CS 3630, Fall 2025

Lecture 22:

Sensing with LIDAR

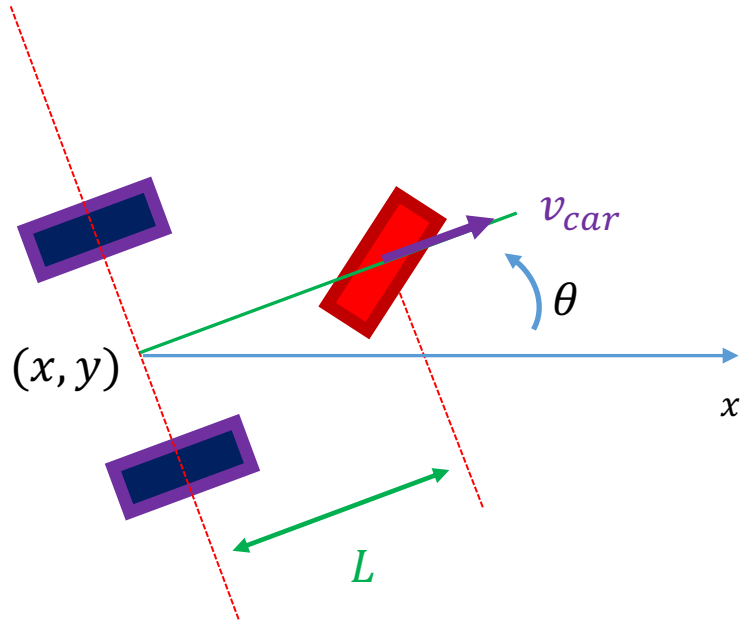
Lecture 21 Recap

Differential Kinematics: simplified form

- It is convenient to write the differential kinematics considering the car angular velocity as an input.
- Instead of controlling θ indirectly via

$$\dot{\theta} = u_1 \frac{1}{L} \tan\phi\,, \qquad \dot{\phi} = u_2$$

we assume that we can directly control ϕ (instead of $\dot{\phi}$) and define $u_2 = \dot{\theta}$ (it's easy to solve for the ϕ that achieves this).



- We now write the differential kinematics as:

$$\dot{q} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta \\ \sin\theta \\ 0 \end{bmatrix} u_1 + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u_2$$

In which

- $q = (x, y, \theta)$
- $u_1 = v_{car}$
- $u_2 = \dot{\theta}$, the angular velocity of car frame

This is reasonable if we can turn the sterring wheel quickly, relative to the forward speed of the car.

The next few lectures…

- LIDAR = light detection and ranging
- Key sensor in Autonomous Driving
  - Used for localization
  - First, need a map to localize in!
- SLAM =
  Simultaneous Localization and Mapping
- Use Iterated Closest Points to relate scans
- Use optimization over SE(n) to do SLAM

Image by Voyage

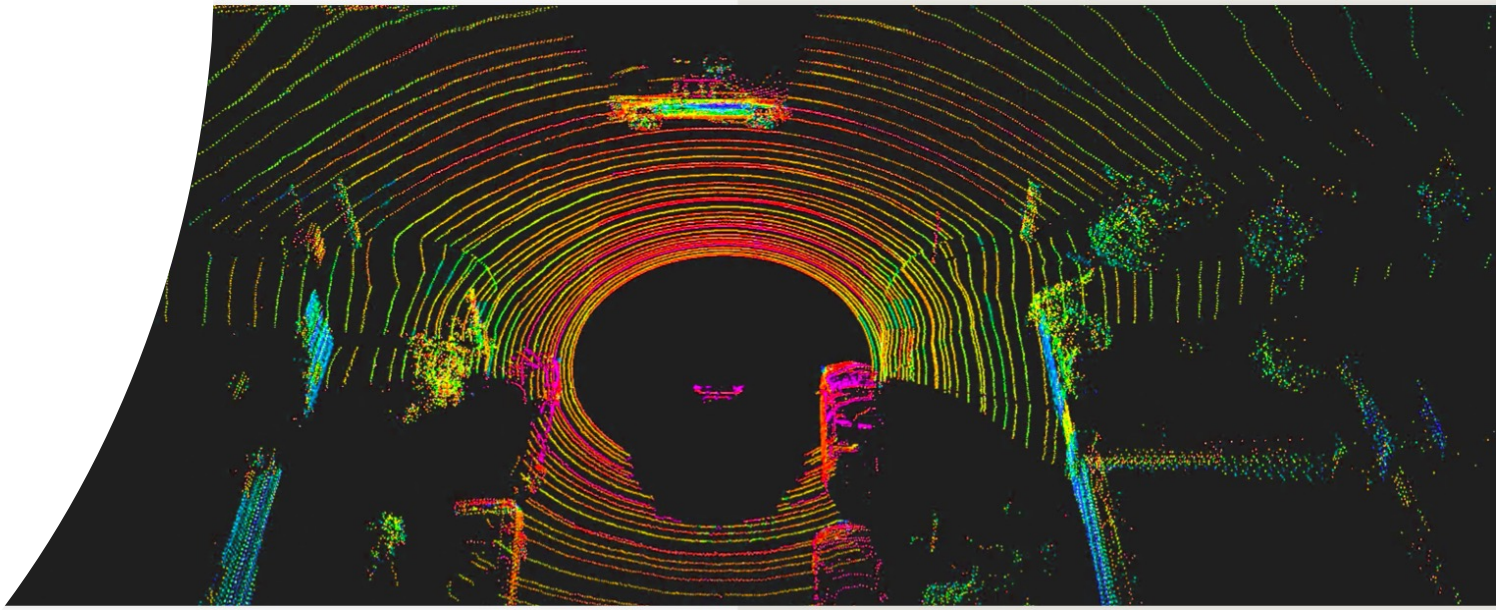
Sensing: LIDAR

If we want to do real-time planning in dynamic environments, we need to be able to sense and understand the environment.

- Cameras provide enormous amounts of data, but computer vision remains a difficult problem.
- Tesla notwithstanding, the computational cost and the error rates for computer vision systems have prevented them from being adopted as the sensor of choice for self-driving cars.
- LIDAR is a fast and effective sensor that can be used to build 3D point clouds in real time.
- LIDAR is the sensor of choice for most robotics systems (including self-driving cars) that navigate in the real world.

LIDAR

- Superpowers:
  - 360 Visibility
  - Accurate depth!
- Almost all AV prototypes have them (not all 360)



[Images and exposition take from excellent Voyage Blog post]

https://news.voyage.auto/an-introduction-to-lidar-the-key-self-driving-car-sensor-a7e405590cff

Some Robots that Rely on LIDAR

Images from the internets

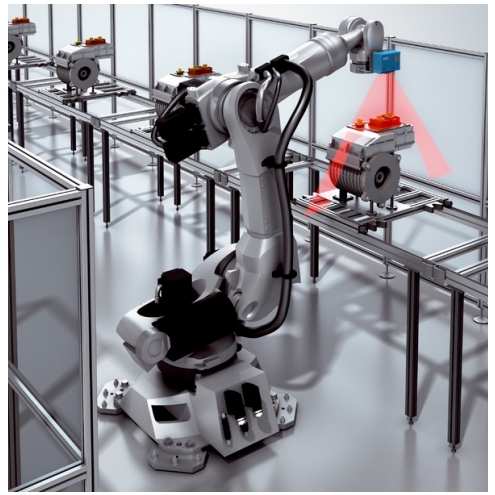
Digit from Agility Robotics

Quadruped at GT (Ye Zhao's lab)

Jackal from Clearpath Robotics

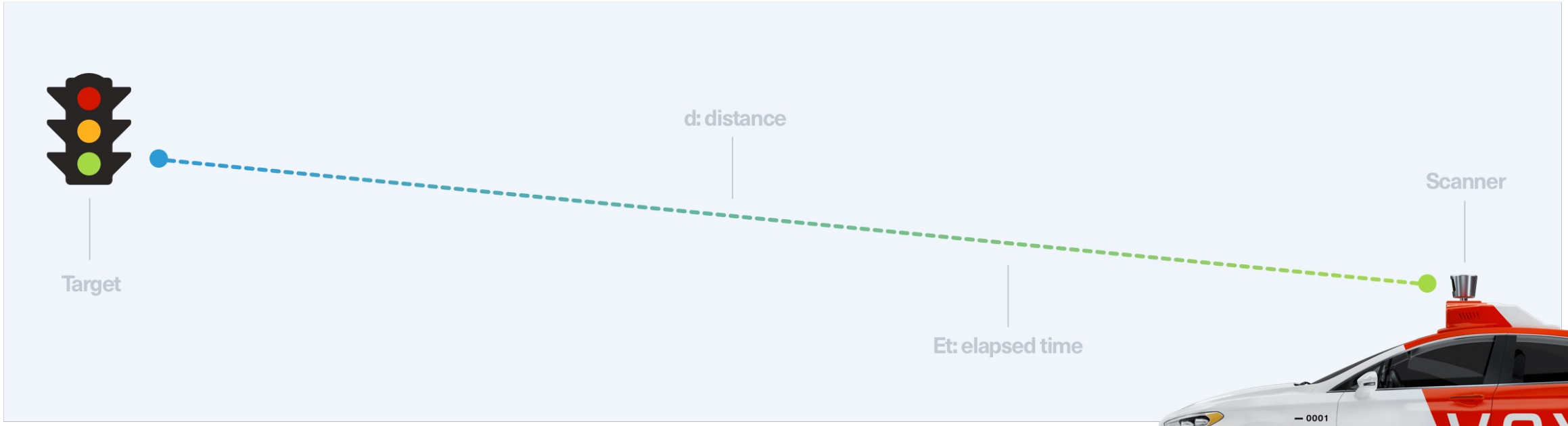
Spot from Boston Dynamics

Yellowscan sensor



SIC sensor

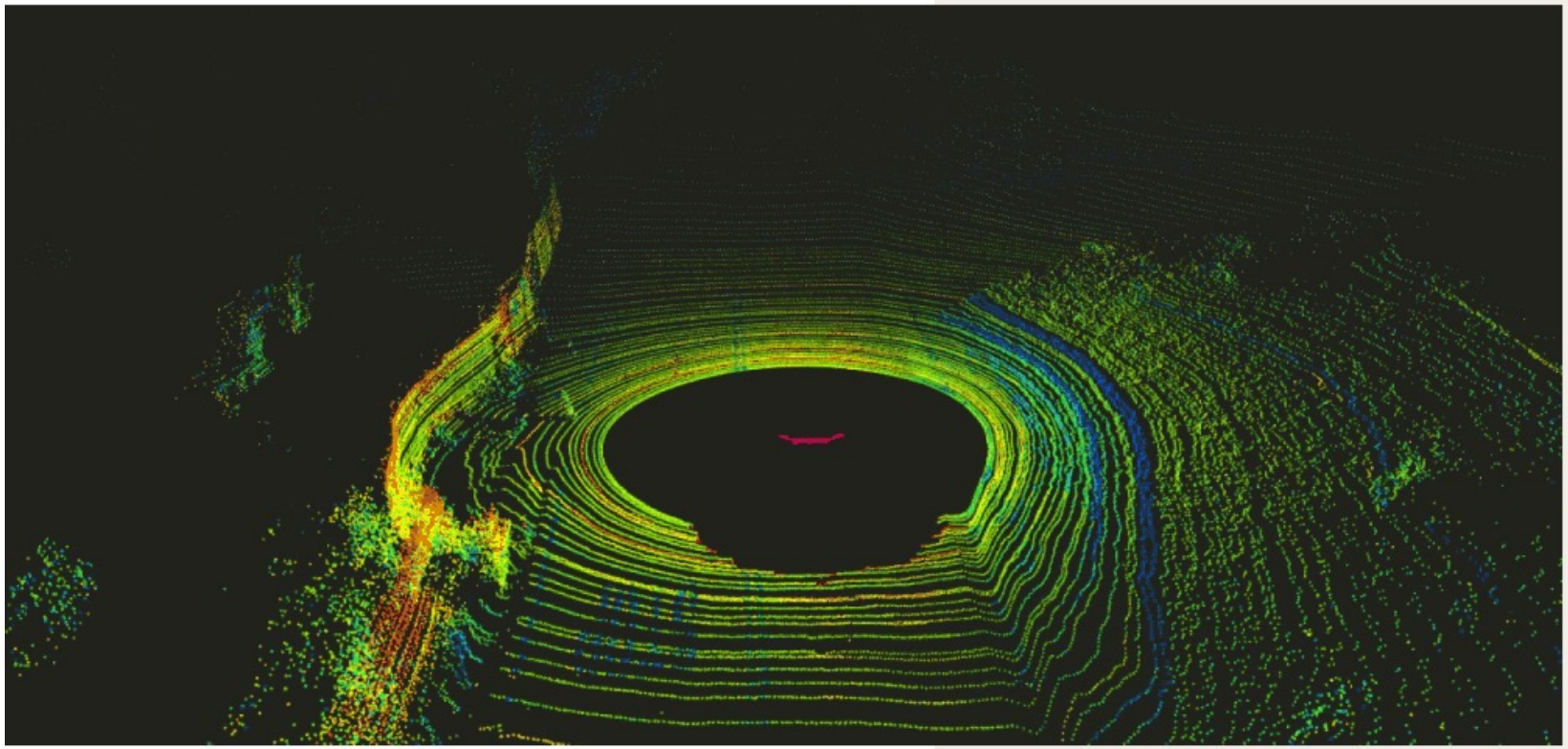
LIDAR Basic Principle



- Send a light pulse
- Measure elapsed time
- Infer distance

[Images and exposition take from excellent Voyage Blog post]

Example : RRT_CS3630



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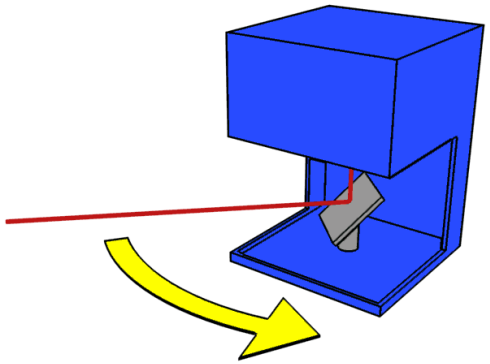
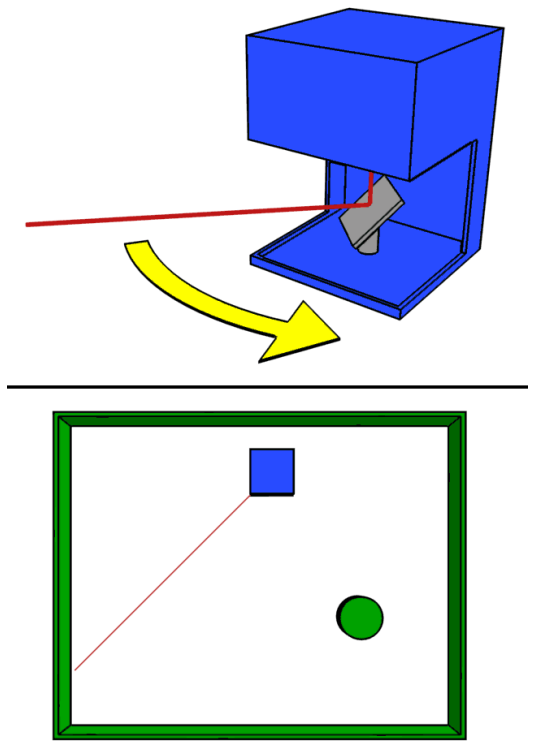
Basic Idea



Sweep a laser beam in a circle.
The beam always lies in a single plane

GIF from Wikipedia

Basic Idea

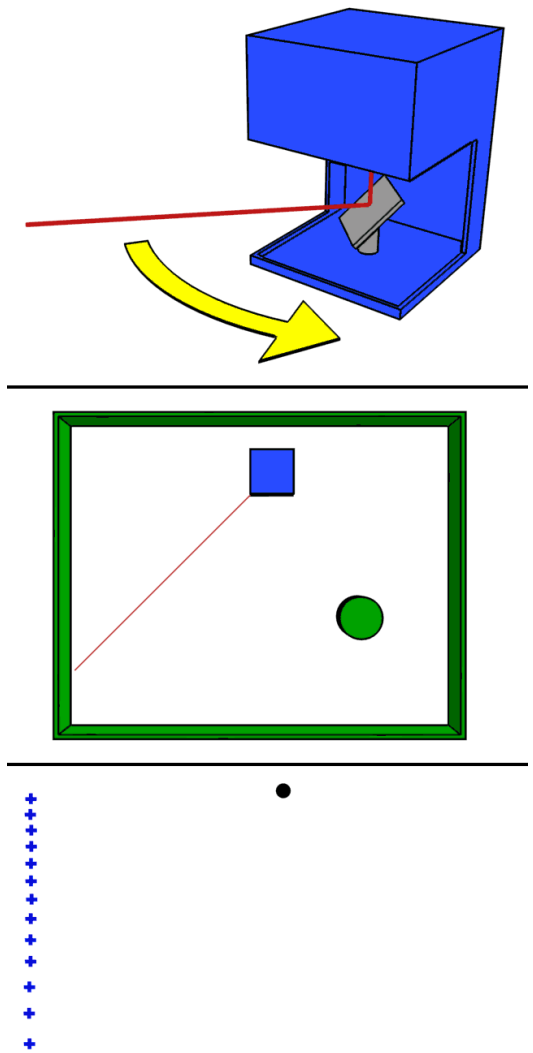


Sweep a laser beam in a circle.
The beam always lies in a single plane

Time of flight of the beam can be measured.
Time of flight is proportional to distance.

GIF from Wikipedia

Basic Idea



Sweep a laser beam in a circle.
The beam always lies in a single plane

Time of flight of the beam can be measured.
Time of flight is proportional to distance.

Compute distance at a discrete set of beam angles.
Once the beam “hits” an object, anything behind the object is occluded.

GIF from Wikipedia

Time of Flight

Emitted laser pulse

Reflected laser pulse

d

This assumes that the motion of the pedestrian is slow relative to the speed of light…

Standard equation: speed × time = distance

$$ct = 2d \rightarrow \boldsymbol{d = 0.5ct}$$

In our case:

- c is the speed of light.
- t is the time from emission to measured return.
- Distance is $2d$, since the light travels to the target, and then returns.

Example:

For an object 15 meters from the detector:

$$0.015 = 300000 \times \frac{t}{2}$$

$$t = \frac{0.030}{300000} = 1 \times 10^{-7} = 0.1\ \mu s$$

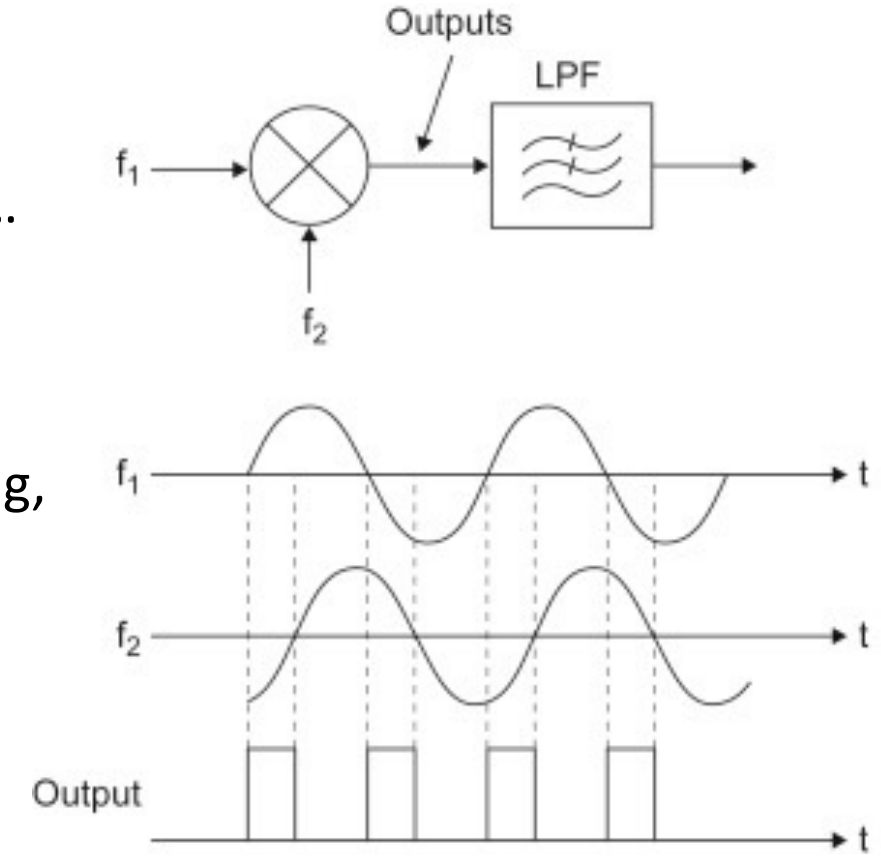
➢ ***We typically don't apply this method literally, because measuring elapsed time between pulses is difficult.***

Coherent Detection

- Instead of measuring time of flight directly for a single pulse…
- ➢ *Emit a periodic signal (e.g., a sine wave), and measure the phase shift between the emitted and received signals.*

- There are plenty of clever circuits that can do this sort of thing, e.g., using a phase locked loop to “lock onto” the received signal.

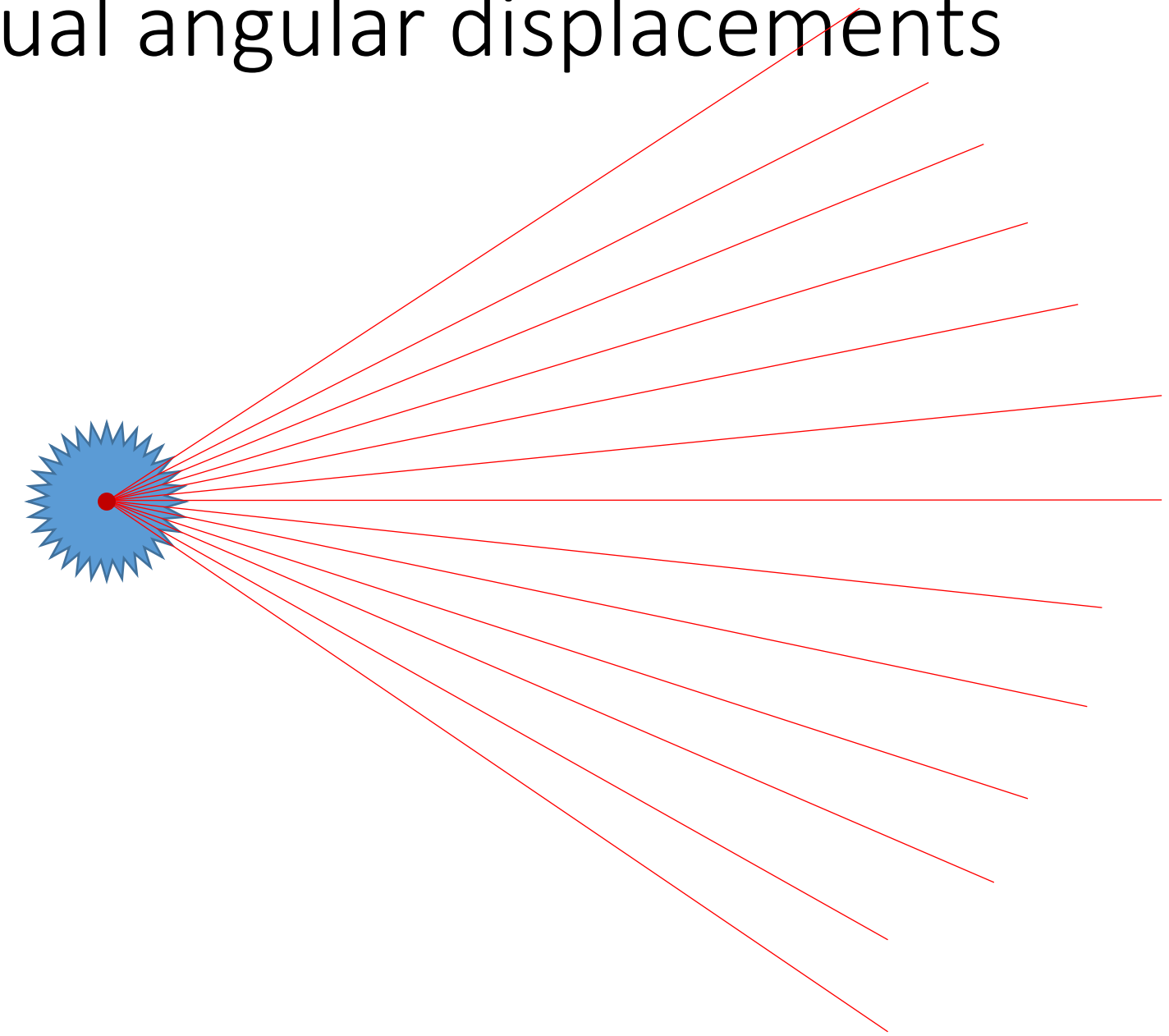
Here, f_1 is the source signal, f_2 is the received signal, and the width of the pulse is the phase shift, which is equal to the elapsed time of flight.



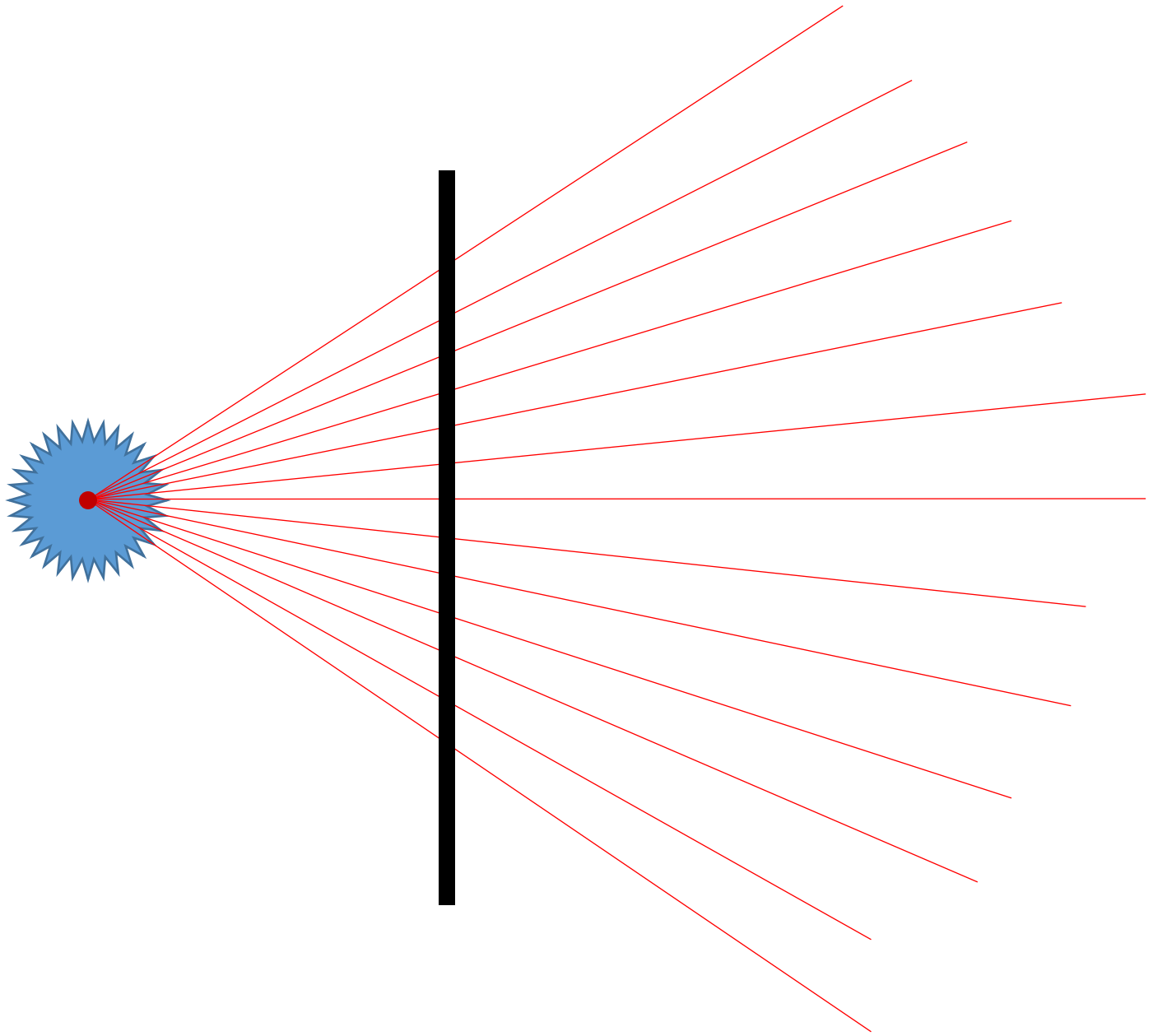
Zero crossings trigger the output.

Figure from: Yongheng Yang, Keliang Zhou, Chapter 4 - Modeling and Control of Single-Phase AC/DC Converters, Editor(s): Frede Blaabjerg, Control of Power Electronic Converters and Systems, Academic Press, 2018, Pages 93-115.

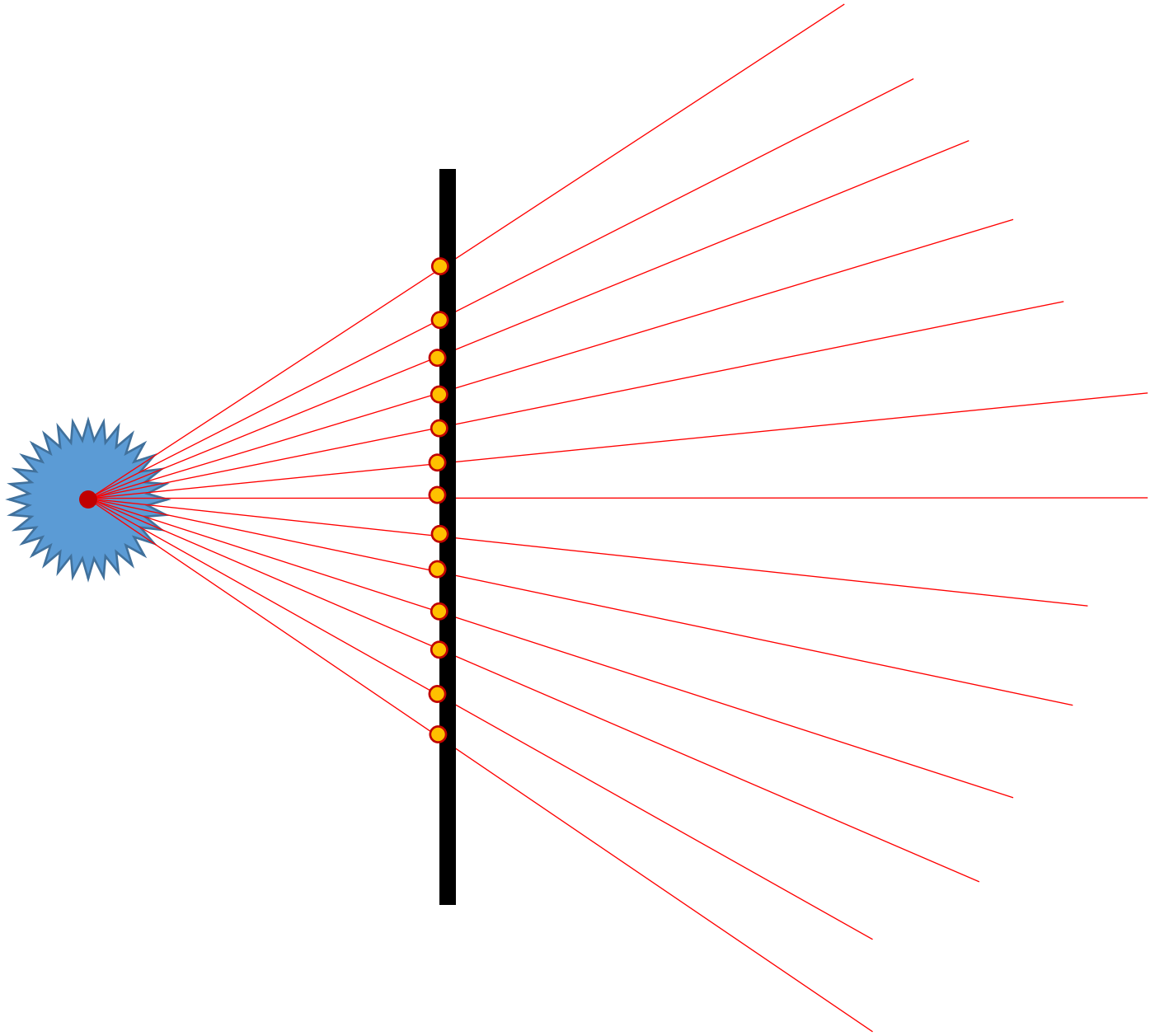
Equal angular displacements



The fact that the measurements are taken at equally spaced orientations does not imply that the measured data (i.e., the point cloud) will be uniformly distributed in space.



Consider a single long wall. The orientation of the wall relative to the sensor determines the distribution of data in the point cloud.



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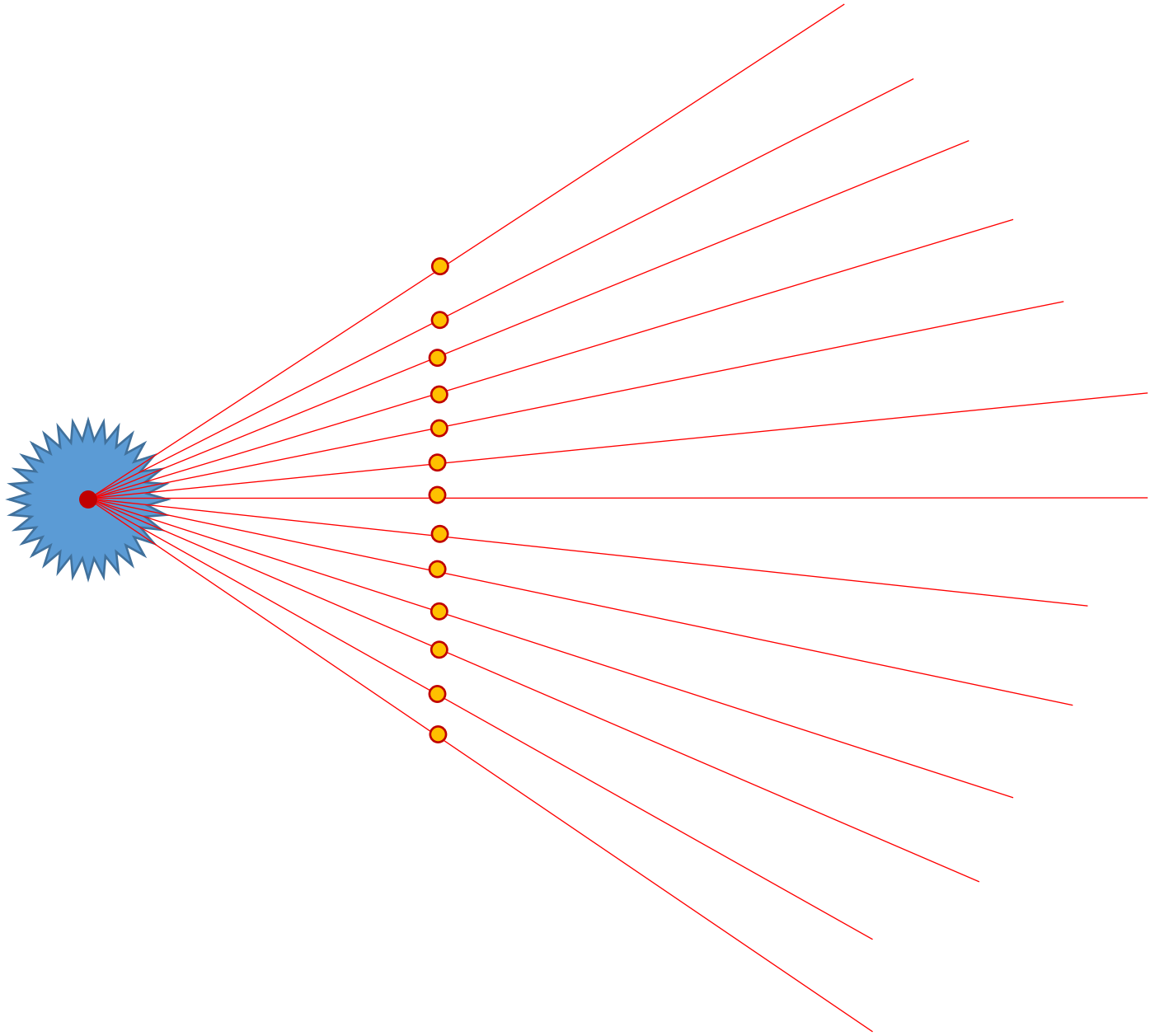
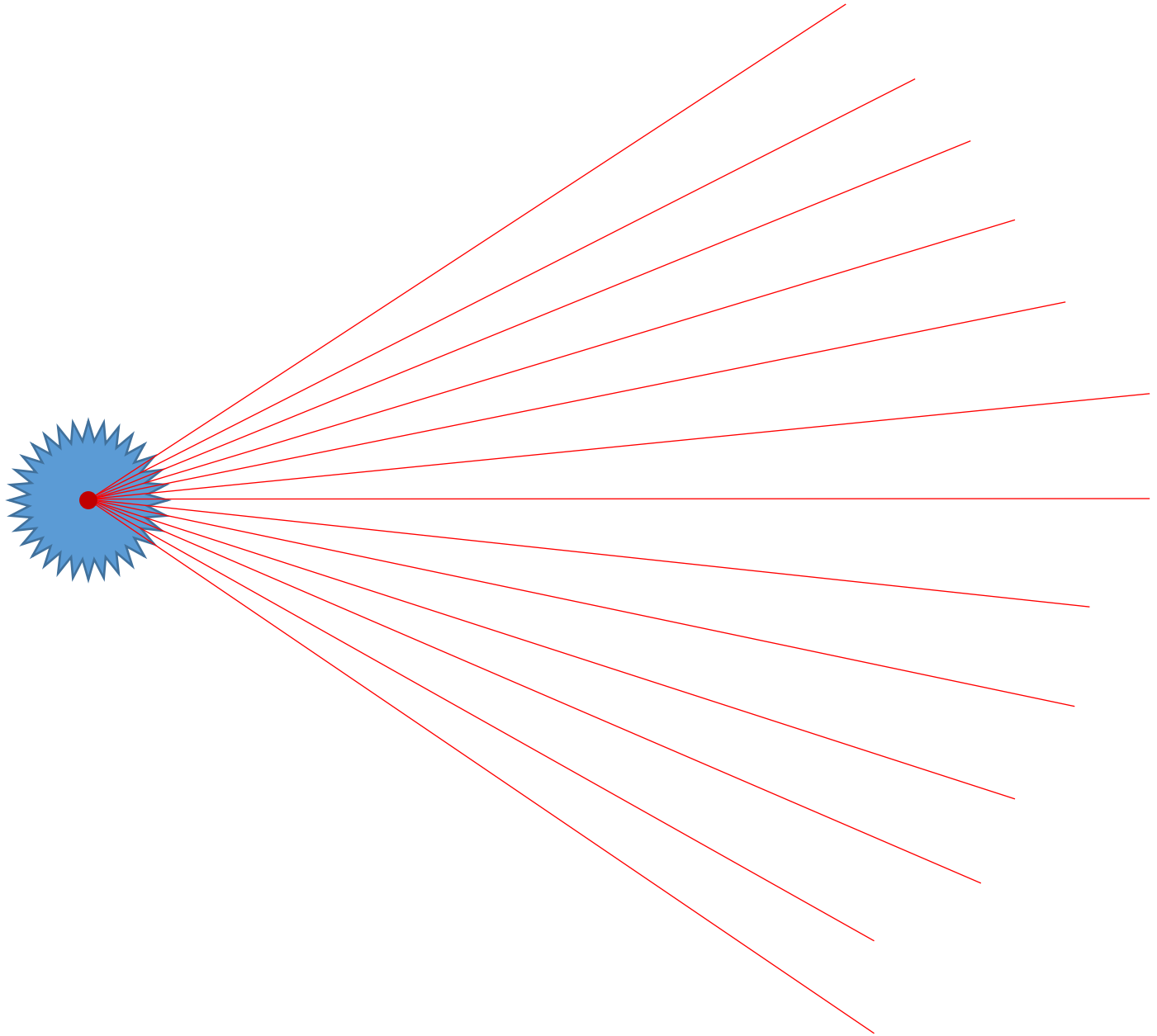
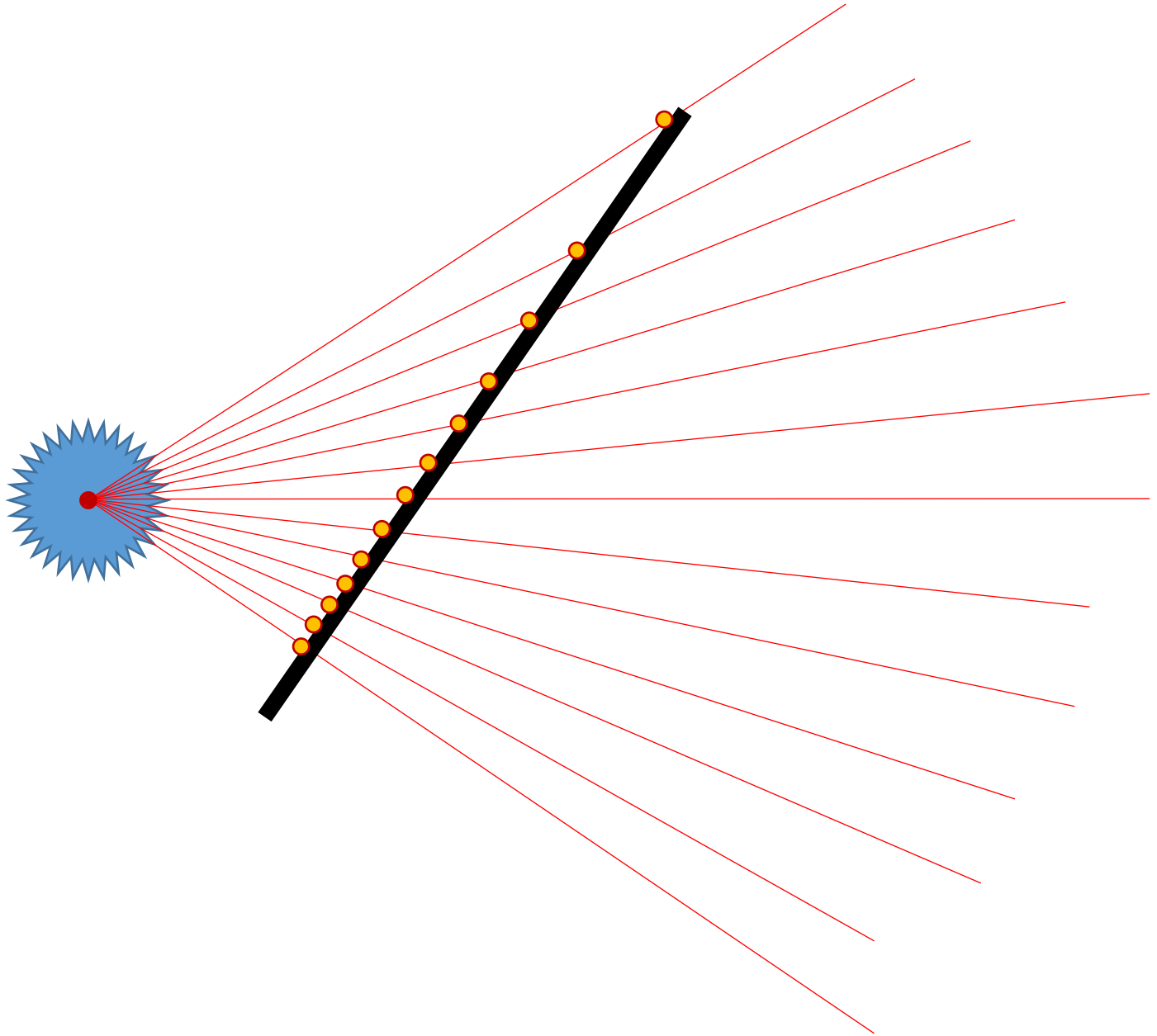


Consider a single long wall. The orientation of the wall relative to the sensor determines the distribution of data in the point cloud.

In this example, the data are spaced uniformly in space (approximately).



Suppose, however, that the wall is at an oblique angle.



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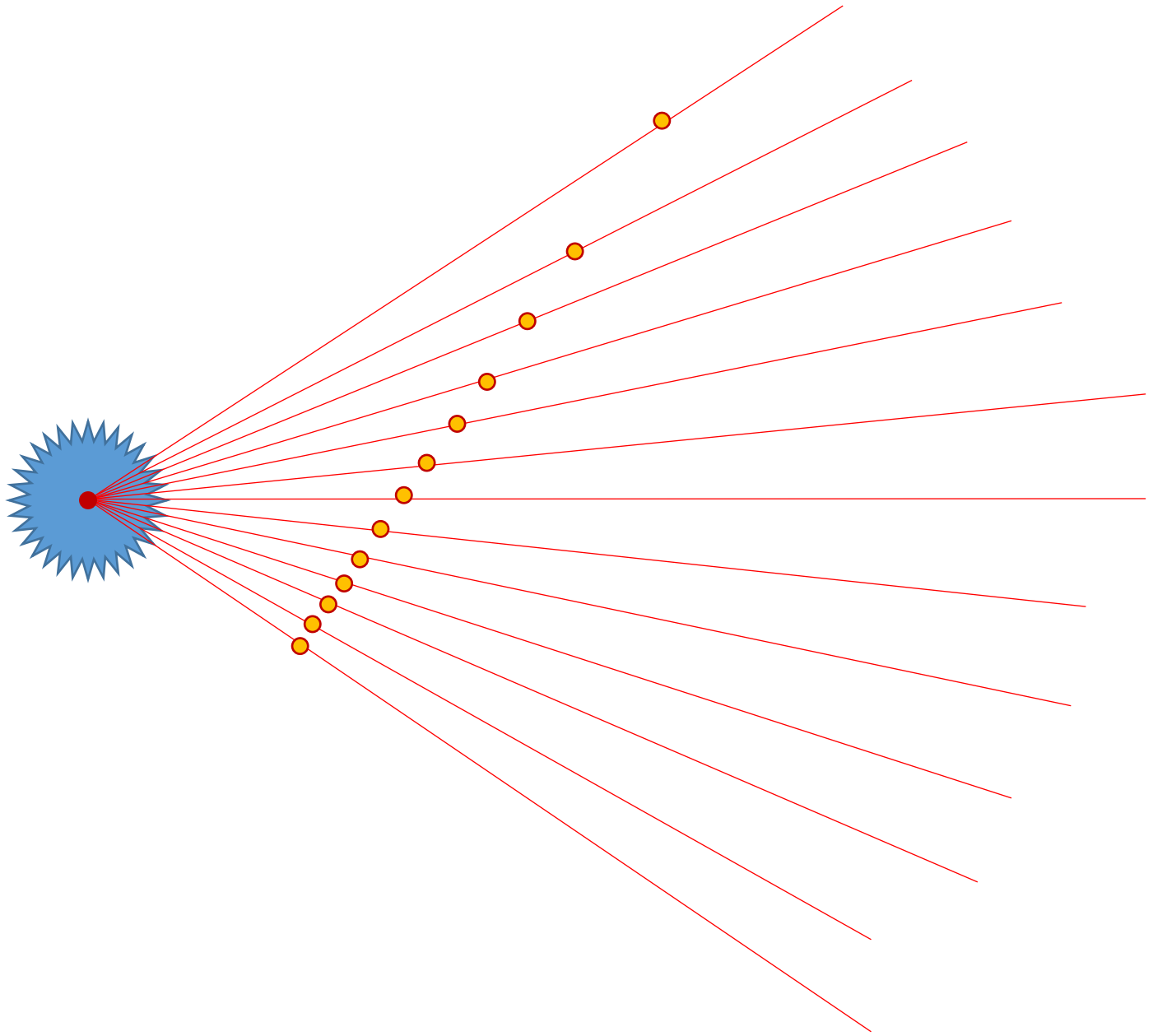
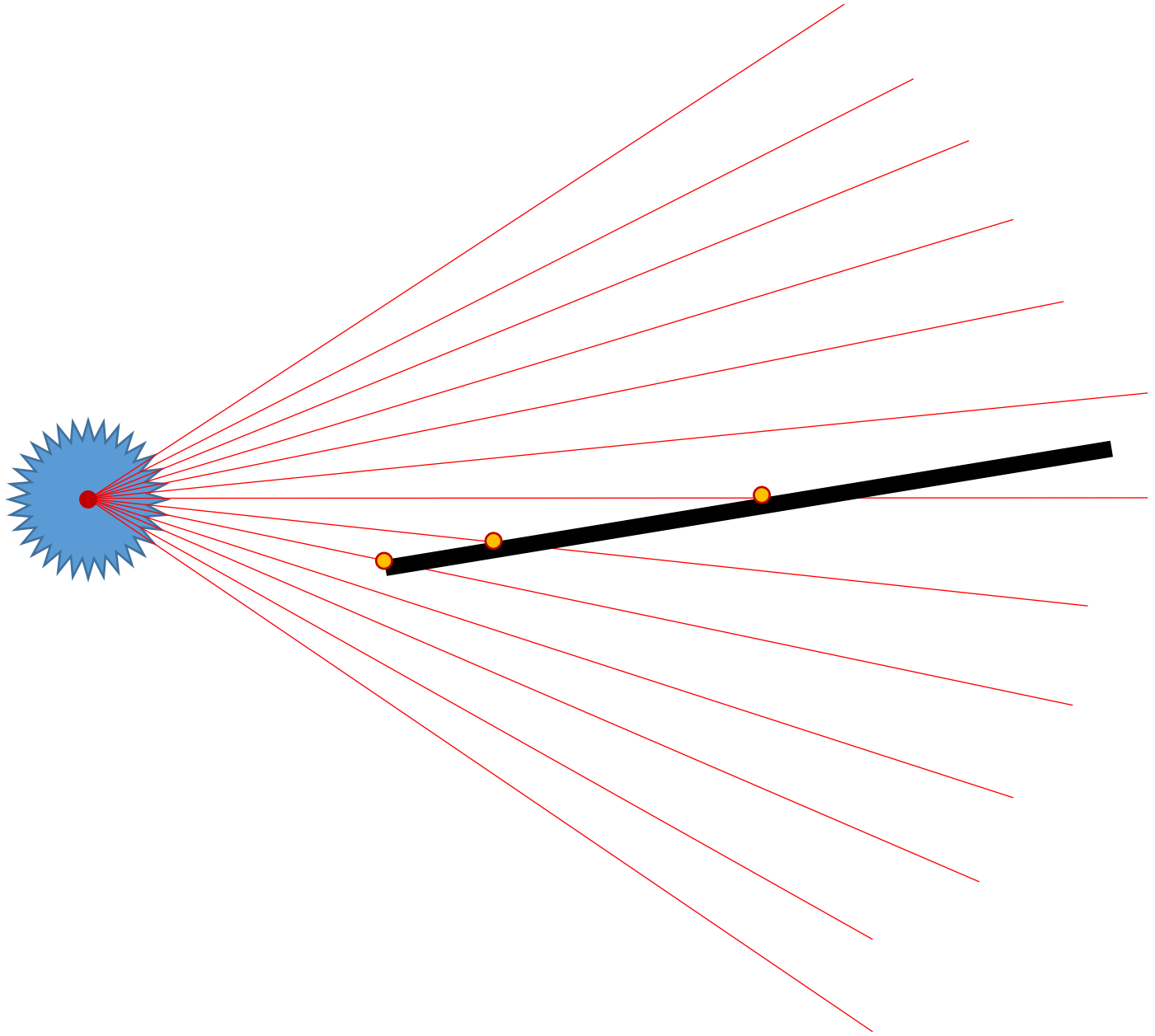


Suppose, however, that the wall is at an oblique angle.

In this case, that data are not at all uniformly spaced.

Sampling uniformity can result in parts of the scene with poor resolution.



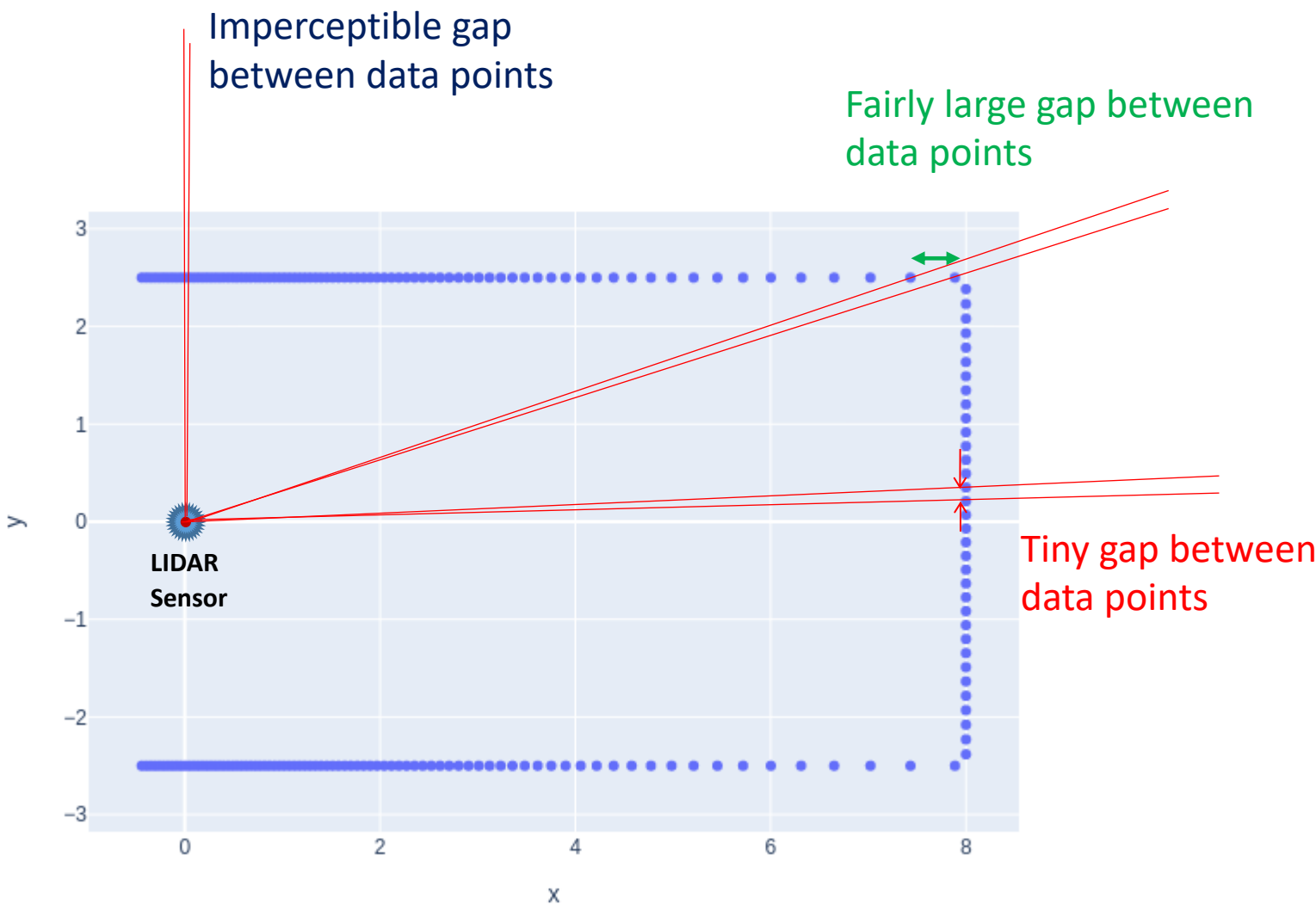
In this case, a fairly large obstacle in the world is represented by only three data points!

You can see these effects in real LIDAR data images.

An Example from the Book

A robot enters a large, rectangular room, and uses its LIDAR sensor to build a model of the room.

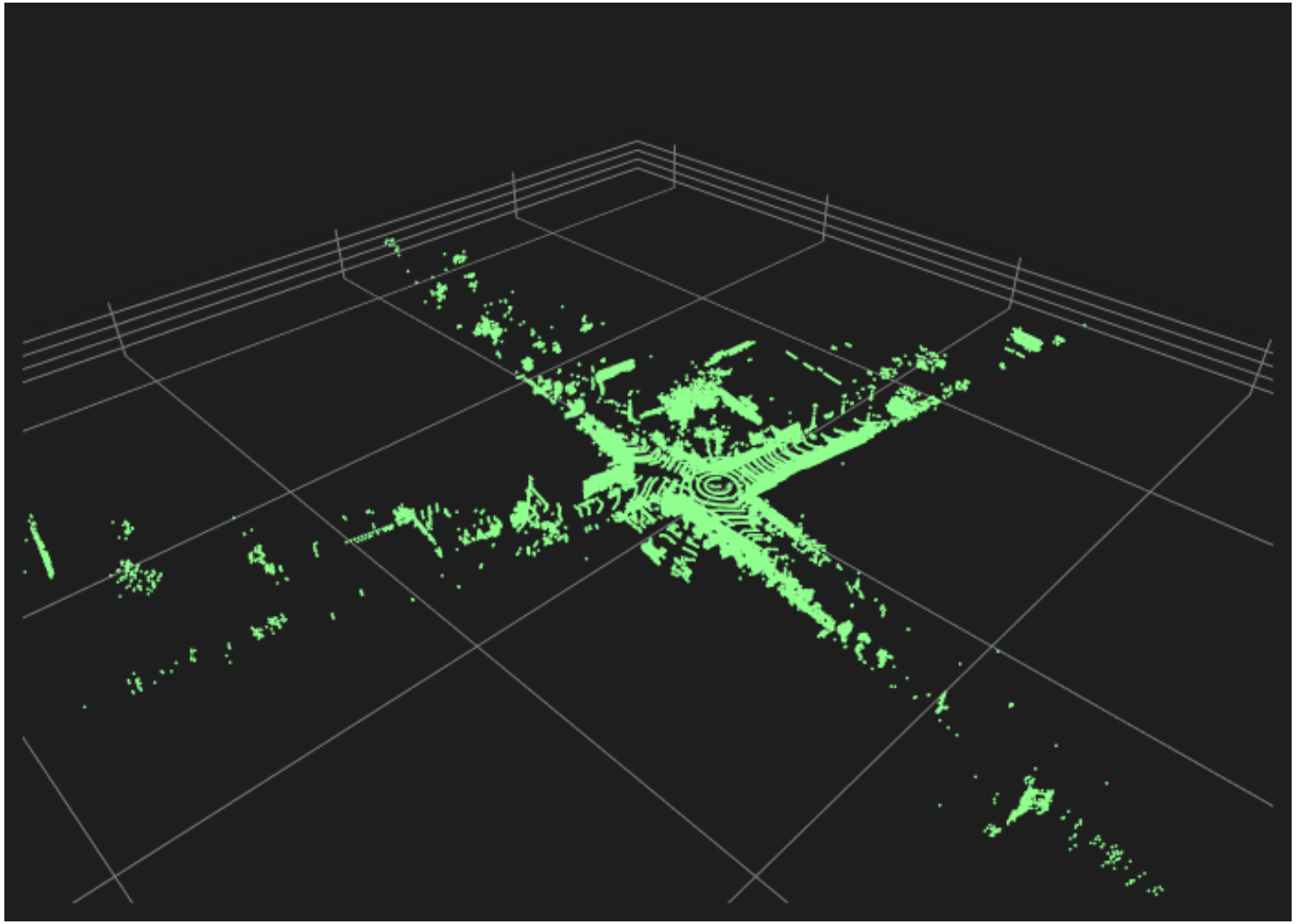
- Points that are nearby and on a surface perpendicular to rays give dense data.
- Points that are distant and on walls that are not parallel to rays give sparse data.
- Points that are distant, but on walls that are perpendicular to rays give moderately dense data.



Real Data (from the book)

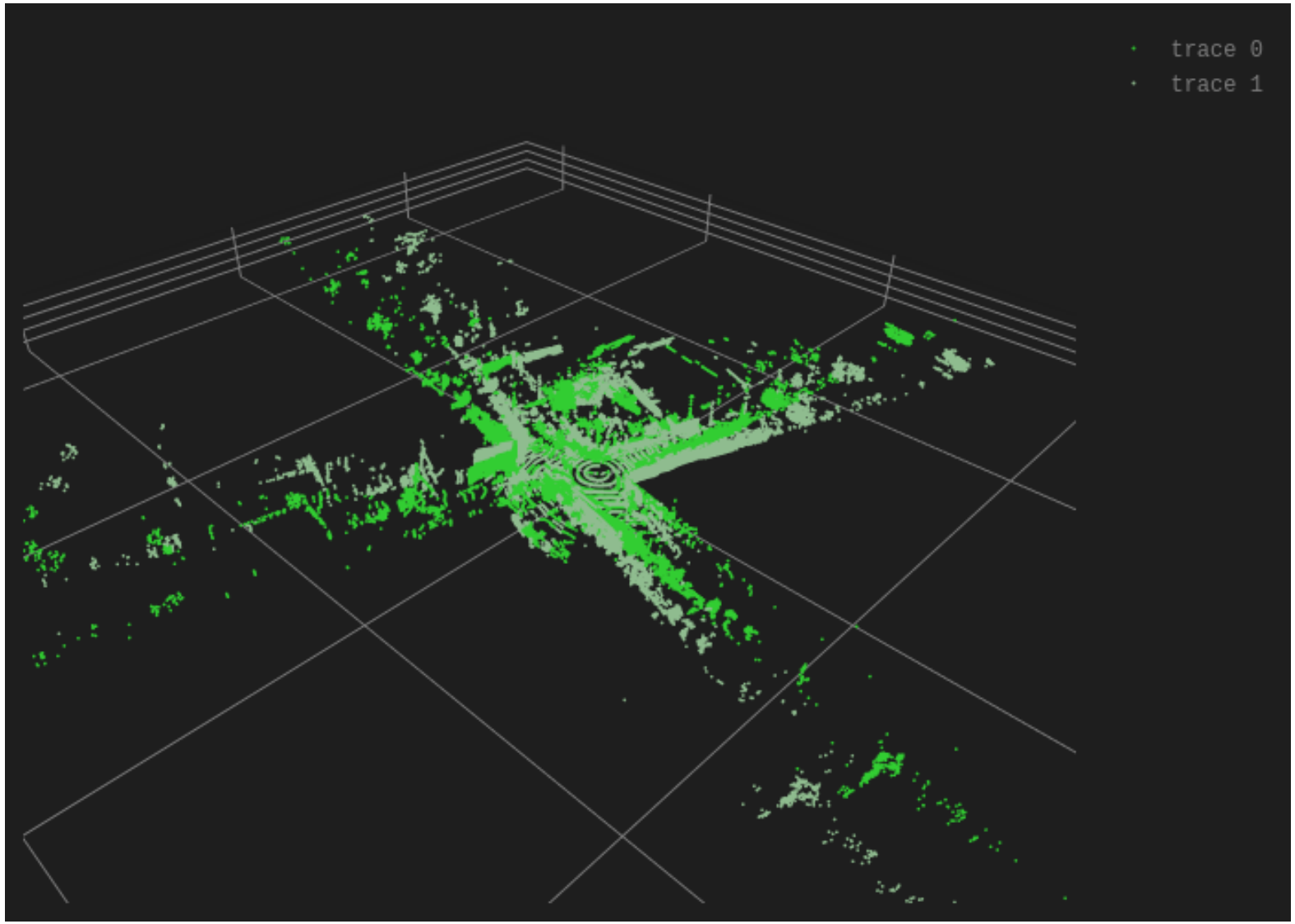
Scan taken when the Argo test car is turning at an intersection:

- The location of the car (at the origin) is marked by concentric circles formed by the lowest beams.
- The range is approximately 200m, so we can see fairly far down the cross streets.
- Occlusion is significant: objects close to the car throw “occlusion shadows”.
- Everything is in *body coordinates*, and the fact that the streets appear rotated betrays that the car is actually turning.



Real Data (from the book)

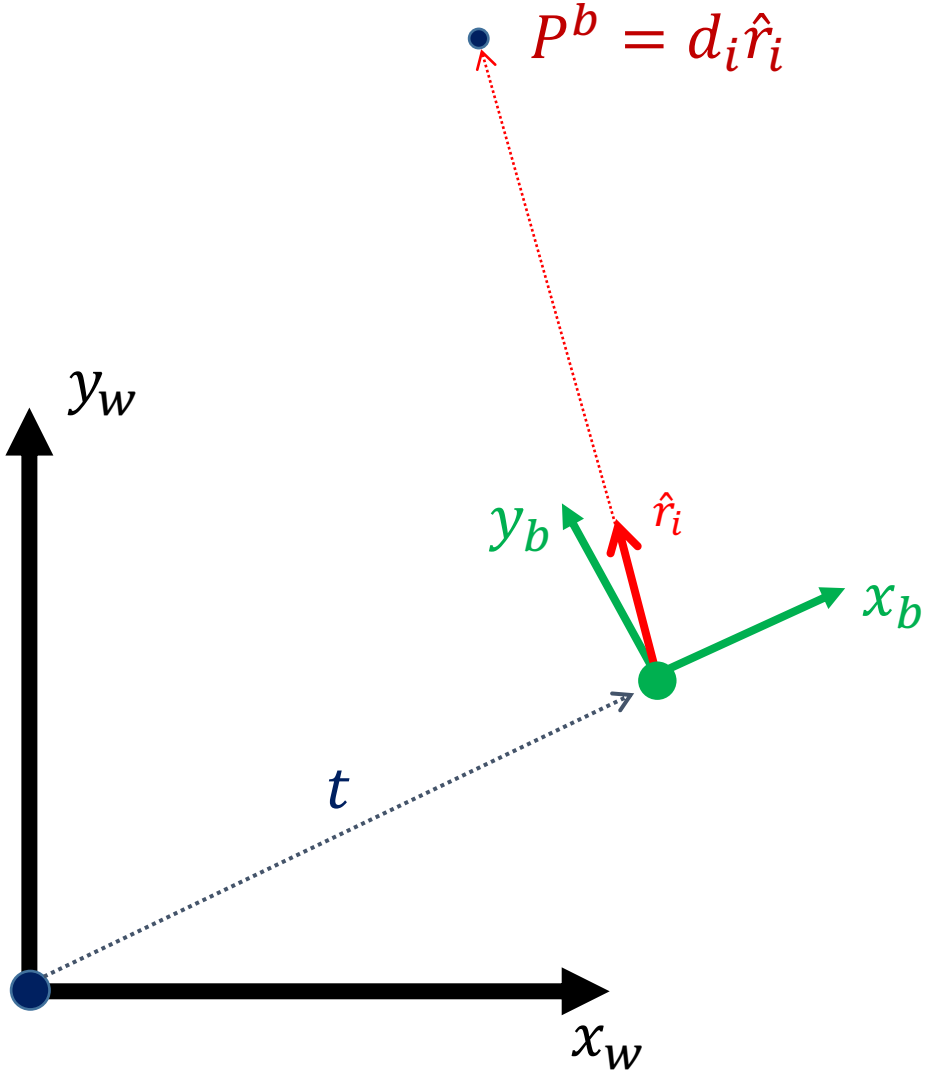
- This image shows two scans: note the two slightly different colors for the data points.
- Both scans are shown w.r.t. the body coordinate frame of the car.
- These aren't successive scans; eight scans have been omitted.
- Notice the difference in orientation of the data: The car is turning!
- Notice also a slight translation: The car is also moving forward.



Building a Point Cloud

- As the sensor moves through its environment, it performs a sequence of scans.
- Each scan acquires a set of points in the world, and the coordinates of these points (either (x, y) for planar data or (x, y, z) for 3D data) are ***expressed with respect to the coordinate frame of the sensor***.
- To make life easier, we will assume that the body frame of the robot is coincident with the coordinate frame of the sensor.
- In order to build a single map of the environment, it is necessary to express these points in a single coordinate system.
- For most applications, we map points to a single, world coordinate frame.
- This frame could be defined in terms of the local environment (e.g., the origin of the frame could be in Klaus), or in terms of GPS coordinates.
- We already know how to do this using coordinate transformations!

Coordinate Transformations for LIDAR Data



$$R_b^w = \begin{bmatrix} x_b \cdot x_w & y_b \cdot x_w \\ x_b \cdot y_w & y_b \cdot y_w \end{bmatrix}$$

$$t^w = \begin{bmatrix} t_x \\ t_y \end{bmatrix}$$

$$\boldsymbol{P^w = R_b^w P^b + t^w}$$

Or, we can write this using homogeneous transformations as:

$$\begin{bmatrix} \boldsymbol{P^w} \\ 1 \end{bmatrix} = \begin{bmatrix} \boldsymbol{R_b^w} & \boldsymbol{t^w} \\ 0_2 & 1 \end{bmatrix} \begin{bmatrix} \boldsymbol{P^b} \\ 1 \end{bmatrix}$$

GTSAM

- The homogeneous transformation

$$\begin{bmatrix} \boldsymbol{P^w} \\ 1 \end{bmatrix} = \begin{bmatrix} \boldsymbol{R_b^w} & \boldsymbol{t^w} \\ 0_2 & 1 \end{bmatrix} \begin{bmatrix} \boldsymbol{P^b} \\ 1 \end{bmatrix}$$

  is a nice, compact representation, but really, it's just one specific way to implement coordinate transformation.

- We can write the coordinate transformation more generally as $\boldsymbol{P^w = \phi\left(T_b^w, P^b\right)}$.
- In GTSAM, this is accomplished by Pose3::transformFrom
- This method can be applied to a single point, or to many points simultaneously by passing in a $3\times N$ matrix.
- Note the "3" in the name… GTSAM works with 3D coordinate transformations (thus, a $3\times N$ matrix).
- It's easy to generalize $SE(2)$ to $SE(3)$. We'll see this in the next lecture.