TECHNICAL NOTE

Understanding the Calculations, Limitations and Opportunities for the Improvement of LiDAR Range for ADAS and Autonomous Driving Applications

An Overview

This Technical Note aims to explain the role of wavelength in LiDAR and how wavelength impacts range, laser power and signal-to-noise ratio. The document starts with a revisit to some fundamental physics concepts, followed by an explanation of wavelength, range and eye safety. It then details key factors that impact LiDAR range and ends with offering solutions to increase LiDAR range within the autonomous driving landscape.

Introduction to Fundamentals

The following mathematical equations are provided to develop a basic understanding of the relationship between various properties of light and LiDARs. These equations are drawn upon in succeeding sessions to illustrate concepts.

- **Distance to object (in a time-of-flight LiDAR) calculation:**

  $R = c * (\Delta t/2)$

  - R = Object distance (m)

    Note: *The maximum distance a LiDAR can detect an object is the LiDAR range.*
  - c = Speed of light (m/s)
  - Δt = Time of flight (s)

    Note: *Time of flight is the time it takes for the laser pulse to return to the sensor and the time it takes for the pulse to reach the object.*

- **Relationship between frequency and wavelength:**

  $f * \lambda = c$

  - f = Frequency (Hz or 1/s)
  - c = Speed of light (m/s)
  - λ = Wavelength (m)

- **Energy calculation:**

  $E = h * f$

  - E = Energy of photon (J)
  - $h = Planck's\ constant = 6.63\ \times 10^{-34}\ Js$
  - f = Frequency (Hz or 1/s)

- **Power calculation:**

  $P = E/t$

  - P = Power (Watts or J/s)
  - E = Energy of photon (J)
  - t = Time (s)

- **Irradiance calculation:**

  $E = {}^{P}/_{A}$

  - E = Irradiance (W/m^2)
  - P = Power (W)
  - A = Area (m^2)

How Does LiDAR Wavelength Affect Its Range and Safety?

Maximum permissible exposure (MPE) is the maximum allowable radiation exposure on human skin or eyes without causing biological damage. The MPE is defined by ANSI Z136 standards or from IEC 60825-1. The MPE provides the maximum allowable beam energy depending on the beam wavelength and emission duration. An example is provided below: how much energy does a laser operating at 700 nm wavelength contain?

$$E = h * f = h * {}^{c}/_{\lambda}$$

$$E = 6.63\ \times 10^{-34} * \left({}^{3\times\ 10^{8}}/_{700\ \times 10^{-9}}\right)$$

$$= 2.84\ \times\ 10^{-19} J$$

The energy value derived in the above example is cross-referenced against IEC 60825-1 standards (time and wavelength) to ensure the safe operation of a laser. IEC standards dictate how much exposure a human can have to this laser operating at 700 nm. Maximum emitted power (aka transmission power) is constrained by MPE limits. In practical applications for autonomous driving, 905 nm and 1550 nm are the most common wavelengths used with laser pulses of very short order (nanoseconds).

A by-product of high-energy pulses is heat generation, which also causes signal interference and complicates signal processing in a LiDAR. Laser pulse duration is controlled by the laser driver board in a LiDAR.

Understanding Range Through the LiDAR Equation

At the basic level, the LiDAR range is determined by:

- Background noise
- Photons detected by the photodetector (signal)

The signal-to-noise ratio (SNR) is a key parameter used to differentiate between object reflected signal and background noise. The maximum LiDAR range can be expressed as the maximum distance at which SNR is high enough to differentiate between signal and background noise. Background noise sources in LiDAR for autonomous driving consist of any source of light close enough to the sensor's operating wavelength that can be mistaken for the signal itself (sunlight, car headlights, road lighting…). For example, electromagnetic waves emitted by the sun are of a broad spectrum and are the main source of ambient noise during the day. Background noise is filtered using narrow-bandpass filters, which are devices that allow frequencies within a specific range to pass through while blocking other wavelengths. The signal-to-noise ratio equation[1] is presented below for reference:

$$SNR\ (r) = \frac{P_r * S_\lambda * M}{\sqrt{2 * e * B * [(P_r + P_B) * S_\lambda + I_D] * F * M^2 + \frac{4 * k * T * B}{R_0}}}$$

- P_r = Received power
- S_λ = Detector's sensitivity
- *M* = Detector's intrinsic gain
- I_D = Detector's dark current
- *F* = Detector's excess noise factor
- *B* = Detection bandwidth
- *T* = Temperature
- *e* = Elementary charge; *k* = Boltzmann constant

As shown above, the SNR is directly proportional to received power, the detector's intrinsic gain and sensitivity. While this paragraph delves into detector technologies, received power is explained in the following paragraph. Some technologies used for detectors in LiDARs are avalanche photodiodes (APDs), single-photon avalanche diodes (SPADs) and silicon photomultipliers (SiPM). Photon detection capabilities determine the detector's sensitivity. While SPAD detects photons individually, SiPM is connected in parallel to SPADs and detects the total number of photons detected by all SPADs. Due to increased sensitivity, SPADs are a popular choice for photon detection.

[1] Hamamatsu Photonics. "Lidar, Radar, and Cameras: Measuring Distance with Light in the Automotive Industry." YouTube, 12 Feb. 2018, https://www.youtube.com/watch?v=D5Hh8EuOD2Q .

One variation of the basic LiDAR equation is presented below[1]:

$$P_r = P_t * \rho * {A_o}/{\pi R^2} * \eta_o * \exp\left(-2R\gamma\right)$$

- P_r = Received power
- P_t = Transmitted power
- ρ = Target reflectivity
- A_o = Aperture area of a receiver
- R = Distance of object from the emitter unit
- η_o = Receiving optics transmission
- γ = Atmospheric extinction coefficient

This LiDAR equation assumes normal incidence, Lambertian reflection, flat beam profile and negligible divergence. As shown in the equation, power received is directly proportional to power transmitted and aperture area but inversely proportional to the object distance. The maximum object distance possible is the LiDAR range.

Improve LiDAR Range for Autonomous Driving by Increasing LiDAR Power

The LiDAR equation shows that higher transmitted power will result in higher received power. However, maximum transmitted power is limited by IEC standards on MPE. As shown, lights with shorter wavelengths (cosmic rays, gamma rays) carry more power than radio and radar waves.

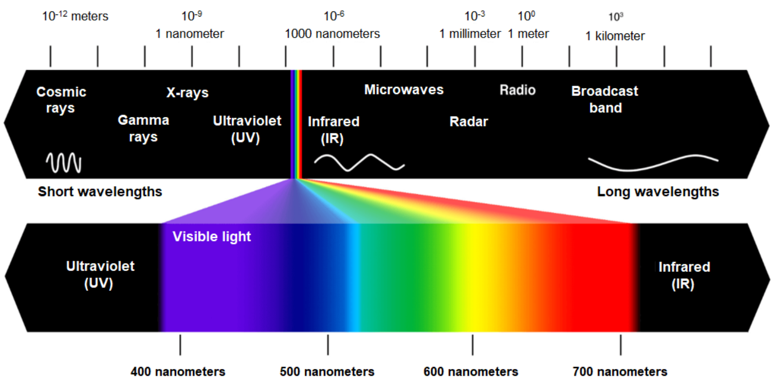

Figure 1 – Light spectrum

Improve LiDAR Performance, Cost and Form Factor for ADAS and Autonomous Driving

The previous sections of this Technical Note explained the limitations of maximum energy that laser beams can transmit. From the equation above, an increase in the aperture area of the receiver lens can increase the LiDAR range. However, this has three significant drawbacks:

- Increased LiDAR form factor (size)
- Increased LiDAR cost due to more expensive and larger lenses
- Increased noise

An alternative method to increase range is through beam steering.

Beam steering refers to redirecting the laser pulse to sub-sections within the field of view, thereby increasing transmitted power, received power and SNR. Beam steering components enable the object-reflected laser signal to be captured by the receiver lens by redirecting the pulses, enabling the receiver to capture the laser signal from a wide field of view without making any physical changes to the receiver unit.

Additional benefits of beam steering are:

- Enhanced signal-to-noise ratio and LiDAR range
- Reduced size, cost and complexity of the LiDAR components
- Smaller optical system required in the LiDAR
- Solid-state technology with no moving parts, for higher MTBF (mean time between failures)
- Extended FoV elevation and azimuth; up to 120° per axis

Videos, pictures and Spec Sheet on digital beam steering and more insights on its role in developing autonomous solutions are available at leddartech.com/solutions/leddarsteer-digital-beam-steering/.

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