MODULE 4 LESSON 1

LIGHT DETECTION AND RANGING SENSORS

Module 4 | LIDAR Sensing

In this module…

- Operating principles of LIDAR sensors
- Basic LIDAR sensor models
- Working with LIDAR point clouds
- Localization via point cloud registration

Light Detection and Ranging Sensors

By the end of this lesson, you will be able to…

- Describe the operating principles of LIDAR sensors
- Use basic LIDAR sensor models in 2D and 3D
- Describe the major sources of measurement error for LIDAR sensors

LIDAR: Light Detection and Ranging

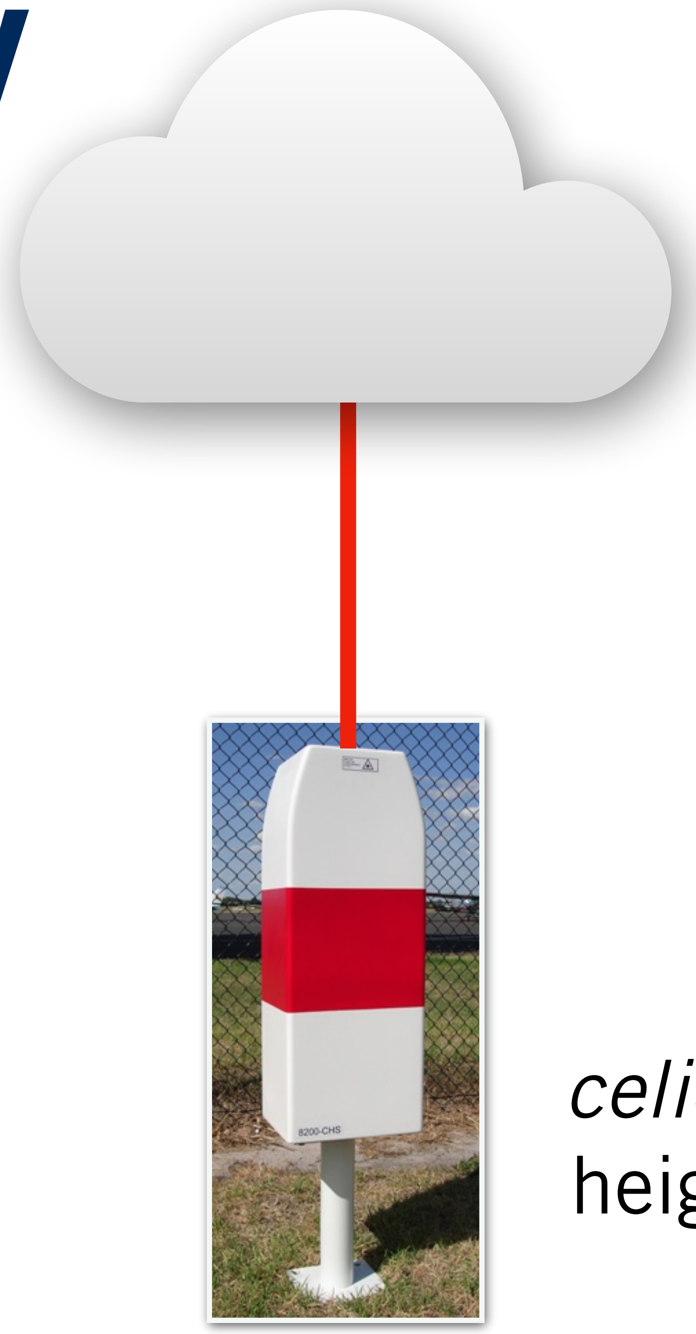
Velodyne

Hokuyo

SICK

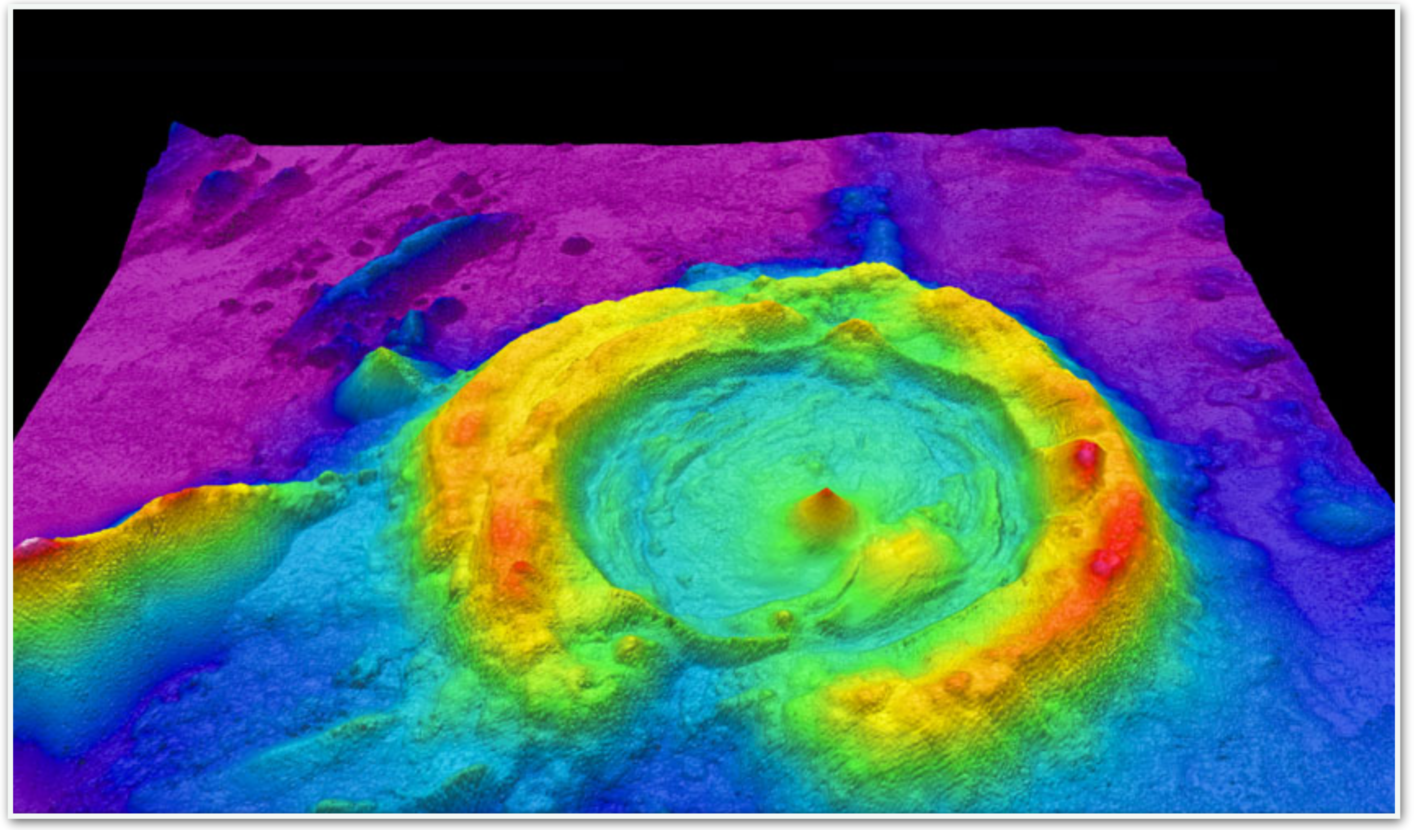
Measuring Earth, Sea and Sky

- LIDAR originated in the 1960s shortly after the invention of the laser
- First used by meteorologists to measure clouds



A ground-based *celiometer* measures the height of a cloud ceiling

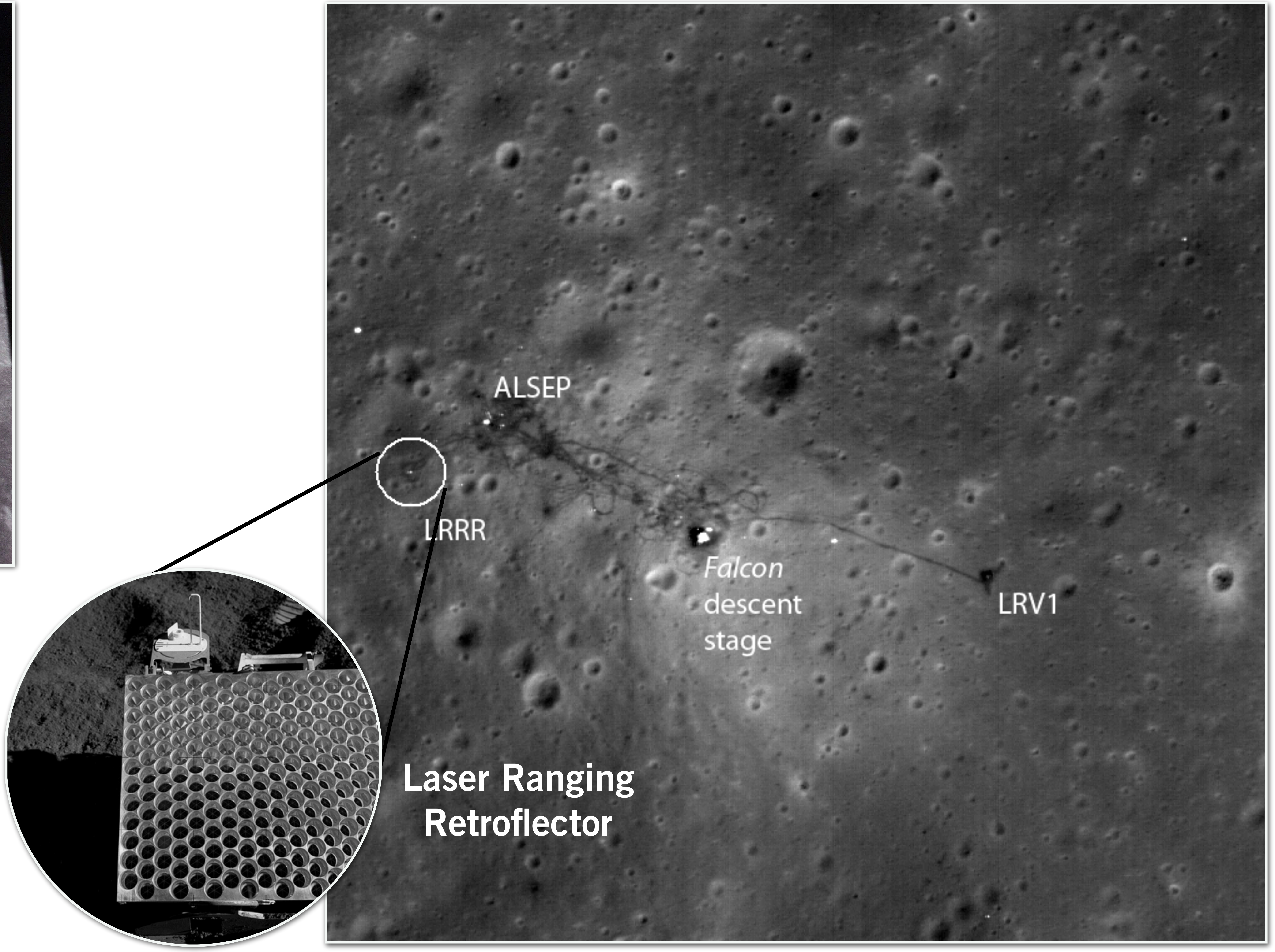
- Now commonly used for surveying and mapping



An airborne LIDAR measures the geometry of the seafloor

Apollo 15

Apollo 15 Command Module



Apollo 15 Landing Site

Measuring Distance with Time-of-Flight

Distance

$$r = \frac{1}{2}\, c \cdot t$$

Time elapsed (round-trip)

time

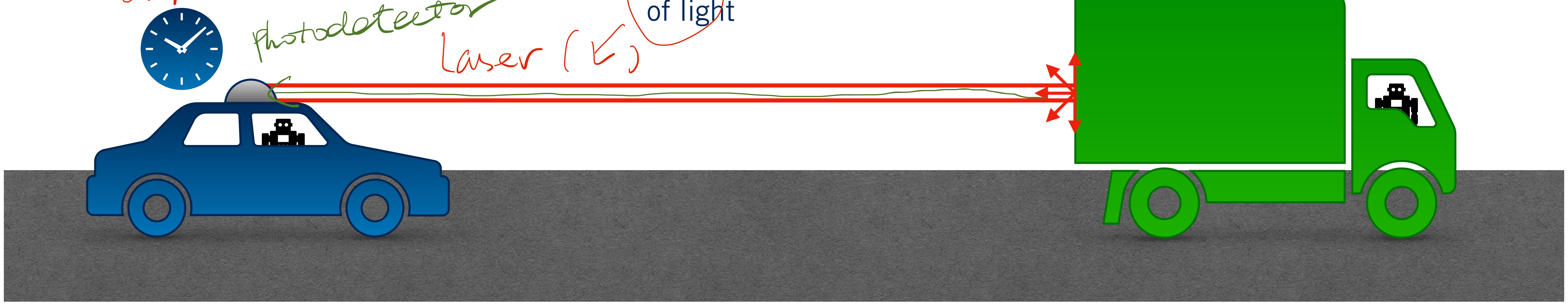
Speed of light

(time & intensity difference)

stopwatch

photodetector

Laser (✗)



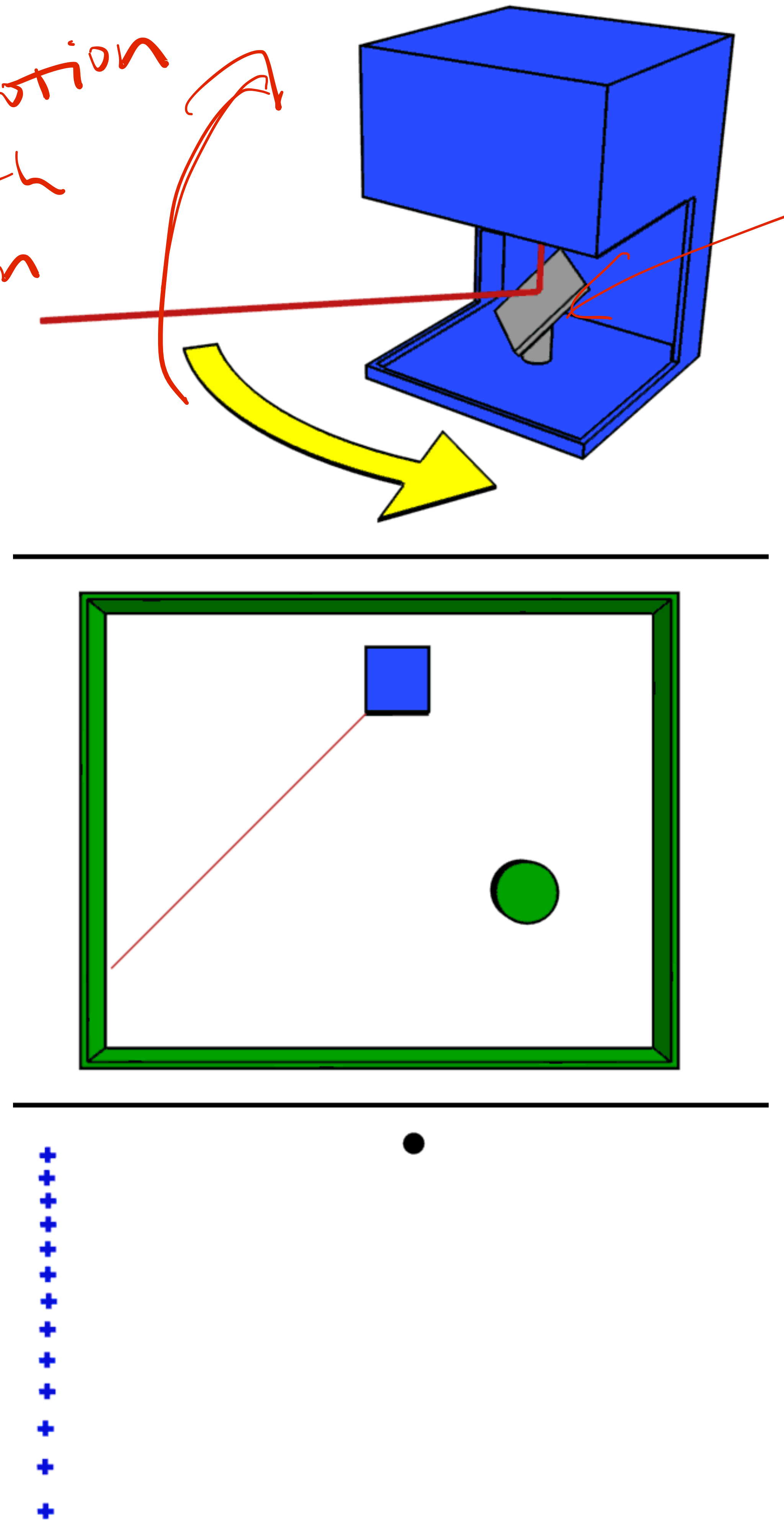
dark (✓)
(own light)

Measuring distance with time-of-flight

nodding motion along with rotation

a scan in 3D

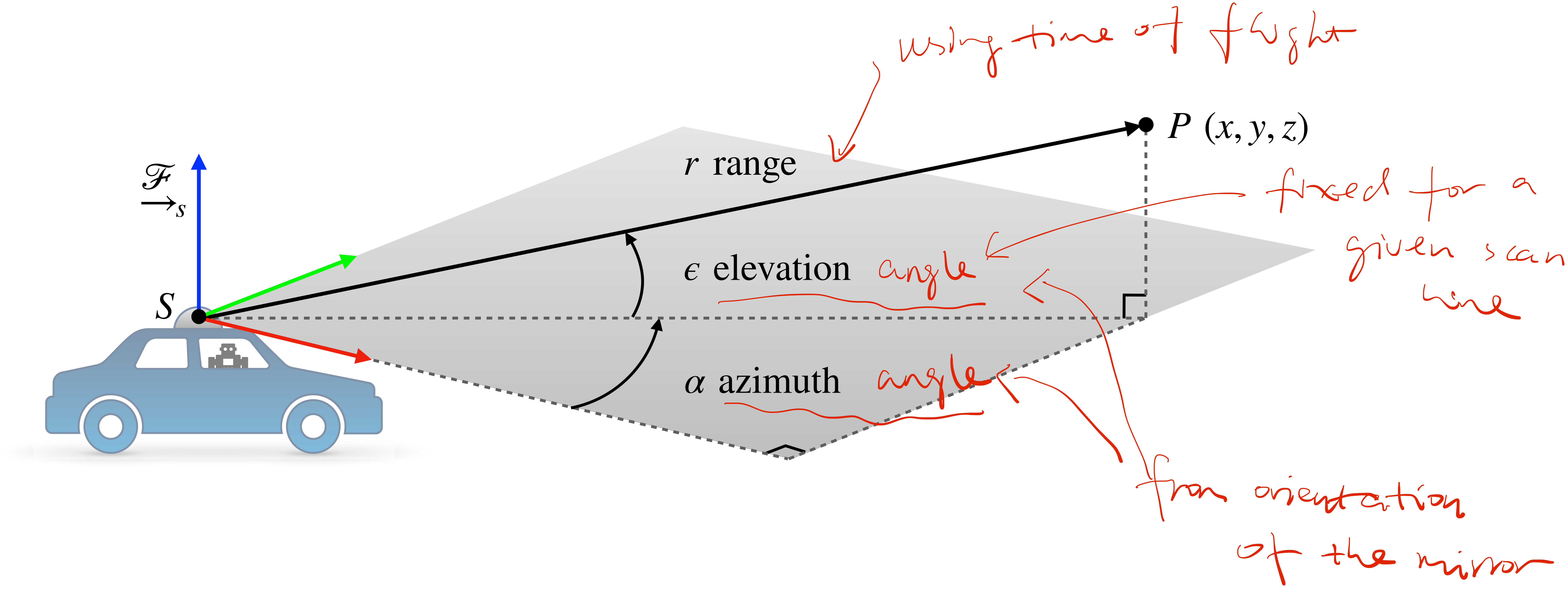
rotating mirror



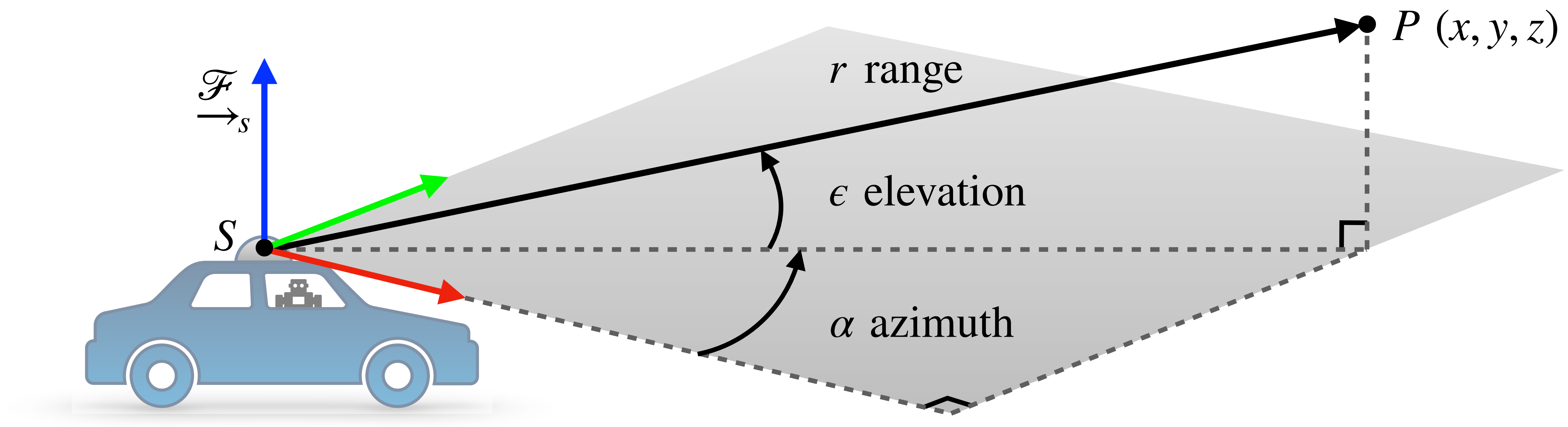

Z
Y
X

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 ← spherical

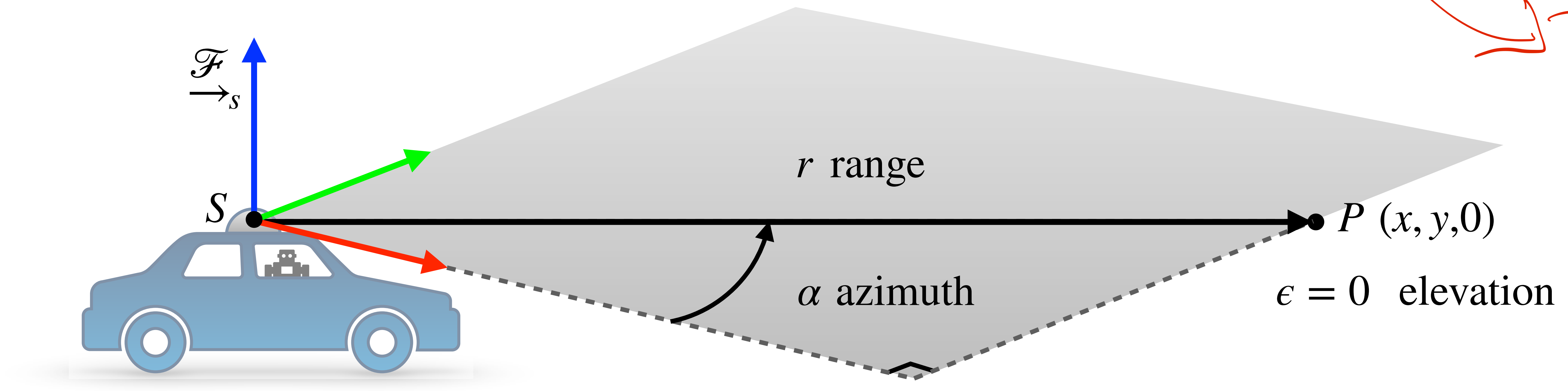
$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \mathbf{h}^{-1}\underbrace{(r, \alpha, \epsilon)}_{\text{actual measurements}} = \begin{bmatrix} r\cos\alpha\cos\epsilon \\ r\sin\alpha\cos\epsilon \\ r\sin\epsilon \end{bmatrix}$$

Forwards Sensor Model

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

Measurement models for 2D LIDAR sensors

for obstacle detection & state estimation in more structured environment (parking garage)



Inverse Sensor Model

$\epsilon = 0$

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

Forwards Sensor Model

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

Sources of Measurement Noise

stop watch: limited resolution

- Uncertainty in determining the exact time of arrival of the reflected signal

encoder to measure this: limited resolution

- Uncertainty in measuring the exact orientation of the mirror
- 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)

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

Forwards Sensor Model (with Noise)

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

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

additive noise

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

↑ from GPS & INS ex.

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