LiDAR: Principles and Types

1 Overview of LiDAR

LiDAR (Light Detection and Ranging) is a remote sensing technology that uses laser pulses to measure distances and create high-resolution maps or 3D models of objects and environments. It is widely used in topography, forestry, autonomous vehicles, archaeology, and more.

The core components of a LiDAR system include:

- **Laser Source**: Emits short pulses of light, typically in the near-infrared or visible spectrum.
- **Scanner and Optics**: Directs the laser beam across the target area.
- **Receiver/Detector**: Captures the reflected light.
- **Position and Navigation System**: Uses GPS and inertial measurement units (IMUs) to track the sensor's position and orientation.
- **Data Processing Unit**: Computes distances and generates point clouds.

2 Theoretical Principles of LiDAR

LiDAR operates primarily on the time-of-flight (ToF) principle, with alternatives like phase-shift and frequency-modulated continuous wave (FMCW) methods. Below, the ToF method is detailed with key equations and units.

2.1 Time-of-Flight (ToF) Principle

The ToF method calculates distance by measuring the time a laser pulse takes to travel to a target and back. The distance d is given by:

$$d = \frac{c \cdot t}{2} \tag{1}$$

- d: Distance to the target (meters, m)
- c: Speed of light (3×10^8 m/s)
- t: Round-trip time (seconds, s)

Example: For $t = 1\,\mu\text{s} = 10^{-6}\,\text{s}$,

$$d = \frac{(3 \times 10^8) \cdot (10^{-6})}{2} = 150\,\text{m}$$

2.2 Point Cloud Generation

Multiple pulses are emitted while scanning, with the laser's direction defined by azimuth (θ) and elevation (ϕ) angles. The 3D coordinates (x, y, z) are:

$$x = d \cdot \cos(\phi) \cdot \sin(\theta) \tag{2}$$
$$y = d \cdot \cos(\phi) \cdot \cos(\theta) \tag{3}$$
$$z = d \cdot \sin(\phi) \tag{4}$$

- x, y, z: Coordinates (meters, m)
- θ, ϕ: Angles (radians or degrees)

GPS and IMU data transform these into global coordinates.

2.3 Intensity of Reflected Signal

The received power P_r depends on target reflectivity and distance:

$$P_r = \frac{P_t \cdot \rho \cdot A_r \cdot \eta_{\text{atm}} \cdot \eta_{\text{sys}}}{4\pi d^2} \tag{5}$$

- P_r, P_t: Received and transmitted power (watts, W)
- ρ: Target reflectivity (dimensionless, 0–1)
- A_r: Receiver aperture area (m^2)
- $\eta_{\text{atm}}, \eta_{\text{sys}}$: Atmospheric and system efficiencies (dimensionless, 0–1)

2.4 Angular Resolution

Angular resolution depends on beam divergence β:

$$\Delta\theta = \frac{\beta}{2} \tag{6}$$

- $\Delta\theta, \beta$: Angular resolution and beam divergence (radians or degrees)

2.5 Range Resolution

Range resolution depends on pulse width τ:

$$\Delta d = \frac{c \cdot \tau}{2} \tag{7}$$

- Δd: Range resolution (meters, m)

- τ: Pulse width (seconds, s)

Example: For $\tau = 1\,\text{ns} = 10^{-9}\,\text{s}$,

$$\Delta d = \frac{(3 \times 10^8) \cdot (10^{-9})}{2} = 0.15\,\text{m}$$

2.6 Atmospheric Effects

Atmospheric attenuation is modeled using the Beer-Lambert law:

$$\eta_{\text{atm}} = e^{-2\alpha d} \tag{8}$$

- η_{atm}: Atmospheric transmission efficiency (dimensionless)
- α: Attenuation coefficient (m^{-1})

3 Types of LiDAR Systems

LiDAR systems are categorized by platform, measurement technique, or application.

3.1 By Platform

- **Airborne LiDAR**: Mounted on aircraft/drones for large-scale mapping (e.g., topography). Requires precise GPS/IMU data.
- **Terrestrial LiDAR**: Ground-based (static or mobile) for detailed surveys (e.g., buildings). Achieves centimeter-level accuracy.
- **Spaceborne LiDAR**: Satellite-based for global mapping (e.g., ice sheet monitoring).

3.2 By Measurement Technique

- **Time-of-Flight (ToF) LiDAR**: Measures pulse round-trip time. Equation: $d = \frac{c \cdot t}{2}$. Used for long-range applications.
- **Phase-Shift LiDAR**: Measures phase difference of a modulated beam:

  $$d = \frac{c \cdot \Delta\phi}{4\pi f}$$

  - $\Delta\phi$: Phase shift (radians)
  - f: Modulation frequency (Hz)
- **FMCW LiDAR**: Uses frequency-modulated laser for distance and velocity:

  $$d = \frac{c \cdot \Delta f}{2 \cdot S}$$

  - Δf: Frequency difference (Hz)
  - S: Frequency sweep rate (Hz/s)

3.3 By Application

- **Topographic LiDAR**: Uses near-infrared lasers (e.g., 1064 nm) for terrain mapping.
- **Bathymetric LiDAR**: Uses green lasers (e.g., 532 nm) for underwater topography:

$$d_{\text{water}} = \frac{d_{\text{measured}}}{n}, \quad n \approx 1.33$$

- **Atmospheric LiDAR**: Measures atmospheric properties:

$$P_r(z) = \frac{P_t \cdot \beta(z) \cdot A_r \cdot e^{-2\int_0^z \alpha(z')\,dz'}}{z^2}$$

  - $\beta(z)$: Backscatter coefficient ($\mathrm{m}^{-1}\ \mathrm{sr}^{-1}$)
  - z: Altitude (m)

4 Practical Considerations

- **Pulse Repetition Rate (PRR)**: Pulses per second (Hz). Higher PRR increases point cloud density.
- **Field of View (FOV)**: Determined by the scanner's angular range.
- **Error Sources**: Timing errors, angular misalignment, and atmospheric effects.

5 Applications and Point Cloud Output

LiDAR generates point clouds with coordinates (x, y, z) and intensity values, used for:

- Digital Elevation Models (DEMs) for terrain mapping.
- 3D models for buildings and vegetation.
- Velocity measurements in autonomous vehicles.

6 Units Summary

7 Conclusion

LiDAR relies on precise measurements of laser pulse travel time or phase shift to calculate distances and generate 3D point clouds. Its types—airborne, terrestrial, spaceborne; ToF, phase-shift, FMCW; topographic, bathymetric, atmospheric—cater to diverse applications, each governed by specific equations and principles.

Variable	Description	Unit
d	Distance	Meters (m)
c	Speed of light	Meters per second (m/s)
t	Round-trip time	Seconds (s)
x, y, z	Coordinates	Meters (m)
θ, ϕ	Angles	Radians or degrees
P_r, P_t	Power	Watts (W)
ρ	Reflectivity	Dimensionless (0–1)
A_r	Receiver area	Square meters (m^2)
$\eta_{\text{atm}}, \eta_{\text{sys}}$	Efficiencies	Dimensionless (0–1)
β	Beam divergence	Radians or degrees
τ	Pulse width	Seconds (s)
α	Attenuation coefficient	Per meter (m^{-1})
$\Delta\phi$	Phase shift	Radians
f	Modulation frequency	Hertz (Hz)
Δf	Frequency difference	Hertz (Hz)
S	Frequency sweep rate	Hertz per second (Hz/s)
$\beta(z)$	Backscatter coefficient	Per meter per steradian (m^{-1} sr^{-1})

Table 1: Summary of variables and units.