Introduction

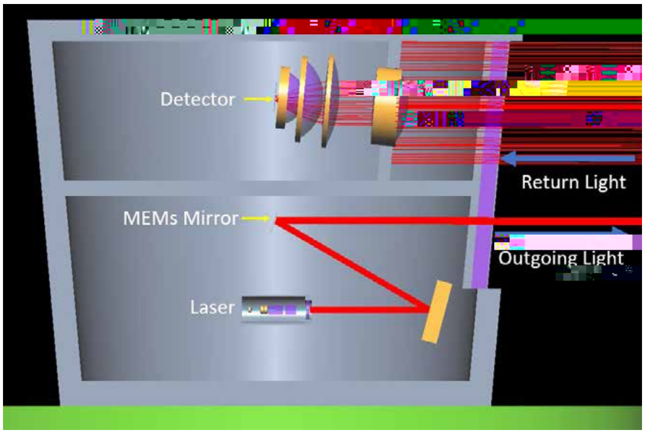

Figure 1: Cutaway diagram of the test LiDAR system

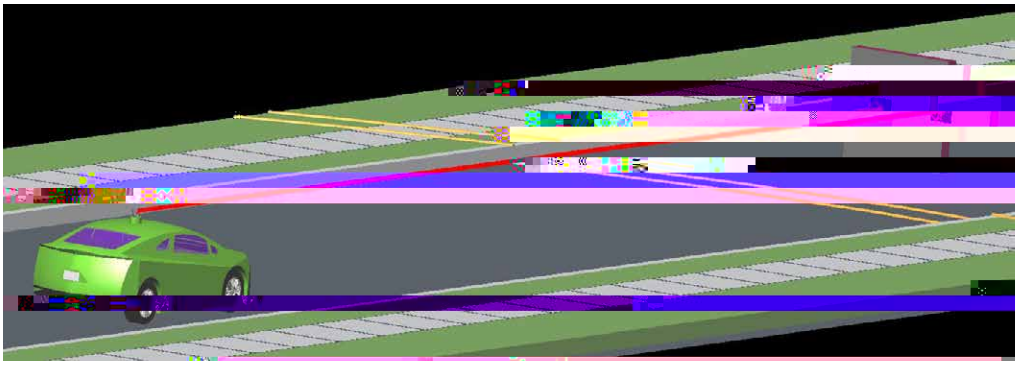

Figure 2: LiDAR system shown illuminating a target cube at 25 m distance

Return Signal Strength

For a LiDAR system to work properly, the return signal must be detectable and distinguishable from any background signals or noise. Sources of background signal can be varied and include sunlight reflecting off the target surfaces or scattered into the receiver from the atmosphere, or even intercepted signals from other, nearby, LiDAR systems. Sources of random noise can also be varied, but often include random noise from the detector and electronics.

If we assume that the target surface is Lambertian, then we can directly calculate the expected return by the following equation:

[illegible]

Where IReturn is the return power at the detector; I_{Launch} is the original launch power; Transmission is the transmission of the system including the atmosphere for a round trip; P is the percentage of the beam energy that falls on the target surface; TIS is the total integrated scatter of the target surface; $PSA_{Detector}$ is the projected solid angle of the entrance aperture of the detector lens system as measured from the target surface; and b is the angle of incidence on the target surface. This does not include any detector sensitivity values that you could also factor in.

If we have a circular aperture for the detector system that is oriented normal to the incoming light, we can expand the above equation to:

[illegible]

Where $D_{Detector}$ is the entrance diameter of the detector system and r is the distance between the LiDAR system and the target.

As an example, if we assume a launch power of 100 W, transmission and TIS of 100%, 100% of the beam power falling on the target, a detector entrance diameter of 25 mm, and a target at 50 m distance and normal incidence, then we calculate a return power of 6.25 W. This is a reduction of more than 7 orders of magnitude over the launch power and can be easily confirmed using LightTools (see Figure 3).

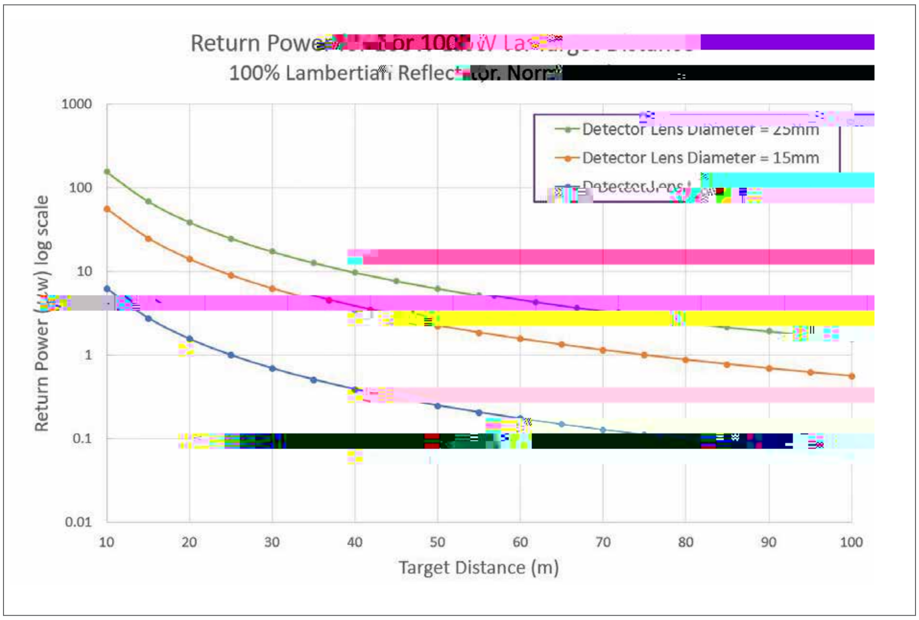

Figure 3: Set of return curves for different detector apertures as a function of target distance using a 100W laser. The target was a 100% Lambertian reflector at normal incidence.

Lambertian surfaces create wide scattered light distributions with intensity patterns that fall off as the cosine of the angle of incidence. Light reflected from Lambertian surfaces looks uniformly bright no matter what the viewing angle is. This makes them reasonable approximations for surfaces that appear matte to the eye such as skin, clothing, and plants when viewed from a distance. Smooth metallic and glass surfaces on vehicles generally do not have Lambertian properties, but exhibit more complex scattering behavior. While for some such surfaces it may be possible to calculate the response, it is much easier to model the surface in LightTools and obtain the result directly, as shown in Figure 4.

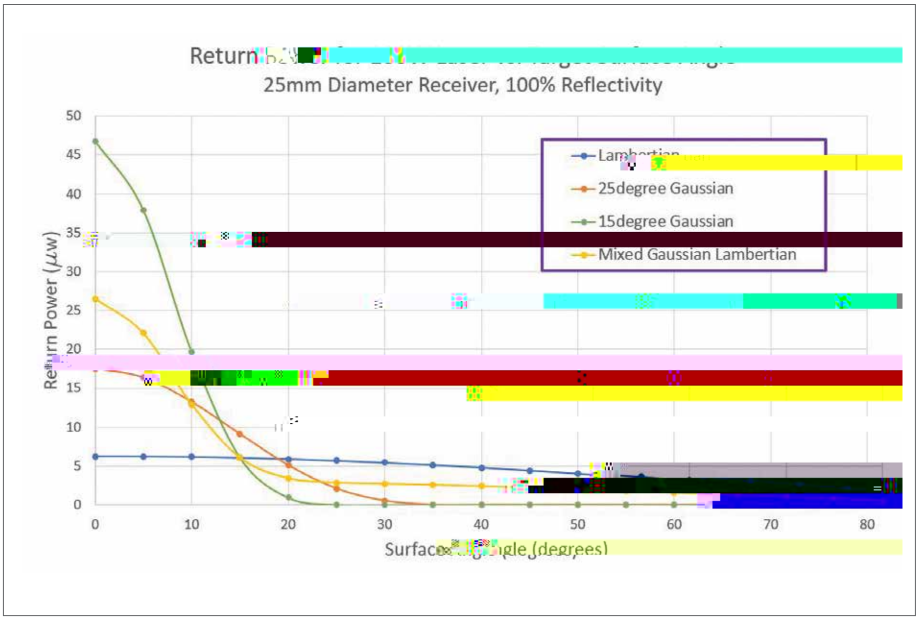

Figure 4: Results from several different scattering surface types for various incidence angles

For all data sets, we use a 25 mm diameter aperture, a 100 W laser and a target distance of 50 m. Figure 4 shows the results from a Lambertian surface, two Gaussian surfaces with differing half-widths, and one mixed surface with a 15° Gaussian (50%) and a Lambertian (50%) component. It is noteworthy that the Gaussian surfaces produce greatly enhanced signals but only at near normal incidence. More complex surface scattering types including measured BRDF can be easily modeled in the same way.

Atmospheric Effects

Another important effect that will influence the return signal is atmospheric conditions such as rain or fog. Raindrops that fall inside the beam will deflect the light that passes through them, excluding some of that power from the return signal. Of course, the system is double-pass, so the precipitation can affect rays going in either direction. The impact of precipitation on the return signal is not easy to calculate directly. The best way to obtain meaningful information is through modeling.

Let's first look at rain and then we will discuss fog as a special case. In order to properly model rain drops in the LiDAR beam, you need to know the size of the drops and the overall density. You also need the index of water at your laser wavelength, which is reasonably easy to obtain. These density and size parameters will vary depending on the strength of the rain. We will use three categories of rain (light, medium, and heavy) with typical drop sizes and densities for each category. Table 1 lists the values that we used for the simulations shown.

The second method, and the one that we utilized for this data, is to use the 3D texture feature with library textures. This feature allows you to create spherical textures to represent individual drops and then translate them up off the base surface into the path of the beam using the z-offset parameter. A simple macro randomly distributes the drops inside a pre-defined volume surrounding the

For each of the different conditions, the size of the drops was held uniform throughout the volume, though this is not a requirement of the software. However, you will notice that the marks from each drop vary considerably. This is the result of their varying position along the length of the beam. Drops that fall in the outgoing beam near the LiDAR system where the beam is small have a greater effect than ones that fall in the beam nearer the target where the beam is much larger. This can be seen in Figure 7, where we happened to have a small drop fall in the outgoing beam near the LiDAR system.

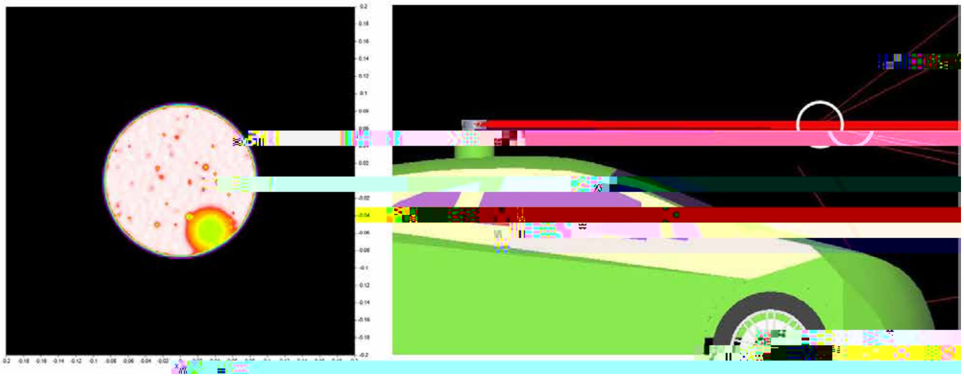

Figure 7: In this figure, we see an illuminance pattern on the target surface with a raindrop falling in the outgoing beam near the LiDAR system, causing an outsized effect on the pattern. The right-hand image indicates the position of the drop (white circle) as evidenced by the scattered red rays.

We have not yet discussed the effect of precipitation on the exit window itself. For spinning LiDARs, such as the one modeled here, this may not be a major issue since the centripetal force may keep any sizeable drops from remaining on the window. However, for fixed systems, the presence of drops on the exit window can be catastrophic, blinding the system to part of its field of view.

Modeling fog is a little different from modeling rain. The primary difference is in the drop size and density. As shown in Table 1, drop sizes for fog are very much smaller than that for rain, and particle densities are much higher leading to many more particles in a given volume. Fortunately, the fog droplet sizes are small enough that we can use Mie theory to model their effect on light. To model fog, we used a volume scattering material with an appropriately sized Mie particle at the correct density for moderate fog (see Table 1). The result is significantly more pronounced than with rain. Figure 8 shows the results of a ray trace using a foggy atmosphere.

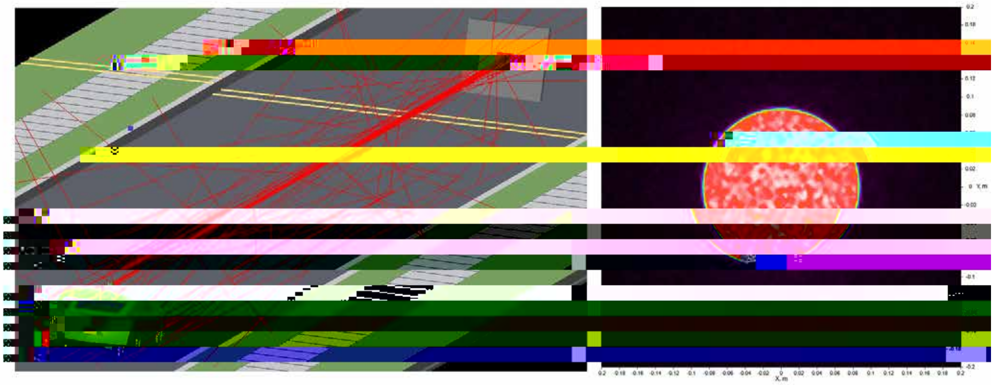

Figure 8: The image on the left shows the LiDAR beam in the presence of a moderate fog. Many rays have been scattered out of the beam by the fog particles. The image on the right shows the illuminance pattern on the target surface. The variation is primarily the result of the random scattering.

While variations in the target illuminance pattern are informative, what really matters to the LiDAR system is the return flux from the target. In this, the results are somewhat surprising. As can be seen in Figure 9, the return signal for the tested rain conditions did not vary significantly from the baseline of no precipitation. Moderate fog, on the other hand, led to a significant signal drop that worsened as the distance increased.