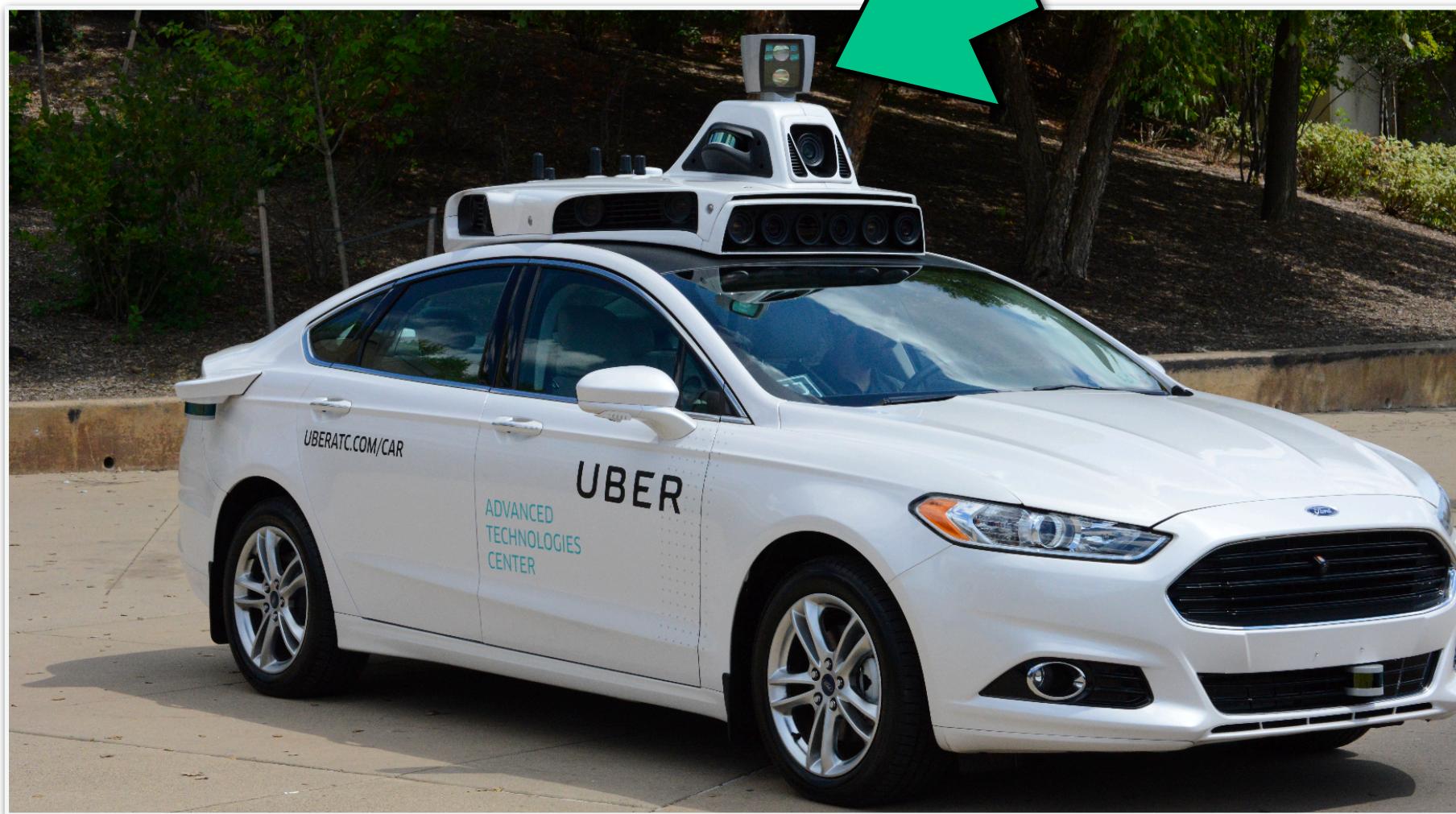


MODULE 4 LESSON 1

LIGHT DETECTION AND RANGING SENSORS

LIDAR: Light Detection and Ranging



Velodyne

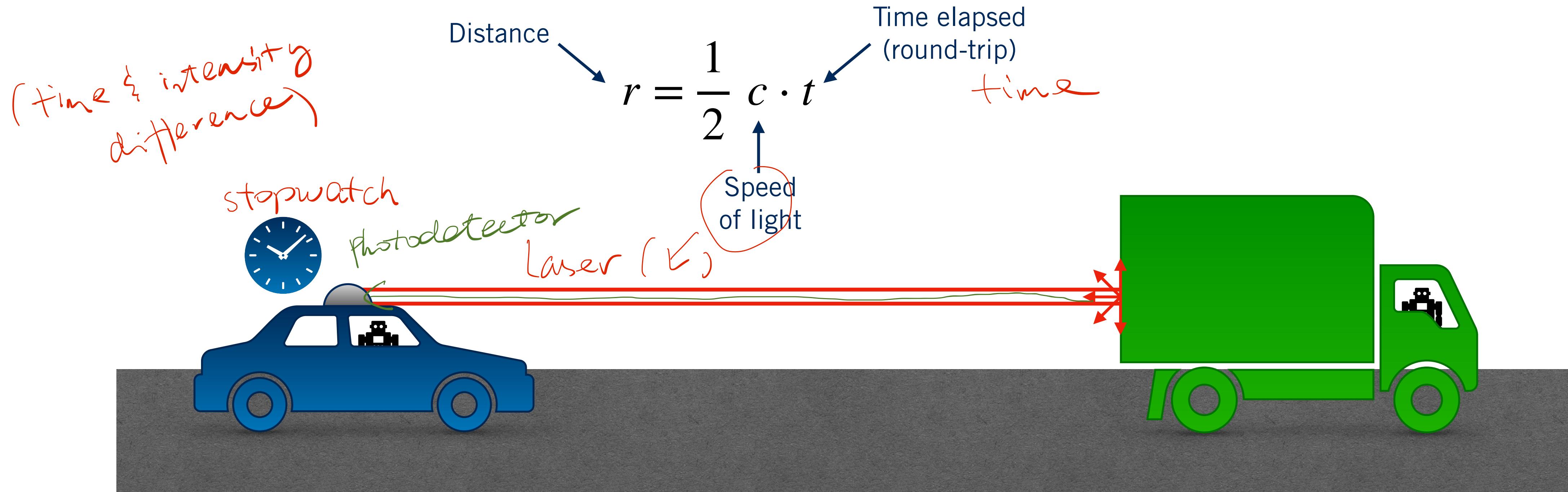


Hokuyo



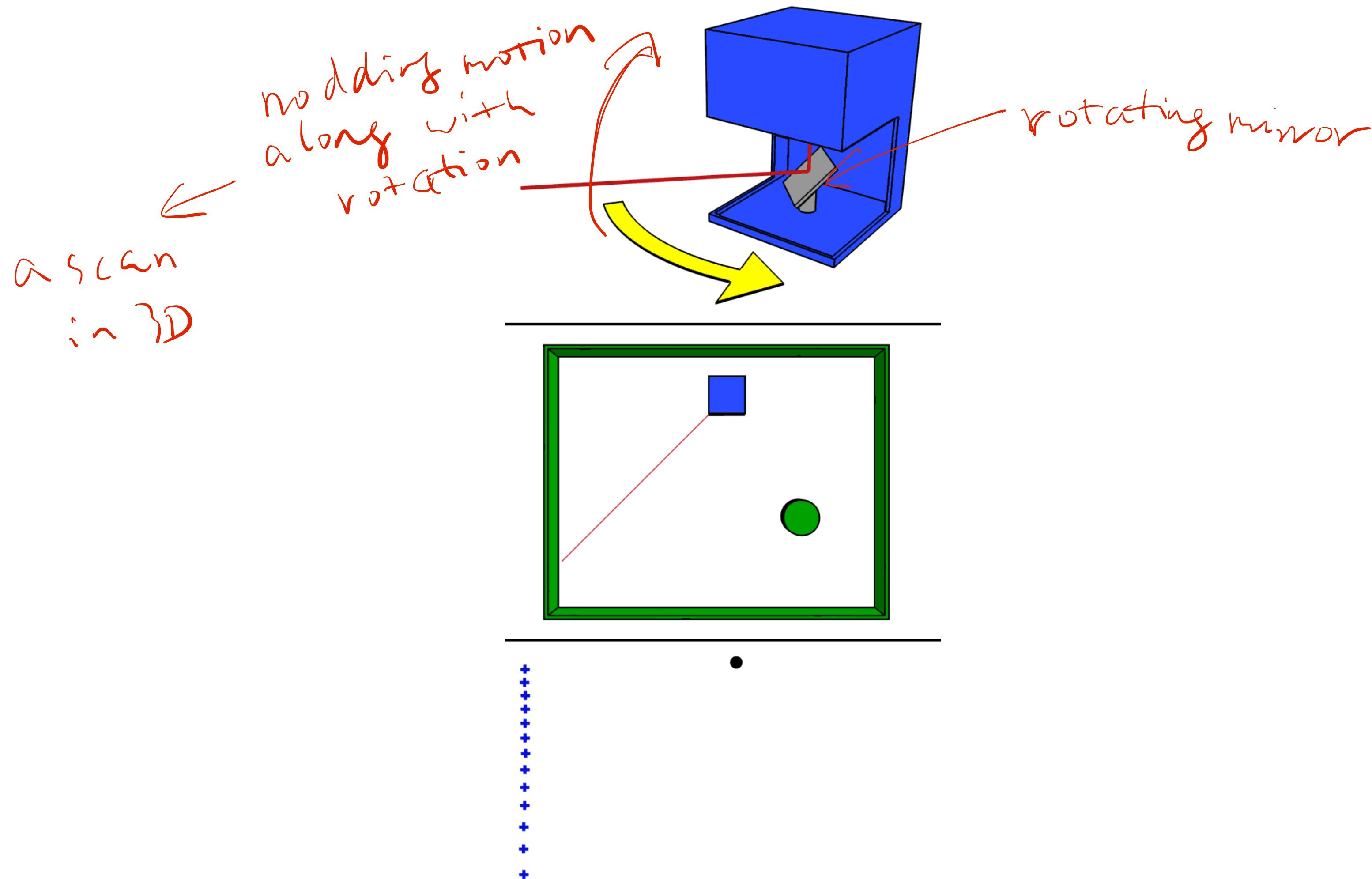
SICK

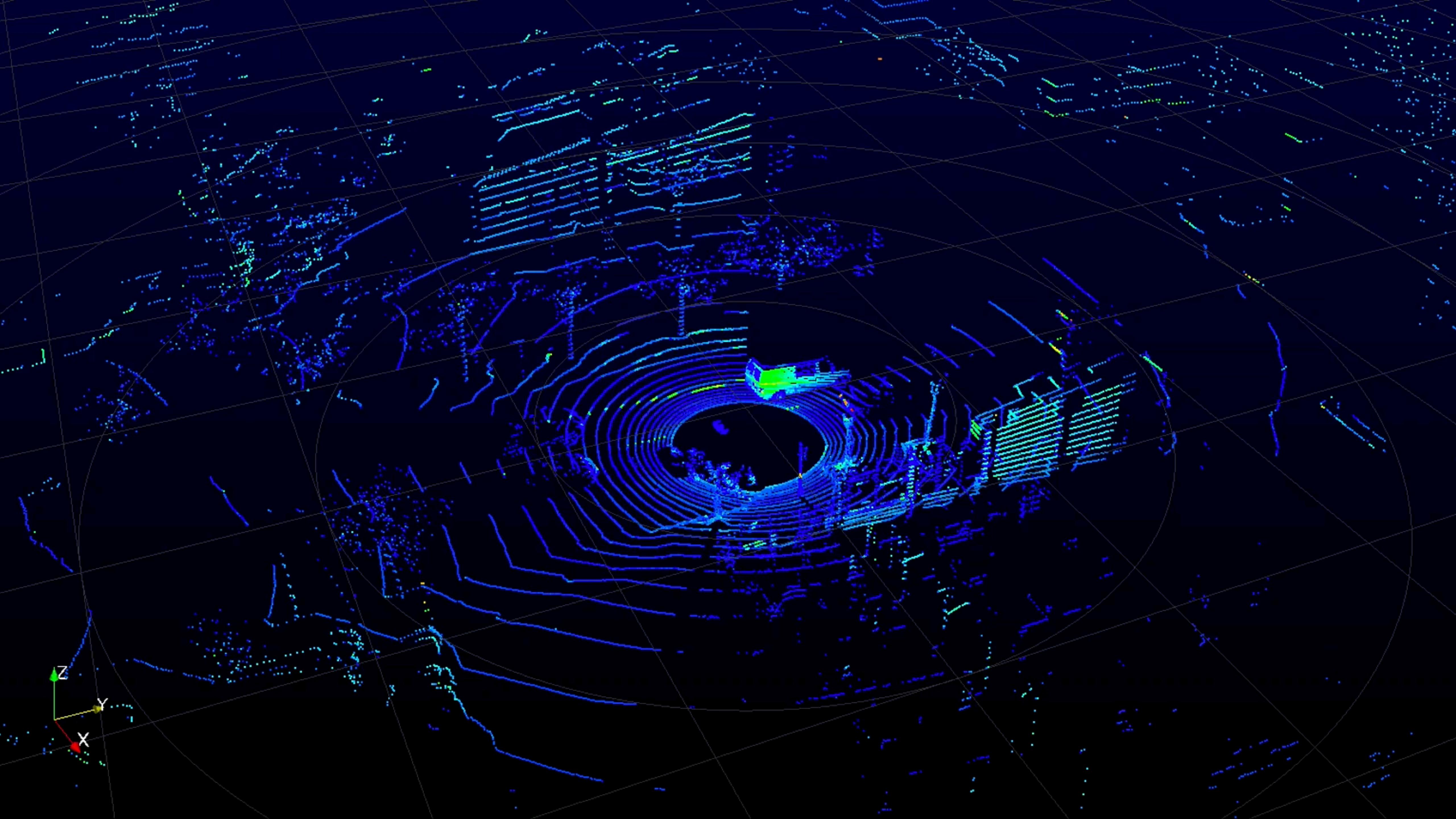
Measuring Distance with Time-of-Flight



dark (✓)
(own light)

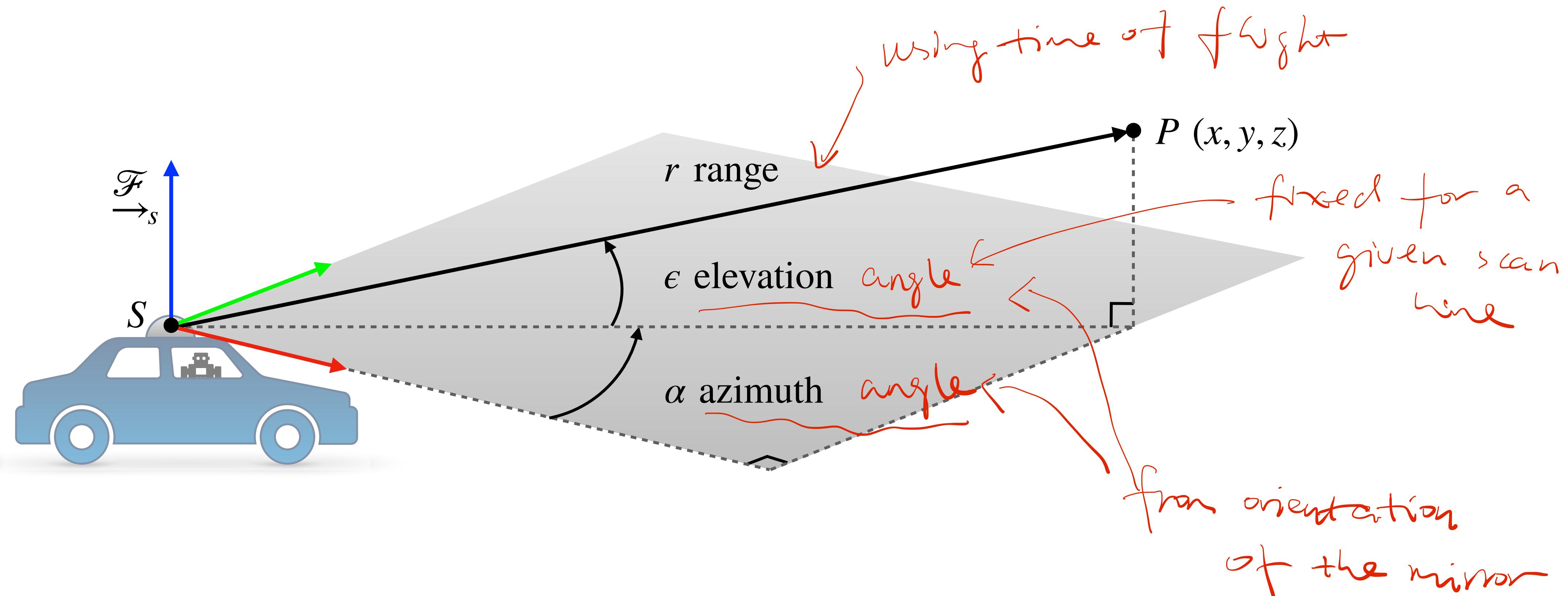
Measuring distance with time-of-flight



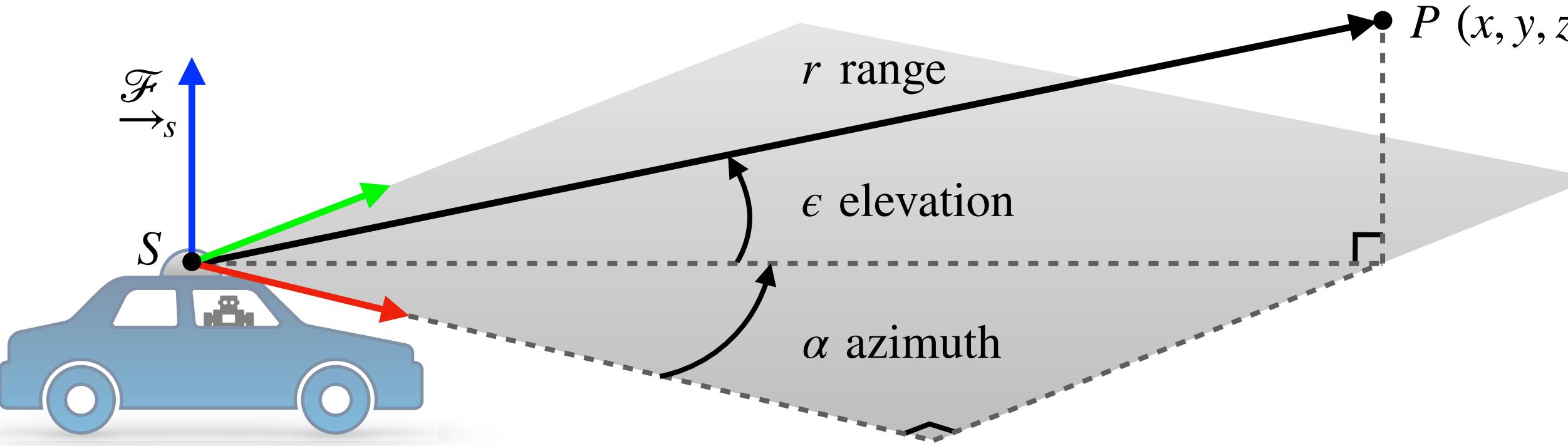


Measurement Models for 3D LIDAR Sensors

3D LIDAR sensors report *range*, *azimuth angle* and *elevation angle* (+ return intensity)



Measurement models for 3D LIDAR sensors



Inverse Sensor Model

Cartesian \leftarrow spherical

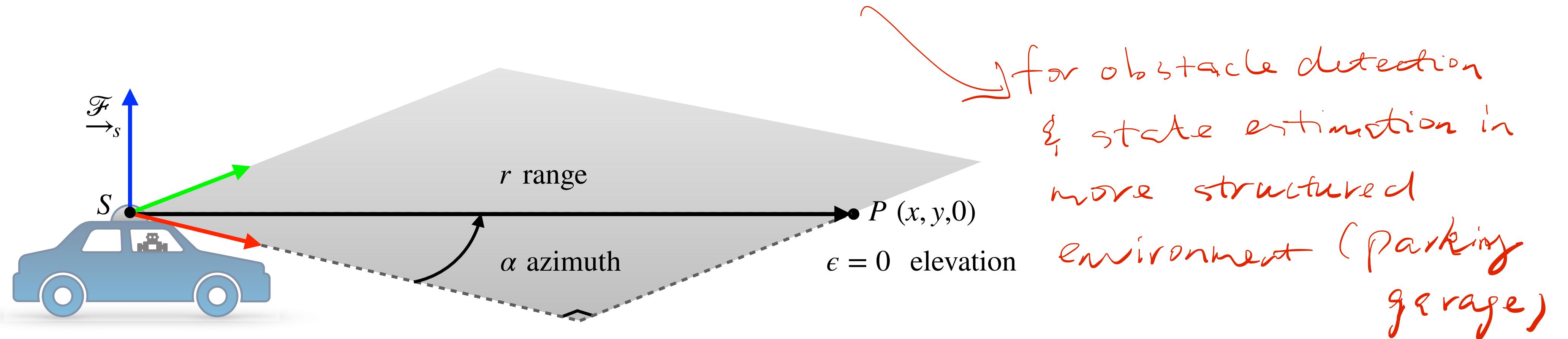
$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \mathbf{h}^{-1}(r, \alpha, \epsilon) = \begin{bmatrix} r \cos \alpha \cos \epsilon \\ r \sin \alpha \cos \epsilon \\ r \sin \epsilon \end{bmatrix}$$

Actual measurement

Forwards Sensor Model

$$\begin{bmatrix} r \\ \alpha \\ \epsilon \end{bmatrix} = \mathbf{h}(x, y, z) = \begin{bmatrix} \sqrt{x^2 + y^2 + z^2} \\ \tan^{-1}\left(\frac{y}{x}\right) \\ \sin^{-1}\left(\frac{z}{\sqrt{x^2 + y^2 + z^2}}\right) \end{bmatrix}$$

Measurement models for 2D LIDAR sensors



Inverse Sensor Model

$E=0$

$$\begin{bmatrix} x \\ y \\ 0 \end{bmatrix} = \mathbf{h}^{-1}(r, \alpha, 0) = \begin{bmatrix} r \cos \alpha \\ r \sin \alpha \\ 0 \end{bmatrix}$$

Forwards Sensor Model

$$\begin{bmatrix} r \\ \alpha \\ 0 \end{bmatrix} = \mathbf{h}(x, y, 0) = \begin{bmatrix} \sqrt{x^2 + y^2} \\ \tan^{-1}\left(\frac{y}{x}\right) \\ 0 \end{bmatrix}$$

Sources of Measurement Noise

- Uncertainty in determining the **exact time of arrival** of the reflected signal
- Uncertainty in measuring the **exact orientation** of the mirror

encoder to measure this:
 limited resolution
- Interaction with the **target** (surface absorption, specular reflection, etc.)

surface
 scattered away from original pulse direction
- Variation of propagation speed (e.g., through materials)

speed of light varies
 (temperature & humidity)

Forwards Sensor Model (with Noise)

$$\begin{bmatrix} r \\ \alpha \\ \epsilon \end{bmatrix} = \mathbf{h}(x, y, z, \mathbf{v}) = \begin{bmatrix} \sqrt{x^2 + y^2 + z^2} \\ \tan^{-1}\left(\frac{y}{x}\right) \\ \sin^{-1}\left(\frac{z}{\sqrt{x^2 + y^2 + z^2}}\right) \end{bmatrix} + \mathbf{v}$$

$\mathbf{v} \sim \mathcal{N}(\mathbf{0}, \mathbf{R})$

additive noise

Lidar reports max range error
 (also empty space along beam direction)

Motion Distortion

- Typical scan rate for a 3D LIDAR is 5-20 Hz
- For a moving vehicle, each point in a scan is taken from a slightly different place → artifacts e.g. duplicate objects
- Need to account for this if the vehicle is moving quickly, otherwise motion distortion becomes a problem

an accurate motion model of vehicle

T from GPS & IMU etc.

Summary | Light Detection and Ranging Sensors

- LIDAR sensors use laser pulses and time-of-flight to measure distances to objects along a specific direction
- 2D and 3D LIDARs work by sweeping the laser pulses in many directions across the whole environment
- In the next video we'll discuss point clouds and how to use them for state estimation