

Active Triangulation in the Outdoors: A Photometric Analysis

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Abstract

Active triangulation is a well established technique for collecting range points. This work performs a photometric analysis of relative irradiance expected at the camera sensor as a result of intended operating conditions and device parameters including laser power. The limiting effects of eye safety compliance, minimum realizable shutter times and pixel bit depth for linear response cameras are considered. Quantitative results are established determining dynamic range requirements on the camera, when exposure control is needed, and when laser return can be expected to produce the brightest pixels in the image.

1. Introduction

Active triangulation is a well-established technique for measuring distance (range) to surfaces. Applications include mobile robotics [10, 9], 3-D photography [2], and assistive technology [14, 6]. An active triangulation system is comprised of a light source and a camera placed at a certain lateral distance (baseline) from the source. It is common practice to add narrow-band optical filtering in front of the camera, to suppress ambient light energy outside the laser wavelength.

In this work we consider systems using a laser striper, which emits a “fan” of radiant energy with a wide spread in one direction and a narrow spread in the orthogonal direction. These systems measure distance to all surface points within the angular sector in the slicing plane determined by the laser fan geometry. For a number of applications (*e.g.* curb detection [11]), measuring range within the spread of the laser fan is sufficient. By rotating the system around an axis parallel to the laser fan, it is possible to obtain a full 3-D measurement of the environment.

The main challenge with active triangulation is the detection of the laser return in the camera image. Ideally, the brightest pixels in the image would correspond to the laser return. Unfortunately, this is not always the case, especially in the case of outdoor scenes, where the sun light may add

a non-negligible contribution to the irradiance induced by the laser at a surface element. The simplest strategy to increase rejection of ambient light is to increase the power of the laser. However, eye safety considerations pose clear limits to the amount of energy in a laser pulse. In particular, ANSI regulations dictate that the duration of a laser pulse should be reduced when the power is increased. For relatively powerful lasers (with power exceeding 1 Watt), the maximum allowable pulse duration can be on the order of 1 microsecond.

Light reflected by a surface element is integrated by the camera over a certain period of time (shutter time). The shutter time should be kept to a value no larger than the laser pulse, in order to avoid integration of useless ambient light. Unfortunately, typical commercial cameras ¹ cannot provide shutter times smaller than a few microseconds. This limits the benefits of using very powerful lasers, with pulse durations smaller than the achievable shutter time.

This paper provides a thorough photometric analysis of active triangulation in the outdoors. Specifically, we address three important questions:

1. What are the dynamic range requirements of the camera?

The imaging system must cope with the dynamic range of the light reflected by surface elements. This can be done via a combination of shutter time, amplification gain, iris, and the sensor’s ability to map irradiance on a pixel into brightness levels. We give a quantitative theoretical expression for the expected dynamic range at a pixel for a triangulation system in the outdoors, which directly translates into requirements placed on the camera.

2. When is exposure control necessary?

Exposure control involves setting the camera’s shutter time, gain and iris to ensure that all pixels with a laser return are correctly exposed. This typically results in a delay of a few frames due to a “settling” period of the exposure control algorithm. Exposure control, though, is only necessary when the dynamic range of the light from the scene exceeds the camera’s own

¹ Recent consumer cameras with high ‘megapixel’ counts have longer minimum shutter times.

dynamic range. Based on our quantitative analysis of the expected range of irradiances at a surface point, one can easily determine when exposure control is necessary.

3. *What are the brightest pixels in the image?* The pixels with a laser return are not necessarily the brightest ones in the image, even when powerful lasers are used. We provide a quantitative analysis of pixel brightness as due to laser return and ambient light as a function of laser power and distance.

2. Related Work

Other works exist modeling the surface irradiance induced by a laser stripe, but using a smooth 1D Gaussian profile [3, 8]. While the authors of [3] consider scene surface geometry and reflectance changes in detail, no consideration is given to interfering ambient light. The authors of [8] rely on a static camera and scene so that image differencing can be used to remove the effect of ambient light.

In [4], the authors attempt to determine the amount of laser power required for an active triangulation application to insure that return is brighter than areas illuminated by sun, yet neglect the effects of illumination angle and surface reflectivity resulting in estimates that are generally too low.

In [9], a *fixed* exposure setting is calculated based on estimated sensor irradiance, typical surface albedo, and the ratio between delivered laser power and (Martian) solar irradiance. The system is designed so that the laser is several times brighter than the ambient illumination.

In [11], the ANSI standard [1] is applied to demonstrate the eye-safety of an active triangulation device. It is also noted that there are some cases falling within intended operating conditions where the laser return does not create the brightest pixel values in the image.

3. Geometric and Photometric Analysis

This section provides an expression of the irradiance at a given pixel as a function of both laser and sun light and of the geometry of the surface being illuminated.

3.1. Surface Irradiance

We begin by deriving the expression of the irradiance on a surface element induced by the laser light. Let's first consider a simplified model of the fanning laser beam geometry. For a laser with divergence γ , minimum beam width w and lens with fanning angle β about the optical center, it can be shown that at range R from the center, $\Omega(R) = \beta(\gamma + w/R)$ is a good model of the solid angle subtended by the laser. Assuming the power W_l emitted by the laser is uniformly distributed through this solid an-

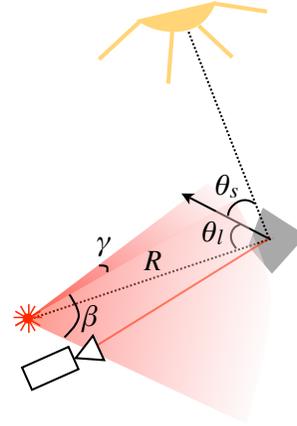


Figure 1. A representation of the active triangulation system with a fanning laser.

gle ², the *radiant intensity* I_l of the laser is $I_l = W_l/\Omega(R)$. Consider a *small* surface element of area dA completely illuminated by the laser. The apparent area of the patch seen from the laser is approximately $dA \cos \theta_l$, where θ_l is the angle between the surface normal and the line joining the surface patch to the optical center of the laser. The solid angle subtended by the patch is then $d\Omega = dA \cos \theta_l/R^2$. Thus the irradiance induced at any point inside the patch by the laser light is $E_{\text{laser}} = I_l d\Omega/dA$, or:

$$E_{\text{laser}} = \frac{W_l \cos \theta_l}{\Omega(R)R^2} \quad (1)$$

If the surface element is also lit by the sun, then there is a component E_{sun} to the total irradiance on the pixel equal to $E_{\text{sun}}^\perp \cos \theta_s$, where θ_s is the angle between the surface normal and the direction to the sun. Values for E_{sun}^\perp can be obtained, for example, from tables for spectral irradiance from the sun (ASTM Standard Tables [7]). Other irradiance components due to diffuse ambient light are usually negligible ³, as they are much smaller than direct sun or laser light.

In conclusion, the total irradiance on a surface element illuminated by laser and sun light is:

$$E_{\text{tot}} = E_{\text{laser}} + E_{\text{sun}} = \frac{W_l \cos \theta_l}{\Omega(R)R^2} + E_{\text{sun}}^\perp \cos \theta_s \quad (2)$$

3.2. From Surface Irradiance to Pixel Values

We model the radiance L from a surface patch resulting from irradiance by the laser and the sun using the Lamber-

²Typical lasers have Gaussian intensity profiles. For the simple model here, extents can be determined by *e.g.* the full width at half maximum (FWHM) intensity.

³ An important exception occurs when laser light at maximum range approaches the same order of magnitude as diffuse ambient light.

tian reflectance model:

$$L = \frac{\rho}{\pi} E_{\text{tot}} \quad (3)$$

where ρ is the surface albedo.

Consider a pixel that ‘sees’ the surface patch. The irradiance on the pixel E_{pix} is equal to [5]:

$$E_{\text{pix}} = L \frac{\pi}{4} \left(\frac{D}{f} \right)^2 A(\alpha) \quad (4)$$

where D is the diameter of the lens, f is the focal length, and α is the off-axis angle that a ray from the pixel through the center of the lens makes with the principal axis. $A(\alpha)$ is a monotonically decreasing function (with $A(0^\circ) = 1$) that accounts for the $\cos^4(\alpha)$ attenuation [5] as well as other vignetting effects.

The equation above assumes a flat spectral response of the sensor element. In fact, in order to reject ambient light, it is customary to apply an optical filter in front of the sensor, with narrow band-pass spectral transmittance. We approximate the filter’s spectral transmittance as being constant and equal to H within the interval $[\lambda_{\min}, \lambda_{\max}]$ with $\Delta_\lambda = \lambda_{\max} - \lambda_{\min}$. We also assume that the laser is monochromatic: $W_l(\lambda) = W_l \delta(\lambda - \lambda_l)$ (with $\lambda_l \in [\lambda_{\min}, \lambda_{\max}]$) and assume that within $[\lambda_{\min}, \lambda_{\max}]$ the surface reflectance spectrum $\rho(\lambda)$ is constant and equal to ρ_{λ_l} . Let $E_{\text{sun}, \lambda_l}$ represent irradiance contributed to E_{pix} by the sun that is not completely removed by the filter. $E_{\text{sun}, \lambda_l}$ can be approximated by summing table values [7] for solar irradiance over the range $[\lambda_{\min}, \lambda_{\max}]$. These assumptions are justified since filters used in these systems are narrow bandwidth, with Δ_λ equal to 10 nm not uncommon. Thus, the irradiance on the pixel is equal to:

$$\begin{aligned} E_{\text{pix}} &= E_{\text{pix}, \text{lsr}} + E_{\text{pix}, \text{sun}} \quad (5) \\ &= \frac{\pi}{4} \left(\frac{D}{f} \right)^2 A(\alpha) \int_{-\infty}^{\infty} L(\lambda) H(\lambda) d\lambda \\ &= H \frac{\rho_{\lambda_l}}{4} \left(\frac{D}{f} \right)^2 A(\alpha) \left(\frac{W_l \cos \theta_l}{\Omega(R) R^2} + E_{\text{sun}, \lambda_l}^\perp \cos \theta_s \right) \end{aligned}$$

For a camera with a linear response function, the measured pixel value M is equal to:

$$M = \Gamma E_{\text{pix}} \quad (6)$$

where Γ represents an *abstract* representation of camera exposure setting. In practice, Γ is the product of the shutter time, T_{sht} , the linear amplifier gain, and the lens aperture area (when iris control is available). Of particular importance in this work is the minimum value that the shutter time $T_{\text{sht}, \text{min}}$ can take. Commercial cameras are widely available with $T_{\text{sht}, \text{min}}$ as low as 10 μs .

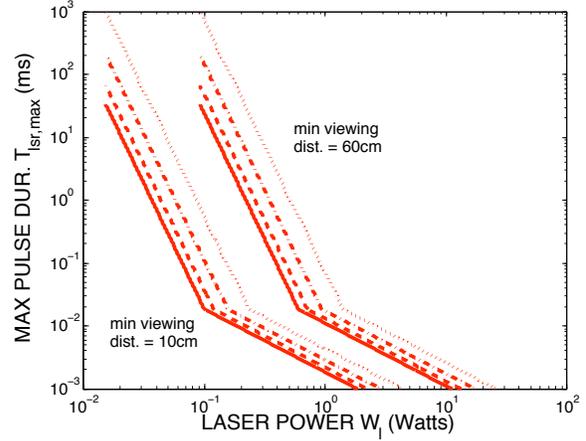


Figure 2. Maximum pulse duration $T_{\text{lsr}, \text{max}}$ vs. power W_l for an IR ($\lambda_l=908$ nm) laser according to the ANSI eye safety standard [1], assuming a minimum viewing distance of 10 cm and 60 cm for different frame rates (solid line: 30 fps; dashed line: 15 fps; dashed-dotted line: 5 fps; dotted line: 1 fps). The laser fan parameters are: $\beta = 60^\circ$, $\gamma=1.5$ mrad, $w=1$ mm.

Note that we don’t consider specular reflection in this work. Specular reflection of sun light from metallic or glass surfaces can produce very high values of irradiance at a pixel, which are not modeled by (5). However, these situations usually manifest themselves as isolated bright spots, and can often be detected and ruled out by suitable image processing.

3.3. Laser Power Considerations

3-D measurements are obtained by precisely measuring the location of laser return on the image. This requires that the pixels receiving reflected laser light be reliably identified. In order to facilitate this operation, it is useful to maximize the power W_l of the laser, so that the pixels corresponding to a laser return will be brighter than the pixels that only receive ambient light.

There are of course constraints on laser power, the need for eye safety being perhaps the most limiting. The ANSI Z.136 standard [1] specifies maximum permissible exposures to laser radiation, establishing the relationship between power W_l , maximum pulse duration $T_{\text{lsr}, \text{max}}$, pulsing rate, wavelength, beam characteristics, and minimum viewing distance. For example, Fig. 2 shows $T_{\text{lsr}, \text{max}}$ as a function of power W_l for a particular choice of beam geometry and for different pulsing rates and minimum viewing distances. Note that smaller minimum viewing distances require shorter pulse durations $T_{\text{lsr}, \text{max}}$ for the same power W_l .

In order to facilitate rejection of ambient light, the camera’s shutter time T_{sht} should be set to a value no larger than the laser pulse duration $T_{\text{lsr}, \text{max}}$. Indeed, if $T_{\text{sht}} > T_{\text{lsr}, \text{max}}$,

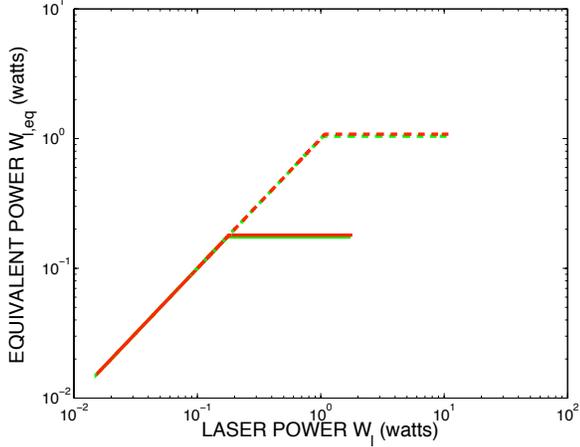


Figure 3. The equivalent power $W_{l,eq}$ vs. laser power W_l as defined in (8) assuming $T_{sht,min} = 10\mu s$. Using same laser parameters as figure 2 at 30 fps. Green lines: green ($\lambda_l=532$ nm) laser; Red lines: infrared ($\lambda_l=908$ nm) laser. Solid lines: min. viewing distance = 10 cm; Dashed lines: min. viewing distance= 60 cm.

the sensor integrates useless non-laser light for a period of length $T_{sht} - T_{l,sr,max}$. However, as shown by Fig. 2, large values for the laser power require very short pulse durations (less than $10\mu s$ for laser power above 100 mW), and thus it is not always possible to ensure T_{sht} is less than or equal to $T_{l,sr,max}$. In general, we can rewrite (6) as:

$$M \propto E_{pix,l,sr} \cdot T_{l,sr,max} + E_{pix,sun} \cdot \max(T_{l,sr,max}, T_{sht,min}) \quad (7)$$

where $T_{sht,min}$ is the minimum shutter time that the camera can realize. This equation accounts for the fact that, if $T_{l,sr,max} < T_{sht,min}$, ambient light is integrated by the sensor for a longer period than laser light. We define the *equivalent laser power* $W_{l,eq}$ as the average irradiance from laser return over the exposure time:

$$W_{l,eq} = W_l \cdot \frac{T_{l,sr,max}}{\max(T_{l,sr,max}, T_{sht,min})} \quad (8)$$

Note from Fig. 3 that, beyond a certain value of power W_l , the equivalent power $W_{l,eq}$ remains constant.

4. Dynamic Range Considerations

4.1. Estimating the Required Dynamic Range

The range of irradiance values onto a pixel receiving reflected laser light from a surface can be computed as follows. The minimum irradiance $E_{pix,min}$ is achieved when no ambient light is present (e.g., indoors in a dark room), the surface is at the maximum considered distance R_{max} , at the maximum considered incidence angle $\theta_{l,max}$ and at the maximum off-axis angle α_{max} , and for a surface with the minimum expected albedo $\rho_{\lambda_l,min}$. The maximum irradiance, $E_{pix,max}$, is achieved at the minimum considered

distance R_{min} for $\theta_l = \theta_s = \alpha = 0^\circ$, and for a surface with the maximum expected albedo $\rho_{\lambda_l,max}$ which is also illuminated by the sun. The ratio of $E_{pix,max}$ and $E_{pix,min}$ is the *full dynamic range* of irradiances incident on the sensor DR_E :

$$DR_E = \frac{E_{pix,max}}{E_{pix,min}} \quad (9)$$

$$= \frac{\rho_{\lambda_l,max}}{\rho_{\lambda_l,min}} \frac{K_1(R_{min}, R_{max}) + K_2(W_{l,eq}, R_{max})}{\cos \theta_{l,max} A(\alpha_{max})}$$

where

$$K_1(R_{min}, R_{max}) = \frac{\Omega(R_{max}) R_{max}^2}{\Omega(R_{min}) R_{min}^2} \quad (10)$$

$$K_2(W_{l,eq}, R_{max}) = \frac{E_{sun,\lambda_l}^\perp R_{max}^2 \Omega(R_{max})}{W_{l,eq}}$$

The presence of ambient light (term E_{sun,λ_l}^\perp in (10)) contributes to the dynamic range through $K_2(W_{l,eq}, R_{max})$, although its effect can be mitigated by increased equivalent laser power. The minimum and maximum operating distances (R_{min} and R_{max}) are application-specific. It is important to note that $(R_{max}/R_{min})^2$ strongly affects the dynamic range and *cannot* be mitigated by increased equivalent laser power. The maximum incidence angle ($\theta_{l,max}$) and extremes of albedo ($\rho_{\lambda_l,min}$ and $\rho_{\lambda_l,max}$) depend on the operating environment. For example, snow or bright white synthetic surfaces may have albedo as high as 0.9 while new asphalt or black matte painted surfaces may have albedo as low as 0.05 [13], giving a ‘surface term’ $\rho_{\lambda_l,max}/\rho_{\lambda_l,min}$ of about 20. Fig. 4 (a) shows DR_E (conveniently expressed in bits, by taking its logarithm base 2) as a function of the laser power W_l for specific choices of parameters, assuming that $T_{sht,min} = 10\mu s$. Note that for large values of W_l the dynamic range DR_E flattens out to a constant value. It is also worth noting that $\Omega(R_{max})/\Omega(R_{min})$ does not depend on β and is close to one for typical values of γ , w , R_{max} and R_{min} .

4.2. Matching the Dynamic Range

In order to produce a usable image, the camera needs to match the expected dynamic range. Let Γ_{min} and Γ_{max} be the minimum and maximum values for the camera’s exposure settings (as defined in Sec. 3.2), and let P_{min} and P_{max} be the minimum and maximum pixel values in the linear response range of the camera. For example, we could choose $P_{min} = 1$ and $P_{max} = 254$ for a typical 8-bit camera. Following [12], we define the *camera’s dynamic range* as

$$DR_P = \frac{P_{max}}{P_{min}} \quad (11)$$

A given value of pixel irradiance E_{pix} will be called *compliant* if it can be linearly mapped onto a pixel value be-

tween P_{\min} and P_{\max} . In other words, E_{pix} is compliant if there exists a value $\Gamma \in [\Gamma_{\min}, \Gamma_{\max}]$ such that $P_{\min} \leq \Gamma E_{\text{pix}} \leq P_{\max}$. This condition can be re-written as:

$$\frac{P_{\min}}{\Gamma_{\max}} \leq E_{\text{pix}} \leq \frac{P_{\max}}{\Gamma_{\min}} \quad (12)$$

4.2.1 Matching the Dynamic Range of a Pixel

The compliance of an irradiance value is determined both by the camera's dynamic range P_{\max}/P_{\min} and by the availability of a suitable exposure setting Γ ⁴. The balance between these two camera properties is examined in detail in the following.

Let $E_{\text{pix},\min}$ and $E_{\text{pix},\max}$ be the minimum and maximum compliant irradiance values at a pixel receiving laser return, as defined in Sec. 4.1. From (12) we derive the condition for all irradiances between $E_{\text{pix},\min}$ and $E_{\text{pix},\max}$ to be compliant:

$$\frac{P_{\max}}{P_{\min}} \geq \frac{\Gamma_{\min}}{\Gamma_{\max}} \frac{E_{\text{pix},\max}}{E_{\text{pix},\min}} = \frac{\Gamma_{\min}}{\Gamma_{\max}} DR_E \quad (13)$$

We will concentrate in the following on the shutter time T_{sht} component of Γ , assuming that the other parameters (gain, iris) are kept fixed. This translates into

$$\frac{\Gamma_{\min}}{\Gamma_{\max}} = \frac{T_{\text{sht},\min}}{T_{\text{sht},\max}} \quad (14)$$

Based on the discussion in Sec. 3.3, $T_{\text{sht},\max}$ should be set to $\max(T_{\text{lsr},\max}, T_{\text{sht},\min})$: increasing T_{sht} beyond this value simply increases the amount of useless ambient light being integrated. We thus obtain the following condition for the camera's dynamic range:

$$DR_P = \frac{P_{\max}}{P_{\min}} \geq \frac{T_{\text{sht},\min}}{\max(T_{\text{lsr},\max}, T_{\text{sht},\min})} DR_E \quad (15)$$

This result states that if the camera enables arbitrarily small shutter time, the required dynamic range DR_P can be arbitrarily small: all of the variations of irradiance at a pixel can be accounted for by properly choosing the shutter time. The fact that the shutter time cannot take arbitrarily small values implies that the variations of irradiance at a pixel must also be accounted for by the each pixel's dynamic range.

Fig. 4 (b) shows the required dynamic range DR_P as a function of the laser power W_l for a particular choice of parameters. Note that $T_{\text{lsr},\max}$ increases as the laser power increases. For large enough values of W_l , the first term in the rhs of (15) becomes equal to 1, and thus DR_P becomes equal to DR_E (shown in Fig. 4 (a)).

⁴Note that selecting an appropriate value for Γ requires some mechanism of exposure control.

When the amplifier gain and/or the iris are allowed to change, then term $\Gamma_{\min}/\Gamma_{\max}$ in (14) may take smaller values. Fig. 4 can be easily modified to account for this, by "lowering" all curves by a constant amount. Gain and/or iris control are especially effective when T_{sht} has reached its minimum value. However, use of iris or gain control cannot change the fact that when $T_{\text{lsr},\max} < T_{\text{sht},\min}$, the camera integrates more ambient light, thus decreasing the system's ability to detect the laser return.

4.2.2 Matching the Dynamic Range Matching of an Image

Within a single frame, the exposure setting Γ is constant. We will say that an *image* is compliant if all pixels in the image receiving laser return are compliant for a given Γ . It is easy to see that the ratio between the maximum and minimum *compliant* irradiances for fixed Γ is equal to the camera's dynamic range DR_P . Hence, a sufficient condition for image compliance is the following:

$$DR_P \geq DR_E \quad (16)$$

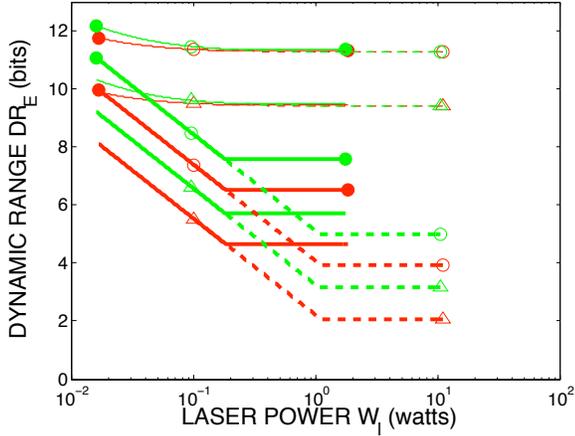
Note that the requirement in (16) is very conservative. It may well be (and often is the case) that all pixels in an image are compliant, even though the camera does not satisfy (16). In fact, the importance of (16) is in that it highlights the fact that if a camera *does* match the dynamic range at a pixel, then exposure control is not necessary (see for example Fig. 5). If this is not the case, a suitable control setting Γ can maximize the number of pixels that are correctly exposed. If the image is non-compliant (as in the case shown in Fig. 6), no exposure setting is able to correctly expose all of the laser return points.

4.2.3 Allowing for Saturation

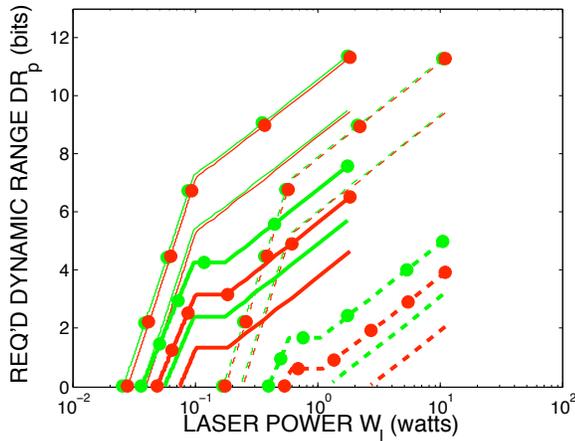
Our compliance requirement can be relaxed if pixels with laser return are allowed to saturate (*e.g.* Fig. 7). If such pixels are safely expected to be the brightest ones in the image, saturation for these pixels can be tolerated (but see Sec 4.3 for limitations of this assumption). This translates into a different expression for the dynamic range at a pixel, which can be substituted for DR_E in (15) and (16). K_2 is defined as in (10):

$$DR_{E,\text{sat}} = \frac{\rho_{\lambda_l,\max}}{\rho_{\lambda_l,\min}} \frac{K_2(W_{l,\text{eq}}, R_{\max})}{\cos \theta_{l,\max} A(\alpha_{\max})} \quad (17)$$

As seen in Fig. 4 (a) and (b), allowing for saturation has the desirable effect of significantly reducing the dynamic range requirements. However, it is critical that values of pixels that *do not* correspond to laser return be *not* saturated. Enforcing this condition via exposure control is a non-trivial problem, since the control algorithm would have to know in



(a)



(b)

Figure 4. Full dynamic range at a pixel DR_E (a) and required camera dynamic range DR_P in order to insure pixel compliance (b) as a function of the laser power W_l . It is assumed that only the shutter time T component of Γ is allowed to vary, and that $T_{\text{sht},\text{min}} = 10\mu\text{s}$. In all plots, the laser is fanned over $\beta = 60^\circ$ with divergence equal to $\gamma = 1.5$ mrad and minimum line width equal to $w = 1$ mm. The maximum considered incidence angle is $\theta_{l,\text{max}} = 60^\circ$. The sun light $E_{\text{sun}}(\lambda)$ is modeled using ASTM Standard Tables [7] for full sun at sea-level. The bandwidth of the optical filter is 10 nm. It is assumed that $\rho_{\lambda_l,\text{max}}/\rho_{\lambda_l,\text{min}} = 20$. A frame rate of 30 fps is assumed. The plots refer to the pixel at the principal point, *i.e.* $\alpha = 0^\circ$. Green lines: green ($\lambda_l = 532$ nm) laser; Red lines: infrared ($\lambda_l = 908$ nm) laser. Lines with circle markers: $R_{\text{max}} = 6$ m; Lines without circle marker: $R_{\text{max}} = 3$ m. Thin lines: saturation not allowed; Thick lines: saturation allowed (see Sec. 4.2.3). Solid lines: min. viewing distance = 10 cm; Dashed lines (hollow markers): min. viewing distance = 60 cm. Points with $DR_P = 0$ bits indicate situations where the laser return can be mapped to P_{min} by a suitable shutter time T .

advance which pixels correspond to a laser return and which don't. A natural use of (17) then is to determine that exposure control is not needed and perform a brightness calibra-



Figure 5. An example of a compliant image. All pixels with a laser return are well exposed.



Figure 6. Example of a non-compliant image. The two images of the same scene have been taken with very different exposure parameters. In the first one, the laser return from the nearby light surface is well exposed, but the laser return from the far away dark surface is not visible. In the second case, the situation is reversed: the first return is saturated and indistinguishable from the saturated background, while the laser return from the far away dark surface is visible. There is no exposure setting that makes both returns correctly exposed.

tion to a *fixed* exposure control value so that the brightest non-laser returns are just below saturation.

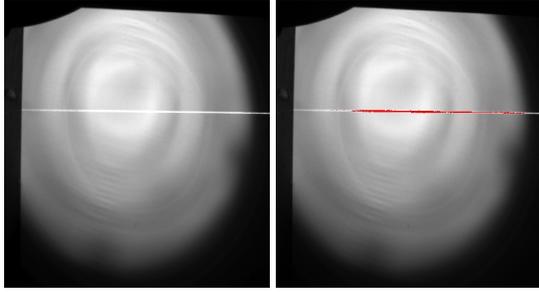


Figure 7. An example image where much of the laser return is saturated, yet can be clearly distinguished from the bright (non-saturated) surrounding background. Saturated pixels are marked red in the right image.

4.3. What is the Brightest Pixel in the Image?

In an active triangulation system, it would be very desirable that the brightest pixels in an image correspond to laser return, as it would simplify laser return detection. Several factors contribute to the balance between the irradiance component due to the laser return and that due to ambient light. We can consider a worst-case scenario, by comparing the maximum irradiance at a pixel as a function of sun light only (which occurs for $\theta_s = 0^\circ$ and high albedo) with the minimum usable irradiance from laser return (for incidence angle equal to $\theta_{l,max}$ and low albedo) as a function of the distance R :

$$\frac{M_{sun,max}}{M_{lsr,min}(R)} = \frac{\rho_{\lambda_l,min}}{\rho_{\lambda_l,max}} \frac{K_2(W_{l,eq}, R)}{\cos \theta_{l,max} A(\alpha_{max})} \quad (18)$$

We define by R_{thr} the value of distance such that $M_{sun,max}/M_{lsr,min}(R_{thr}) = 1$. Only when $R < R_{thr}$ are the pixels with laser return certain to be the brightest ones in the image. This means that if $R_{max} > R_{thr}$, one cannot rely on brightness alone to identify the laser return on an image, and other detection mechanisms should be employed. For example, one may turn the laser on for one frame and off at the next frame, and compute the difference between the two images to reject stationary background pixels. One may also exploit the characteristic shape of the laser return, and only consider conforming brightness ridges in the image as possible candidates.

Fig. 8 shows plots of R_{thr} vs. laser power W_l for a green and an IR laser, with minimum viewing distance of 10 cm and 60 cm. The IR laser allows larger R_{thr} since sun light has more power in the green spectrum than in the IR spectrum. R_{thr} becomes constant beyond a certain value of W_l because the shutter time cannot take arbitrarily low values. Fig. 9 shows a case in which all pixels with a laser return take lower values than pixels in a region of strong sun light.

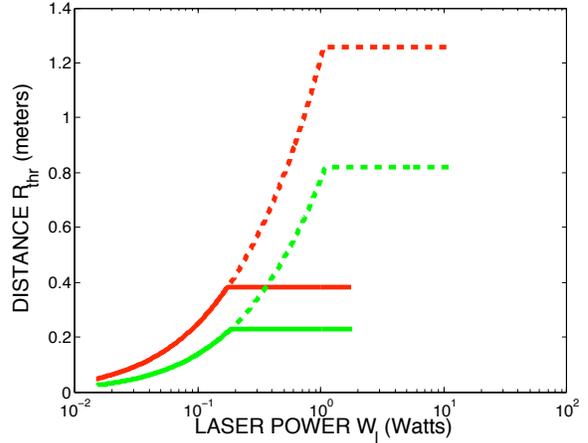


Figure 8. The maximum distance R_{thr} at which a pixel with laser return is certain to be brighter than any other pixel receiving only ambient light, as a function of the laser power $W_{l,eq}$. Green lines: green ($\lambda_l=532$ nm) laser; Red lines: infrared ($\lambda_l=908$ nm) laser. Solid lines: min. viewing distance = 10 cm; Dashed lines: min. viewing distance= 60 cm. See caption of Fig. 4 for the parameters of the system considered for these plots.

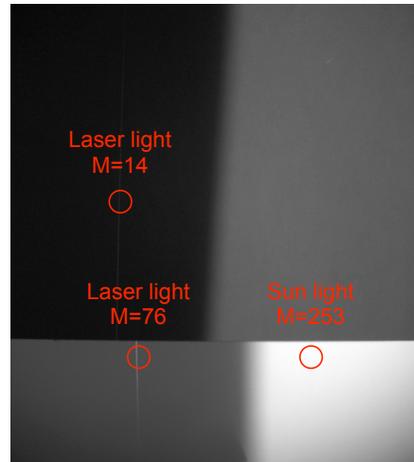


Figure 9. An example of an image in which the pixels receiving laser return are not the brightest ones.

5. Conclusions

Perhaps the most obvious conclusion from our analysis is that although increasing the laser power in an active triangulation system can improve rejection of ambient light (and thus detection of the laser return), this improvement is limited by the fact that cameras cannot accommodate arbitrarily small shutter times. Indeed, even with powerful lasers, ambient light may generate higher values of pixel brightness than laser return from surfaces after a certain distance. Furthermore, we have shown that increasing the laser power leads to higher requirements in terms of camera's dynamic range for correct exposure, as the range of realizable shut-

ter times is decreased. Our analysis has also highlighted the dynamic range requirements of a camera in order to avoid the need for exposure control.

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