WHITE PAPER

Application in Optical Design: Optimization for Receiver Enclosed Energy in LiDAR Systems

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Introduction

In general, optical systems perform best when they are optimized to create sharp images. For example, macro lenses are optimized to provide sharp images of nearby objects, while zoom lenses are optimized to image over a range of object distances. In each case, sharp imagery is the goal.

However, not all optical systems use image quality to gauge performance. Many systems such as spectrometers or solar concentrators have requirements for irradiance that must be met by the designer. For systems like this, enclosed energy optimization is a better description of the performance requirements. In this paper, we describe an example system where enclosed energy optimization is critical for final system performance. We show results of this type of modeling, analysis and optimization in Synopsys' CODE V® optical design software.

LiDAR: An Enabling Technology for Autonomous Vehicles

LiDAR (Light Detection and Ranging) is an optical technology often cited as a key method for distance sensing for autonomous vehicles. In LiDAR, laser light is sent from a source and reflected from objects in the scene. The reflected light is detected and the time of flight (TOF) is used to develop a distance map of the objects in the scene. Many manufacturers are working to develop cost-effective, compact LiDAR systems. Virtually all producers pursuing autonomous driving consider LiDAR a key enabling technology, and some LiDAR systems are already available for Advanced Driver Assistance Systems (ADAS).

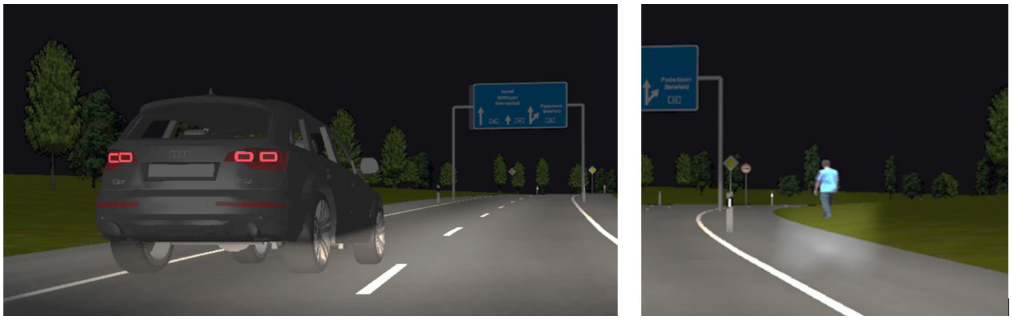

Figure 1: Example driving situations where LiDAR sensing can support driver (and pedestrian) safety

Different Optical Systems - Different Performance Requirements

Unlike photographic lenses where imaging metrics such as Modulation Transfer Function (MTF) guide the designer, LiDAR systems are driven by different performance requirements. For a LiDAR system, if the energy returned to the detector from different points in the field of view is not uniform, TOF fidelity and scene resolution will be lost. Therefore, optimizing the collected energy over the field of view is critical.

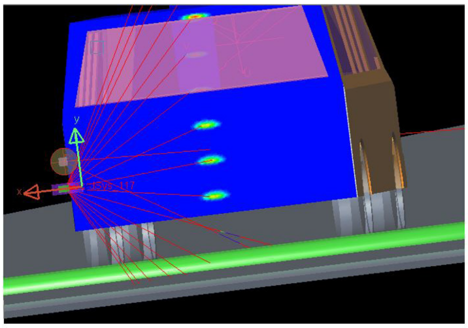

Figure 2: Simulated vehicle with representative laser spots from 1D scanning LiDAR system

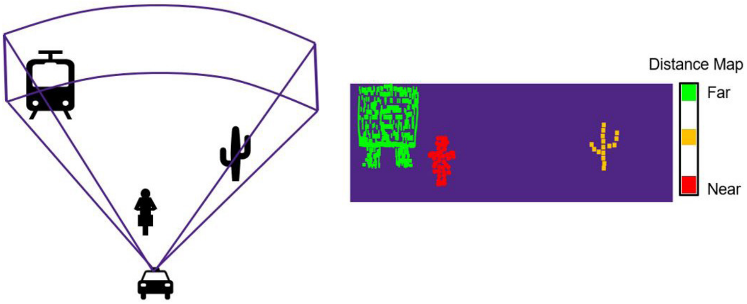

Figure 3: 3D flash LiDAR (purple envelope) and representative distance map (TOF mapping)

For short ranges below 50 meters, 3D flash LiDAR (where outgoing laser pulses illuminate the entire Field of View, or FOV, for the system)[1] often works best. For these systems, a wide horizontal FOV with uniform energy collection is important. In the following example, we consider such a flash system. The goal is to obtain uniform enclosed energy in a given detector area across the FOV, to ensure depth resolution of objects across the viewing area of the sensor.

LiDAR Receiver Design Considerations

Our design example is a front-looking, short-range LiDAR. The view distance and FOV requirements are 30 meters and 90° horizontal FOV x 20° vertical FOV, respectively.

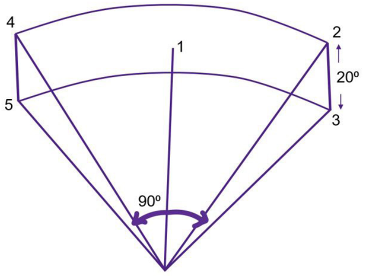

Figure 4: Sketch of horizontal and vertical FOV for short-range LiDAR receiver design - the numbers 1 to 5 correspond to a few field points for the receiver optical design

Optimization for Uniform Enclosed Energy: An Easy Process Using Enclosed Energy Functions in CODE V

For the receiver optics of the LiDAR example system, we start with an expired patent lens with four elements covering a 45° semi-FOV. CODE V has a large library of these lenses, enabling efficient starting point generation. The goal of optimization is to improve the uniformity of energy for simulated detector elements. For the detector elements, we assume a rectangular aspect ratio array to cover the 90° x 20° FOV. We assume a 1376 x 768 array of Vertical Avalanche Photo Diodes (VAPDs), representative of currently developed technology[2] with an active area of approximately 16.0 mm x 9.0 mm.

Based on the data, a focal length of 8.0 mm is chosen to cover the 90° horizontal FOV.

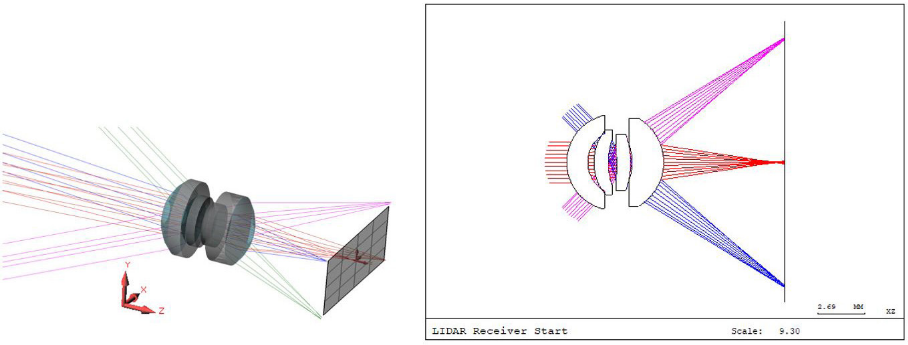

Figure 5: Starting point optical system for collecting energy over wide horizontal field of view

LiDAR Receiver System Initial Performance

To understand the initial design performance, we examine the spot diagrams for each field point. In the following figure, 100 µm x 100 µm boxes are drawn at each field point on the detector plane, along with the corresponding focused spots (representing a geometric spread of energy). These correspond to light coming from the center and four corners of the area of observation.

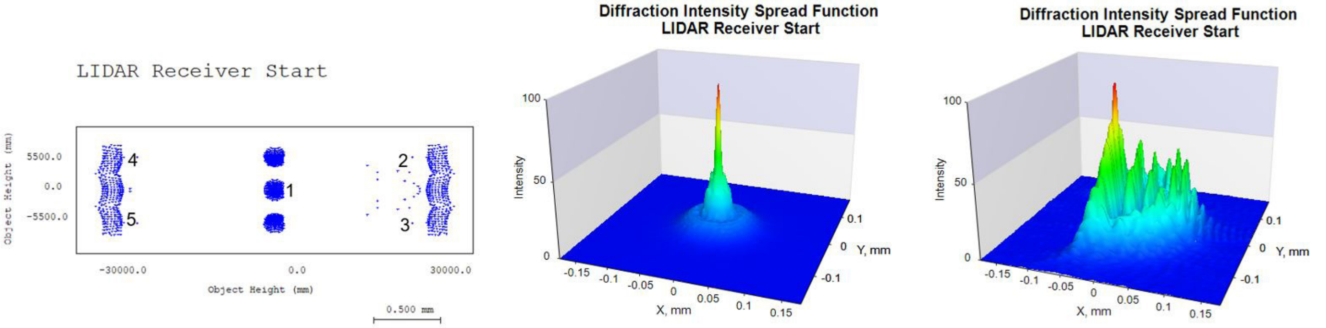

Figure 6: Starting point spot diagrams (scale at left is 500 µm) for numbered field points shown in the previous sketch and 3D PSF plots for the center and one edge field point (note asymmetry)

As the plots show, the lens has substantial aberration and asymmetric energy distribution at the receiver plane. Next, we will optimize for uniform enclosed energy and show the final system performance.

Description of CODE V Enclosed Energy Macro-PLUS Functions

A new set of tools available in CODE V optical design software is ideally suited to help optical engineers working on systems where energy enclosed is of primary importance for analysis or optimization[3]. The tools are delivered as Macro-PLUS™ functions in CODE V to help designers analyze and optimize the amount of energy on a detector of specific size or enclosed in a specific diameter.

To use the functions to evaluate enclosed energy, the designer provides information about the targeted energy enclosing geometry, the method for computing the energy (fixed about the centroid or scanning in X, Y, or both directions) and the sampling. CODE V can also be used to optimize the system in the context of the energy and other optical system constraints. CODE V has the flexibility to perform an enclosed energy evaluation on the output from many analysis options. These include options such as point spread function (PSF), beam propagation (BSP), and illumination analysis (LUM). In addition, the PSF data can be used for optimization, as we show in the following example.

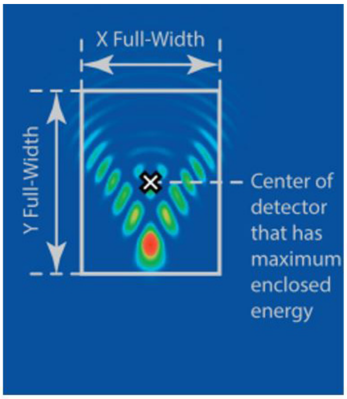

Figure 7: Example of energy enclosed on a rectangular detector of size X Full-Width x Y Full-Width

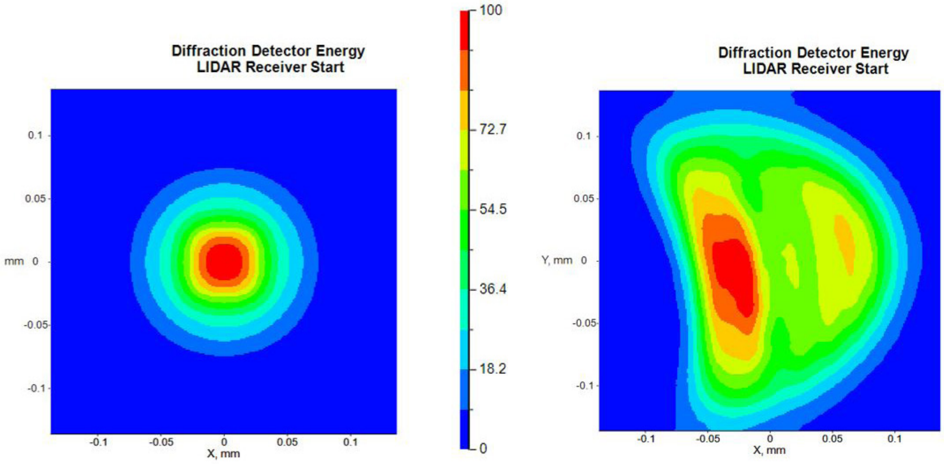

Figure 8: Starting energy distributions, center (left), and upper left corner of FOV, 200 μm x 200 μm area, examining 50 μm x 50 μm detector element (corresponds to 145 mm x 145 mm square in object space)

The starting distributions of energy show a spread of light into more than ten times the area we require given the individual APD detector size (approximately 15 μm x 15 μm). Much of the light from a single observation patch (object resolution element) will spread over several pixels in the receiver plane. This is especially true for off-axis points in the FOV, which precludes accurate depth mapping.

Optimization for Uniform Receiver Energy

To address the non-uniformity of energy spread, we next optimize for enclosed energy in CODE V. We achieve this by creating enclosed energy constraints in the CODE V Macro-PLUS™ programming language as described above, using the new enclosed energy functions. We set targets of 75% energy, contained within a 15 μm diameter circle for each field point. Optimization is achieved very quickly (just over one minute of computation time is required). Note that enclosed energy geometry does not need to be minimized; distributions of arbitrary size can be targeted, depending on the application.

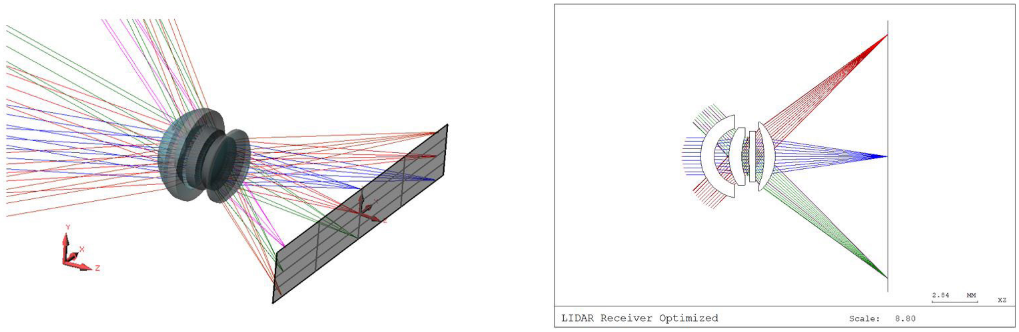

Figure 9: Resulting optimized LiDAR receiver optical system

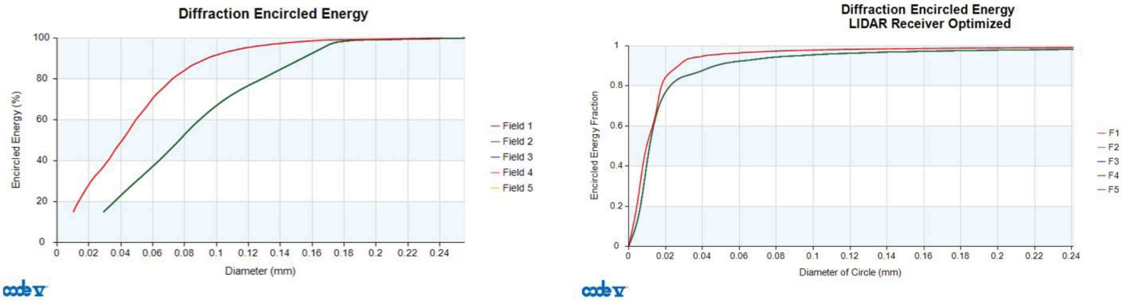

Figure 10: Encircled energy plots prior to (left) and after (right) optimization for enclosed energy constraints

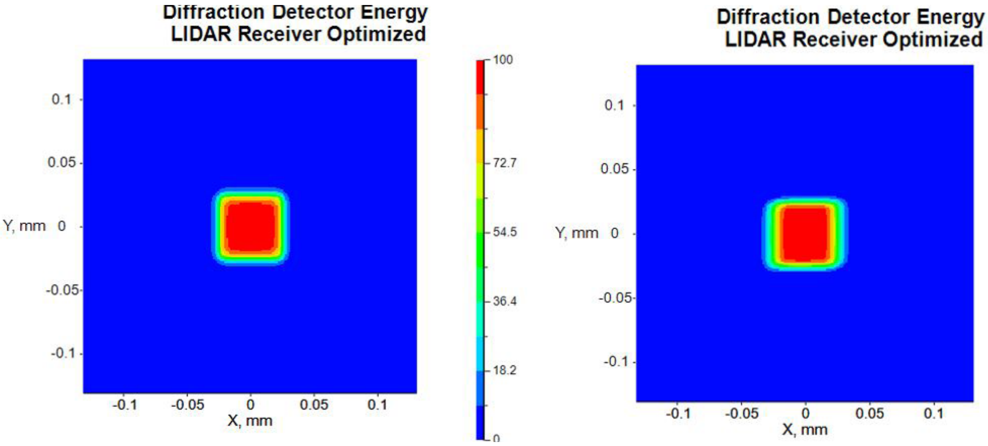

Figure 11: Energy distributions, center of observation area (left), upper left corner of FOV, 200 μm x 200 μm area, examining 50 μm x 50 μm detector element (corresponds to 145 mm x 145 mm patch in object space)

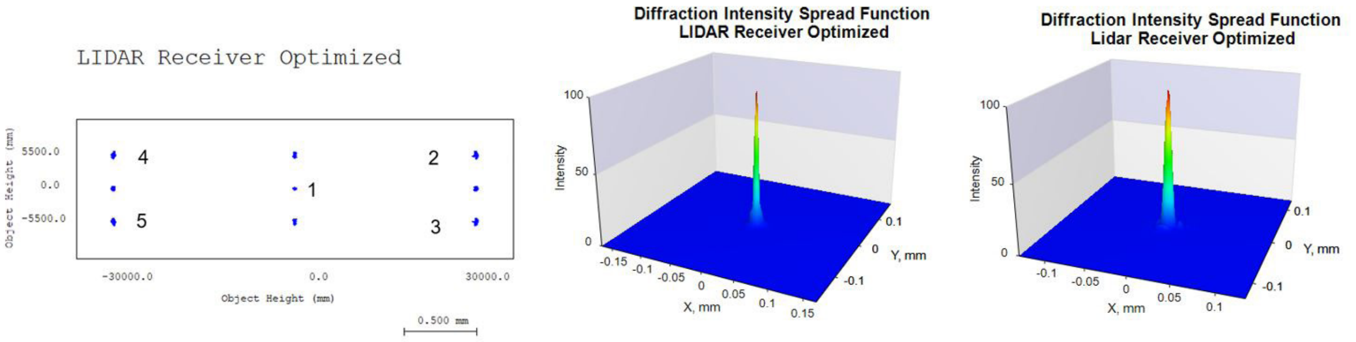

Figure 12: Post-optimization spot diagrams (scale at left is again 500 µm) for numbered field points shown in the previous sketch and 3D PSF plots for the center and one edge field point (note asymmetry)

From these analyses, we see the diffraction encircled energy plots for the final system have now met our design target of 75% energy in a 15 µm circle. We see that 145 mm x 145 mm square patches in object space map to a much more uniform corresponding energy area at the APD array (LiDAR receiver) plane, and the final plots of spot diagrams and 3D PSF show the uniformity of the system across the FOV, ideal for depth mapping for the example LiDAR system.

Summary

A new set of CODE V Macro-PLUS functions is available to optical engineers that provide easy analysis and optimization for enclosed energy in various geometries. The functions are useful for designing systems where enclosed energy is an important part (or indeed perhaps the key definition) of the requirements for the design. We discussed an example LiDAR receiver system and showed the result of an optimization for uniform enclosed energy at the detector array plane for a given object patch size and resolution. There are many optical systems that would benefit from this type of flexible, efficient design capability. Synopsys' CODE V optical design software now provides all users this efficient enclosed energy optimization, for any optical system where this is a valid performance metric.

References

1. Jang, C., "Design factor optimization of 3D flash LiDAR sensor based on geometrical model for automated vehicle and advanced driver assistance system applications", International Journal of Automotive Technology, February 2017, DOI: 10.1007/s12239-017-0015-7
2. Yutaka, H., et. al., "A 250 m Direct Time-of-Flight Ranging System Based on a Synthesis of Sub-Ranging Images and a Vertical Avalanche Photo-Diodes (VAPD) CMOS Image Sensor", Sensors, MDPI Journals, October 2018
3. CODE V Reference Manuals, CODE V 11.2 SR1, January 2019.

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Pub: Sept. 2017