown. The size of these enlarged beam diameters is then analyzed for feasibility of the application LPB. The analysis concludes that an eye safe minimum expanded beam diameter of 43 cm occurs for a wavelength of 1297nm. However, for the unmanned vehicles discussed in this analysis a beam diameter of this size is not practical for application due to the required size and weight of the photovoltaic array or focusing lens. Wavelengths ranging from 1100nm to 1400nm can eliminate skin hazards with a beam diameter of 28cm. This size beam diameter can be feasible for the application but will require the use laser eye protection and the determination of nominal ocular hazard distances.

# **Introduction**

Laser power beaming (LPB) is the wireless transmission of electrical power with the use of a laser source and a receiving device in the form of a photovoltaic array. High powered class 4 continuous wavelength lasers with the use of beam expanders are required for this application. A typical LPB arrangement is shown in Figure 1. There is a recent increase in the desire for systems utilizing LPB to power unmanned aerial and ground vehicles limited by short operational time due to battery life. It is often not practical to equip these vehicles with larger batteries due to weight and space restriction. Consequently LPB serves as a solution to extending the operational time by allowing for battery charging during the vehicles operation at distances far from the operator. A major concern of LPB are the hazards associated with high power lasers. This can be a limiting factor for LBP, allowing its application to limited areas of laser hazard zones and requiring drone operators wear personal protection equipment. A better understanding of laser safety and its application to LPB can provide a safer operational environment and reduce or possibly eliminate the hazards associated with the high power lasers.

ANSI Z136.1 American National Standard for Safe Use of Lasers (<https://www.lia.org/>) serves as the standard guide for the safe use of lasers and hazard analysis in industry, research laboratories and military programs. These safety standards and hazard analysis will be utilized for the application of laser power beaming. The major topics included for hazard analysis discussed in this paper are laser hazard fundamentals with topics on maximum permissible exposure (MPE) and viewing conditions in Section II, evaluation of a gaussian profile beam with topics discussing limiting aperture, beam diameter as a function of distance and hazard evaluations of gaussian beams in section III, direct beam exposure, diffuse reflection and direct reflection hazard distance in section IV, and laser eye protection and optical density in section V.

The wavelengths for hazard analysis range from 800 to 1400 nanometers. These wavelengths match commercially available photovoltaics exhibiting high quantum efficiencies. This wavelength range is also an ideal for laser safety due to the higher acceptable exposure levels of radiation that are permitted to the eyes and skin compared to the visible range. This paper seeks to find a wavelength range that is both optimal for safety and the application of LPB.

The iRobot 510 Packbot (<http://www.army-technology.com/projects/irobot-510-packbot-multi-mission-robot/>) is an unmanned ground vehicle that is powered by BB290/U lithium ion batteries. Unmanned aerial vehicles such as the DJI Phantom 4 (<https://www.dji.com/phantom-4/info>) are powered by Lithium-polymer batteries that operate at 1.2 A at 7.4 V. Providing 25 W of electrical power to these batteries by LPB should allow for charging during operation. The application discussed here will assume a 20% conversion efficiency from laser power to electrical power from the photovoltaic array. Photovoltaics arrays under monochromatic illumination can have efficiencies as high as 50% with specific combinations of photovoltaics and wavelengths in the near infrared. Modeling the low-end efficiency will allow for the analysis of a broader spectrum of wavelengths for application and provide more conservative laser hazard safety requirements. The 20% efficient photovoltaic array will require a 125-watt continuous wavelength laser to provide the 25 W to the battery of the drone. All hazard analysis discussed in this paper will be based upon this criteria for the application. The duration of exposures for hazard analysis will range from 10 to 30,000 seconds. This time range will also meet application needs for battery charging. The intent of the application is to target a photovoltaic array on an unmanned ground or aerial vehicle a distance of 1 kilometer away.

After the hazard analysis of the selected wavelengths was performed, a method for determining beam diameters to reduce or eliminate beam hazards and meet application requirements will be shown in section VI. This will be done by determining the hazardous exposures levels of irradiance from the selected wavelengths and expanding the beam diameters to reduce irradiance below these hazardous levels. The expanded beam diameters will then be analyzed for both size and wavelength to determine and ideal combination of safety and application requirements.

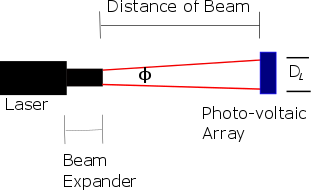


Figure 1: Illustration of laser beam forming geometry. The diameter of an output beam from a high power laser is expanded using a diverging and converging lens pair. After propagating in free-space of a distance, the laser beam is incident on a photo-voltaic array of dimension DL. Typically the laser and beam expander would be enclosed such that eye and skin safety requirements would only be considered for the beam propagation after the beam expander.

# **Laser Hazard Fundamentals**

This section discusses Maximum Permissible Exposures (MPE) for laser radiation and viewing conditions applicable for retina hazards. Retina, cornea and skin all have MPE limits. For wavelengths that are both retina and cornea hazards, the limiting MPE is most hazardous of the two.[1, 2] An understanding of these concepts is essential for the safe use of lasers with the application of LPB.

## **Maximum Permissible Exposure (MPE)**

ANSI defines Maximum Permissible Exposure (MPE) as the level of laser radiation to which an unprotected person may be exposed without adverse biological changes in the eye or skin.[1, 2] The retina, cornea and skin are vulnerable to damage from direct beam exposure, diffuse and direct reflections from a laser. The area and seriousness of injury will depend on the wavelength, irradiance and duration of exposure. Injuries can range from minor burns on the skin to permanent eye damage.

Criteria for determining MPE for a continuous wavelength laser depends on the wavelength of laser, duration of exposure, the apparent size of the source due to viewing conditions and the power transmitted by the aperture of eyes and skin. Determination of MPE from these criteria is made with the use of tables and corrective factors in the American National Standard for Safe Use of Lasers. Retina, cornea and skin have individual MPE values and are measured by irradiance in units of Watts per centimeter squared.[1] Point source MPEs for the selected wavelengths and laser specifications disused in this paper are provide in TABLE I.

## **Viewing conditions**

Lasers that operate in the wavelength range from 400 nm to 1400 nm are potential retinal hazards. Two types of viewing conditions are defined for these wavelengths: point source and extended source. The observers’ position from a laser source or reflected surface will determine the appropriate viewing condition.

ANSI Z136.1-2014 defines a point source as a source that subtends an angle at the cornea equal or less than 1.5 mrad.[1, 2] The image formed is a point on the retina. The amount of power transmitted and focused on a point in the retina determines if a hazardous condition is present.

A source of optical radiation that subtends an angle at the cornea larger than 1.5 mrad is considered an extended source.[1] The power transmitted by the eye is spread over a larger area in the retina and allows for a larger MPE when compared to point source values. The subtended angle changes with the position of the viewer. As the viewer moves further from an extended source, the subtended angle will decrease and viewing conditions will change.[3] At distances far enough from the source, the image will form a point on the retina, and MPE will be determined from point source conditions. With the possibility of various viewing distances, the most conservative approach is to determine MPE from point source criteria.[1-3]

TABLE I: Point source MPE for wavelengths ranging from 800nm to 1000µm. Retina, cornea, and skin each have individual MPE values. For wavelengths that are both retina and cornea hazards, the limiting MPE is utilized for hazard evaluations.

|  |  |  |  |
| --- | --- | --- | --- |
| Wavelength 𝜆  (nm) | MPE  Retina (W/cm2) | MPE  Cornea (W/cm2) | MPE  Skin (W/cm2) |
| 800 | 0.0015 | N/A | 0.31 |
| 1000 | 0.0039 | N/A | 0.79 |
| 1100 | 0.005 | N/A | 1.0 |
| 1200 | 0.040 | 3.0 | 1.0 |
| 1250 | 0.045 | 1.0 | 1.0 |
| 1290 | 0.23 | 0.44 | 1.0 |
| 1295 | 0.35 | 0.40 | 1.0 |
| 1300 | 0.54 | 0.37 | 1.0 |
| 1305 | 0.83 | 0.33 | 1.0 |
| 1320 | 3.1 | 0.25 | 1.0 |
| 1400 | N/A | 0.10 | 0.1 |
| 𝜆>1400 to 1000µm | N/A | 0.10 | 0.1 |

# **Evaluation of a Gaussian Profile Beam**

This section discusses the terminology and methods of hazard evaluations for a Gaussian profile beam. Most commercial high-power lasers that can be used for LPB have this type of beam profile. Hazards evaluations of this type of beam are determined by how much of the beam profile travels through a limiting aperture such as the retina of the eye, and then averaging the beam power over the exposed area.

## **Limiting Aperture**

Gaussian beam irradiance is evaluated by averaging incident power transmitted through a limiting aperture  .[1, 2, 4] A limiting aperture is the maximum diameter of a circle over which radiant exposure is averaged for hazard evaluations of the retina, cornea and skin.[1, 2, 5] The irradiance averaged over the aperture is then compared with the MPE to determine if a hazardous condition exists.

Limiting aperture diameters for retina, cornea, and skin exposures vary with wavelength and duration of exposure. The required limiting aperture diameters needed for the specifications of the lasers discussed in this paper are provided in TABLE II.

TABLE II: Limiting apertures  for wavelengths ranging from 400nm to 2600nm. Duration of exposure time ranges from 10 to 30,000 seconds.

|  |  |  |  |
| --- | --- | --- | --- |
| Wavelength,  𝜆 (nm) | Aperture Diameter (mm)  Retina Cornea Skin | | |
| 400 to 1200 | 7.0 | N/A | 3.5 |
| 1200 to 1400 | 7.0 | 3.5 | 3.5 |
| 1400 to 2600 | N/A | 3.5 | 3.5 |

## **Beam Diameter as a Function of Distance**

The beam diameter changes with distance from the exit port of the laser source.[2, 6] In the LPB configuration, it is assumed that the laser as well as the beam expander are enclosed so that MPE levels need only be evaluated for light after it emerges from the beam expander. After the beam expander, the beam diameter as a function of distance is

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 is the smallest beam diameter for 1/e points along the path of the beam referred to as the beam waist. [2, 7]. The distance  is measured from the exit port of the laser (after the beam expander) to the beam waist.  is the distance from the exit port to the target and  is the beam divergence in radians of light after it emerges from the beam expander. It is assumed that the beam expander has been designed such that the beam waist is located at the exit port the beam expander with .

## **Hazard Evaluations of Gaussian Beams**

For hazard evaluations, Gaussian beam diameters are determined at the 1/e irradiance points.[1, 2, 4-6] This accounts for 63% of the beam power. The irradiance of a Gaussian beam through a circular aperture is given by

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In this equation  is the diameter of the beam at the 1/e irradiance points and  is a distance from the center of the beam.[4, 6]  is the peak irradiance of the beam given by

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with  being the power of the laser in watts and  is the beam diameter at the exit port of the laser.[1, 6] The amount of power transmitted through a limiting aperture of diameter  is found by the integral of the circular area of Eq (2) given by

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Substituting Eq (3) into (2) and integrating leads to

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giving the power transmitted through a limiting aperture .[1, 2, 4, 5] The beam irradiance averaged over the limiting aperture is then determined by

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where  is the area of the limiting aperture. If the beam irradiance *E* is greater than the MPE, a hazard condition is present.

# **Direct Beam Exposure, Diffuse Reflection and Direct Reflection Hazard Distance**

The distances for the application of LPB discussed in this paper are limited to a maximum of 1 kilometer from the laser source. However, if the laser misses the targeted photovoltaic array on the unmanned ground or aerial vehicle, a potentially hazardous condition can extend for tens or hundreds of kilometers from the laser source. This section provides the equations to determine the potential hazard distance from direct beam exposure, diffuse reflections and direct reflections in the event a missed target with the laser occurs.

Areas where exposure levels of radiation from direct beam, diffuse or direct reflection exceed MPE are labeled nominal hazard zones (NHZ).[1, 2] All MPE values assume worst case viewing possibilities and are determined from point source viewing conditions. For hazard evaluations, neglecting atmospheric attenuation will give the most conservative distances for nominal hazard zones.[2]

## **Direct Beam Exposure**

Distances along the beam where exposures to eyes or skin exceed MPE are referred to as nominal ocular hazard distances (NOHD) and nominal skin hazard distances (NSHD).[1, 2, 7] This distance can be determined by placing Eq into Eq , replacing  with  (the product of ocular MPE or skin MPE and limiting aperture area) and solving for. This gives the direct beam hazard distance [2, 7]

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The high-powered lasers with beam expanders required for LPB are low diverging and can present a direct beam hazard for distances of tens or hundreds of kilometers. For example, an 1100nm 125-watt laser/beam expander with a beam waist  of 29cm and beam divergence  of 0.0118 mrads will have a direct beam hazard distance  of 149 kilometers when atmospheric attenuation is neglected. This demonstrates the importance of precision targeting and beam interrupt systems in the event the laser misses or loses contact with the photovoltaics.

## **Diffuse and Direct Reflections**

The irradiance from a diffuse reflecting surface is given by Lamberts Law[1, 2, 8]

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The reflectance of the surface is given by  , is the distance from the viewer to the reflecting surface and is the angle from the viewer to the reflecting surface measured from the normal. [2, 8] Replacing irradiance with MPE and solving for  will give the diffuse reflectance distance of the nominal hazard zone

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It is not practical to predetermine reflectance values in the event that the laser misses its target or an object crosses the path of the beam. Reflectance values  will vary and are material/object dependent. The position of personal and the possibility of multiple viewing angles  will also be unknown. Assuming a worst-case reflectance value of 1 (100% reflectance) and a viewing angle  of 0 will give the most conservative distances for hazards due to diffuse reflections. Diffuse reflectance distances for the wavelengths and laser specification discussed in this paper are provided in TABLE III.

TABLE III: Diffuse reflection distances for a laser power of 125 watts with reflectance value of ρ=1 and =0, giving the most conservative hazard distances.

|  |  |
| --- | --- |
| Wavelength (nm) | Diffuse Reflection Hazard Distance at 100% reflectance, = 0  (cm) |
| 800 | 158 |
| 1000 | 99 |
| 1100 | 89 |
| 1200 | 31.5 |
| 1250 | 29.7 |
| 1300 | 10.4 |
| 1400 | 20 |
| 𝜆>1400 | 20 |

The NOHD due to direct reflection can be determined from

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where  is the size of the beam incident on the reflected surface and  is the divergence of the beam after reflection.[2] Due to the uncertainty of objects that could interrupt the beam, and therefore the uncertainty in the values for  and  , the conservative approach is to treat direct reflections in the same manner as direct beam exposures.

# **Laser Eye Protection and Optical Density**

The class 4 lasers needed for LPB will require eye protection for personnel within the nominal hazard zones. Laser eye protection (LEP) is usually in the form of goggles or glasses with absorptive filters and reduce ocular exposures to levels below MPE for direct and diffuse exposures. [1] . Optical density  of absorptive filters is determined by

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Equation 11 provides the minimum optical densities required. The use of higher optical densities is recommended.[1] The minimum required optical densities for the laser specifications given for this application of LPB are given in TABLE IV.

TABLE IV: Required minimum optical density for laser eye protection (LEP) with the use of a 125 watt laser.

|  |  |
| --- | --- |
| Wavelength (nm) | Optical Density |
| 800 | 5.34 |
| 1000 | 4.91 |
| 1100 | 4.81 |
| 1200 | 3.91 |
| 1250 | 3.86 |
| 1300 | 3.54 |
| 𝜆>1400 | 4.11 |

# **Determining Beam Diameters to Reduce or Eliminate Beam Hazards and Meet Application requirements**

The application of LPB for the charging of drones will require a beam diameter equal in size to the photovoltaic array or focusing lens if the photovoltaic array is smaller than the beam diameter. This larger beam diameter will carry a decreased power density and less power will be transmitted by a limiting aperture, potentially reducing or eliminating beam hazards. Solving Eq (5) for  will give the beam diameter of a Gaussian laser beam having total output power  and a measured power  through a limiting aperture. Substituting  (the product of MPE and limiting aperture area) for  leads to

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Equation (12) gives the beam diameter  at the 1/e points large enough to eliminate or reduce direct beam hazard conditions. Recalling that the beam diameter at the 1/e points contain 63% of the total power of the beam power, multiplying the beam diameter at the 1/e points by will give 86% of the beam power. This is the 1/e2 point and is referred to as the beam width D.[9] 99% of all the beam power is contained within a beam width of 1.5D.[9] The photovoltaic array or a collecting lens on the drone will require this 1.5D diameter for efficient collection of all of the transmitted power. A visual representation of these beam diameters is shown in Figure 2.



Figure 2. Beam diameters for 1/e points, 1/e2 points and 1.5D points representing 63%, 86%, and 99% of the total beam power.

Expanded beam diameters to eliminate eye hazards for the wavelengths analyzed in this discussion are given in TABLE V. Wavelengths ranging from 1295nm to 1320nm are the most practical for the application of LPB having beam diameter ranging from 43cm to 53cm. The most ideal wavelength occurs at 1297nm, allowing for the smallest beam diameter of 43cm to meet application needs.

**TABLE V: Expanded Beam Diameters for Eye Safe Exposures. Hazard evaluations are performed at the 1/e points. Applications will require beam diameters at the 1.5D points to match the size of the photovoltaic array or focusing lens.**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Wavelength, 𝜆  (nm) | Limiting Factor | Area of Limiting Aperture, *af*  (cm2) | MPE Area of Limiting Aperture, 𝜱MPE  (W) | Diameter of Expanded Beam  (cm)  1/e points 1/e2 1.5D  63% power 87% power 99% power | | |
| 800 | Retina | 0.385 | 5.78 | 326 | 461 | 692 |
| 1000 | Retina | 0.385 | 1.54 | 200 | 283 | 424 |
| 1100 | Retina | 0.385 | 1.93 | 179 | 253 | 379 |
| 1200 | Retina | 0.385 | 1.54 | 64 | 91 | 136 |
| 1250 | Retina | 0.385 | 1.73 | 60 | 85 | 127 |
| 1295 | Retina | 0.385 | 1.36 | 21 | 30 | 45 |
| 1297 | Cornea | 9.62 | 3.75 | 20 | 29 | 43 |
| 1300 | Cornea | 9.62 10-2 | 3.56 | 21 | 30 | 45 |
| 1320 | Cornea | 9.62 | 2.40 | 25 | 35 | 53 |
| 1400-2600 | Cornea/Skin | 9.62 10-2 | 9.62 | 40 | 57 | 85 |

For LPB systems where eye safety is not feasible for the application, expanding the beam diameter for skin safety could meet application needs. The expanded beam diameters for skin safety are listed in TABLE VI. The ideal wavelength range is between 1100 to 1400nm requiring beam diameters of 28 cm to eliminate skin hazards. This size beam diameter could be utilized for the application of unmanned aerial vehicles. The main safety requirement for this type of system would be eye protection with the proper optical density as listed in TABLE IV.

**TABLE VI: Expanded beam diameters for skin safe exposures. Wavelengths ranging from 1100-1400nm allow for the small skin safe beam diameters.**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Wavelength, 𝜆  (nm) | Limiting Factor | Area of Limiting Aperture, *af*  (cm2) | MPE Area of Limiting Aperture, 𝜱MPE  (W) | Diameter of Expanded Beam  (cm)  1/e points 1/e2 1.5W(z)  63% power 87% power 99% power | | |
| 1000 | Skin | 9.62 | 7.66 | 14 | 20 | 30 |
| 1100-1400 | Skin | 9.62 | 9.62 | 13 | 18 | 28 |
| 1400-2600 | Skin | 9.62 | 9.62 | 40 | 57 | 85 |

# **Discussion**

From the MPE values in TABLE I and the beam diameters determined in TABLE V, 1297 nm is the ideal wavelength for both eye safety and the application of LPB. The reasoning for this can be explained by analyzing Figure 3. As wavelength size increases and approach 1297nm, less radiation is focused by the retina and the MPE for the retina increase. At wavelengths between 1296nm and 1297nm the cornea hazard and retina hazard intersect, making the cornea the limiting MPE for wavelengths beyond this intersection. At 1297nm absorption by the cornea is at a minimum and the MPE is at a maximum when compared to longer wavelengths. As the wavelengths increase in size, more radiation is absorbed by the cornea and the MPE decreases to a minimum value at 1400nm. This minimum value for cornea MPE is then a constant for wavelengths up to 1000µm.

At the 1297 nm wavelength a minimum beam diameter of 43 cm is needed to eliminate eye hazards. Given that the size dimensions of DJI Phantom 4 are 28.5x28.5 cm and the iRobot 510 Packbot are 68.6x52.1 cm with flipper extended, a photovoltaic array or focusing lens of 43 cm would not be realistic for application due to size and weight limitations of these unmanned vehicles.

Figure 3: Retina and cornea MPE for wavelengths ranging from 800nm to 1500nm. The dashed line is retina MPE and the solid line is cornea MPE. The intersection of the MPEs occur slightly before 1300nm allowing for the highest ocular exposure of laser radiation.



Skin hazards can be eliminated by expanding beam diameters to 28cm in the 1100nm to 1400nm wavelength range. Figure 4 shows that as wavelengths increase in size toward 1100nm, the MPE increases. The MPE for skin reaches a maximum value at 1100 nm and drops off at 1400nm when analysis is performed under the ANSI Z136.1-2014 guidelines. This drop in MPE is due to wavelengths between 1400nm and 1000µm penetrating the skin deeper, causing more biological damage.

The 28cm diameter needed for skin safety could be an upper limit size for photovoltaic arrays for focusing lens need for LPB applications with the DJI Phantom 4 or the iRobot 510 Packbot. This will allow for skin safe LPB systems with these drones. The major safety concern will be limited to ocular exposures which can be addressed with LEP.

Figure 4: Skin MPE for wavelengths ranging from 800nm to 1500nm and longer. Wavelengths ranging from 1100nm to 1400nm allow the highest skin exposures.



# **Conclusion**

At a 1297nm wavelength and a laser power of 125 watts, a minimum beam diameter of 43 cm is need for eye safe LPB. This is the smallest possible eye safe beam diameter for a laser of this power. A photovoltaic array or focusing lens of this size diameter will be required for the application of charging the DJI Phantom or the iRobot 510 Packbot. For these specific drones having length and width dimensions of 28.5x28.5 cm and 68.6x52.1 cm, housing a photovoltaic array or focusing lens with a 43 cm sized diameter would not feasible due to the size and weight limitations.

Wavelengths ranging from 1100nm to 1400nm have a skin safe beam diameter of 28 cm. A 28 cm photovoltaic array or lens should be feasible for the iRobot 510 Packbot and could be an upper limit size for the DJI Phantom allowing for skin safe laser operations. Eye hazards can be mitigated with LEP and determining of NOHD will be required for the safe application of LPB. Beam interrupt systems will be necessary in the event an object cross the path of the laser. Precision targeting with a system that detects a missed targeted photovoltaic array will also be required due to extremely far distances that a beam hazard can exist.

Future development of photovoltaics with 50% efficiency or greater for wavelengths ranging from 1295nm to 1300nm would allow for smaller beam diameters that are eye safe and suitable for application. Photovoltaics with 50% efficiency at 1297nm would allow for eye safe beam diameters of 26 cm. A photovoltaic array of this diameter would fall within the size and weight limits for LPB applications with the size dimensions of the UAV and UVG discussed in this analysis.

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