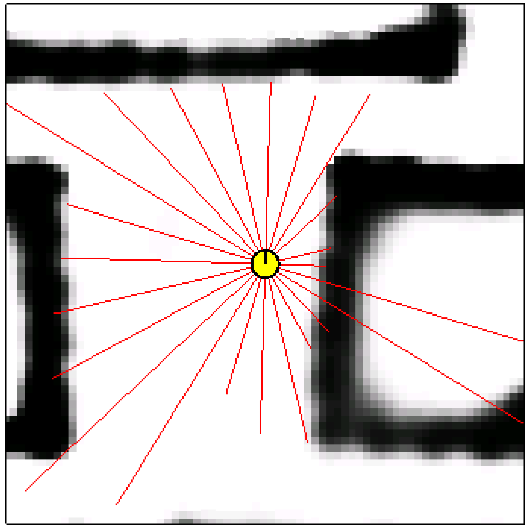
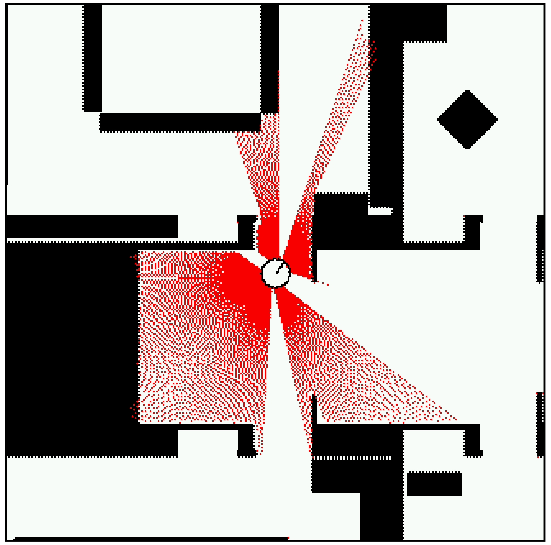
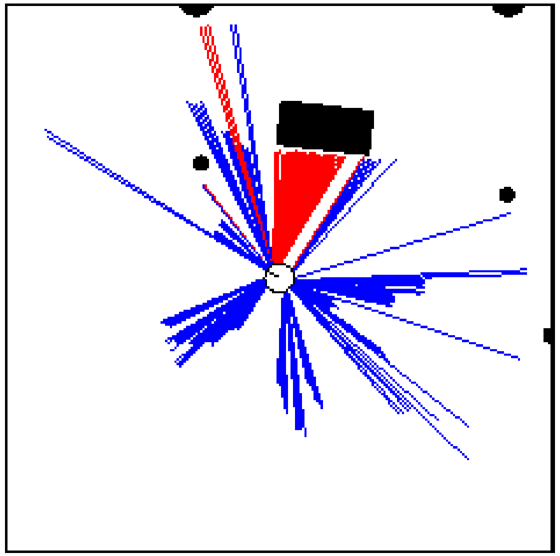
Sensors for Mobile Robots

- Contact sensors: Bumpers
- Proprioceptive sensors
  - Accelerometers (spring-mounted masses)
  - Gyroscopes (spinning mass, laser light)
  - Compasses, inclinometers (earth magnetic field, gravity)
- Proximity sensors
  - Sonar (time of flight)
  - Radar (phase and frequency)
  - Laser range-finders (triangulation, time of flight, phase)
  - Light-based (intensity)
- Visual sensors: Cameras
- Satellite-based sensors: GPS

Proximity Sensors

- The central task is to determine *P(z|x)*, i.e., the probability of a measurement *z* given that the robot is at position *x*.
- **Question**: Where do the probabilities come from?
- **Approach**: Let’s try to explain a measurement.

Beam-based Sensor Model

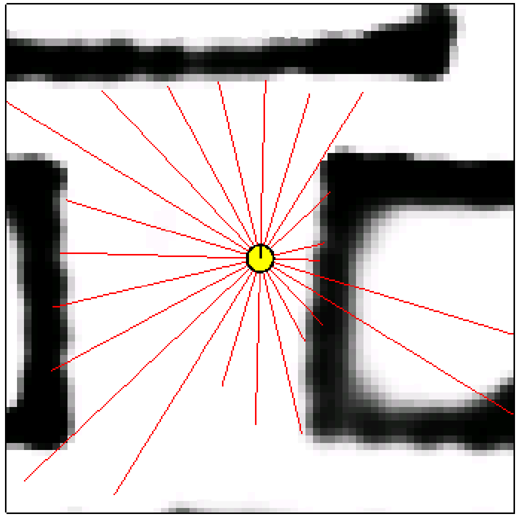
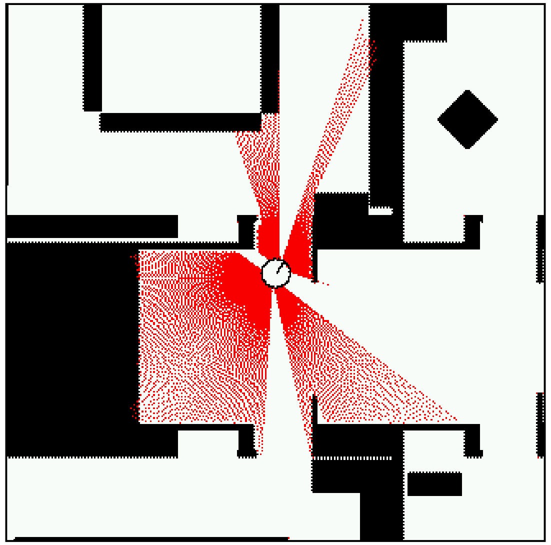
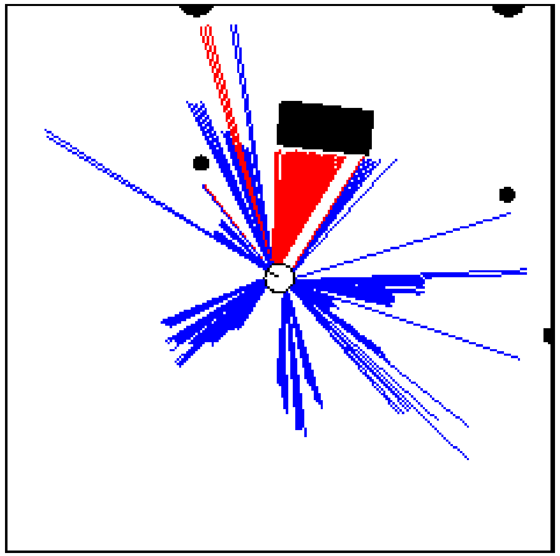
- Scan z consists of K measurements.

$$z = \{z_1, z_2, ..., z_K\}$$

- We split the state into the robot pose x and a map of the environment m which we here assume as given
- Individual measurements are independent given the robot position and map.

$$P(z \mid x, m) = \prod_{k=1}^{K} P(z_k \mid x, m)$$

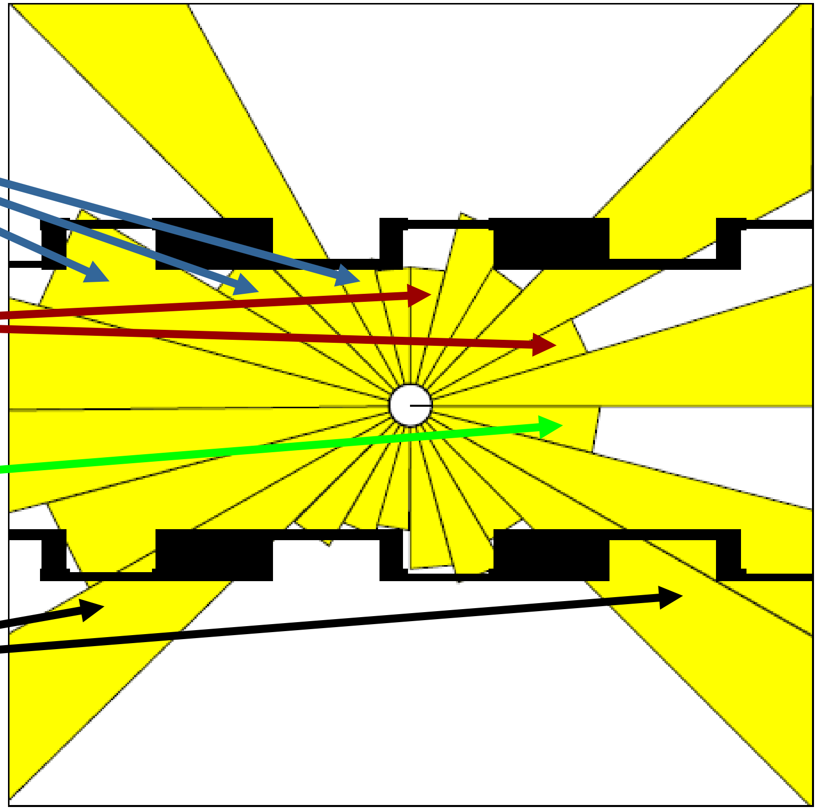
Beam-based Sensor Model

$$P(z \mid x, m) = \prod_{k=1}^{K} P(z_k \mid x, m)$$

Typical Measurement Errors of Range Measurements

1. Beams reflected by obstacles
2. Beams reflected by people / caused by crosstalk
3. Random measurements
4. Maximum range measurements



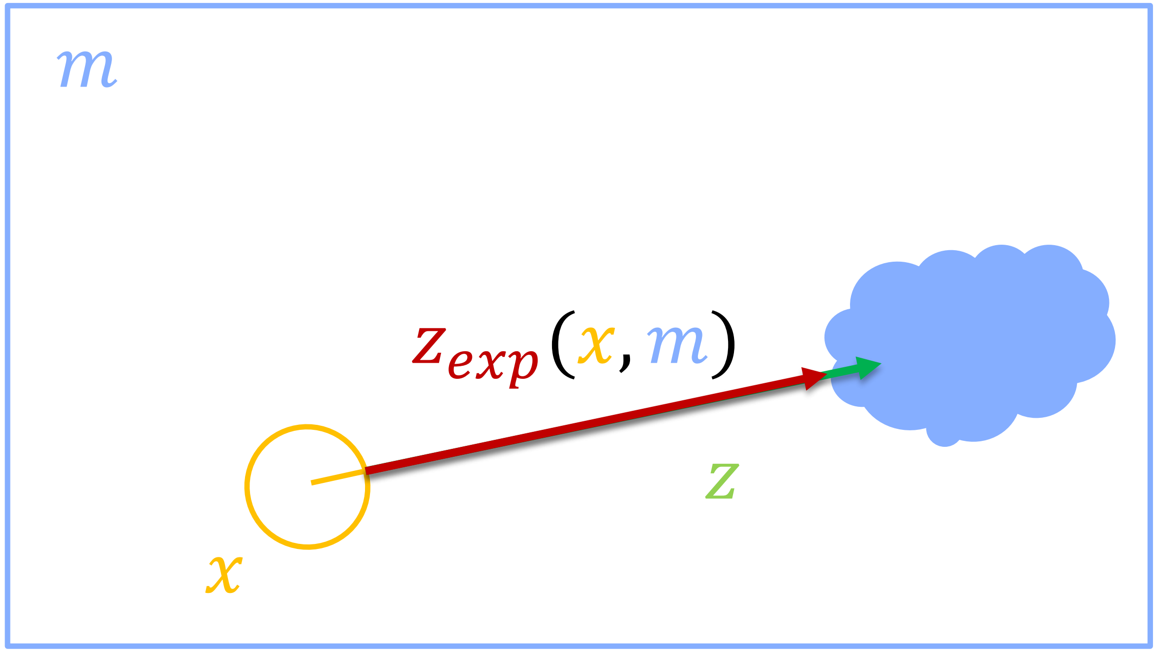
Proximity Measurement

- Measurement can be caused by …
  - a known obstacle.
  - cross-talk.
  - an unexpected obstacle (people, furniture, …).
  - missing all obstacles (total reflection, glass, …).
- Noise is due to uncertainty …
  - in measuring distance to known obstacle.
  - in position of known obstacles.
  - in position of additional obstacles.
  - whether obstacle is missed.

Key Idea of the Beam-based Model

- Considers beams individually
- Uses the following approximation:

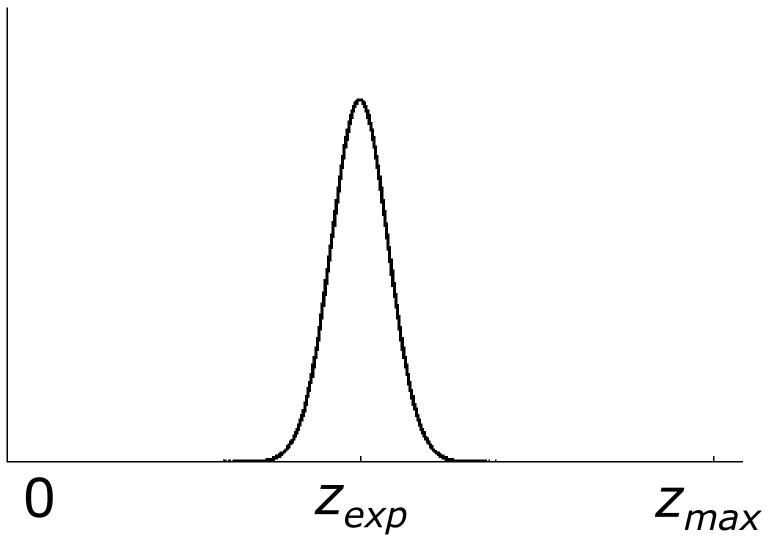
$$P(z \mid x) = P(z \mid x, m) \approx P(z \mid z_{exp}(x, m)) = P(z \mid z_{exp})$$



$z_{exp}(x, m)$ equals distance to closest obstacle in direction of measurement (obtained by ray casting)

Beam-based Proximity Model

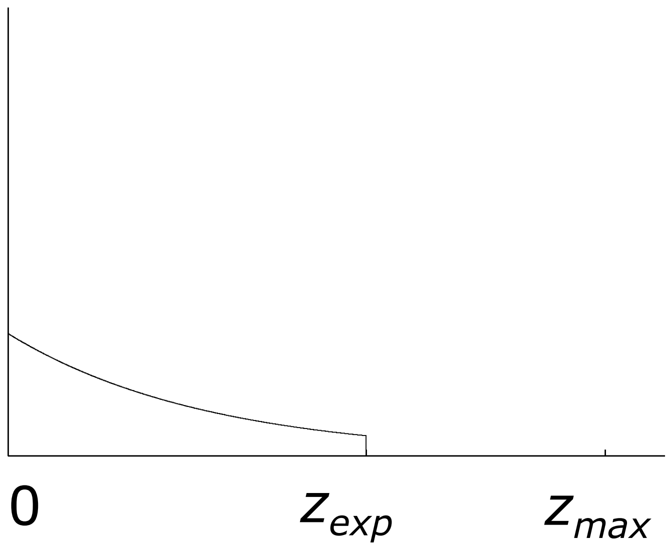
Measurement noise



$$P_{hit}(z \mid x, m) = \eta \frac{1}{\sqrt{2\pi b}} e^{-\frac{1}{2}\frac{(z - z_{\exp})^2}{b}}$$

η is a normalizer

Unexpected obstacles

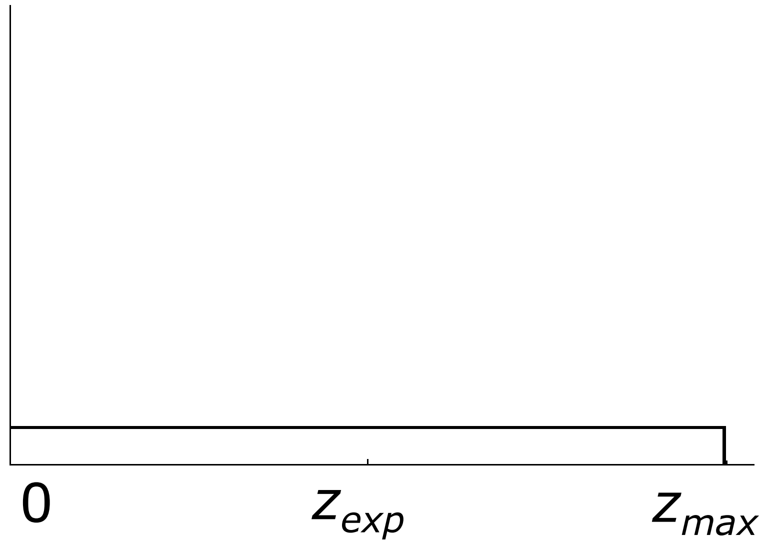


$$P_{\text{unexp}}(z \mid x, m) = \begin{cases} \eta \, \lambda \, e^{-\lambda z} & z < z_{\exp} \\ 0 & \textit{otherwise} \end{cases}$$

η is a normalizer,
λ a model parameter

Beam-based Proximity Model

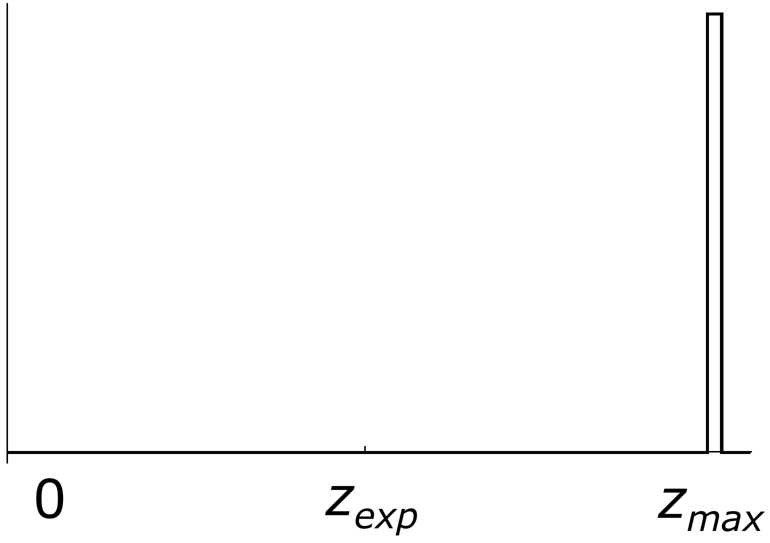
Random measurement



$$P_{rand}(z \mid x, m) = \eta \frac{1}{z_{\max}}$$

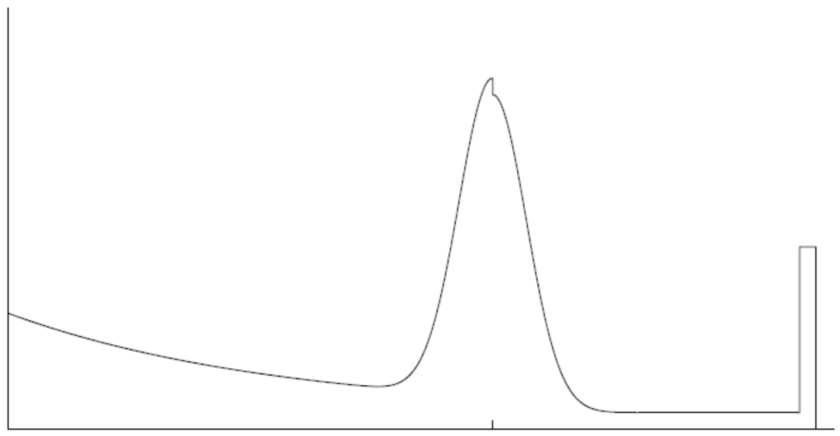
η is a normalizer

Max range



$$P_{\max}(z|x,m) = \begin{cases} 1 & z = z_{\max} \\ 0 & \text{otherwise} \end{cases}$$

Resulting Mixture Density

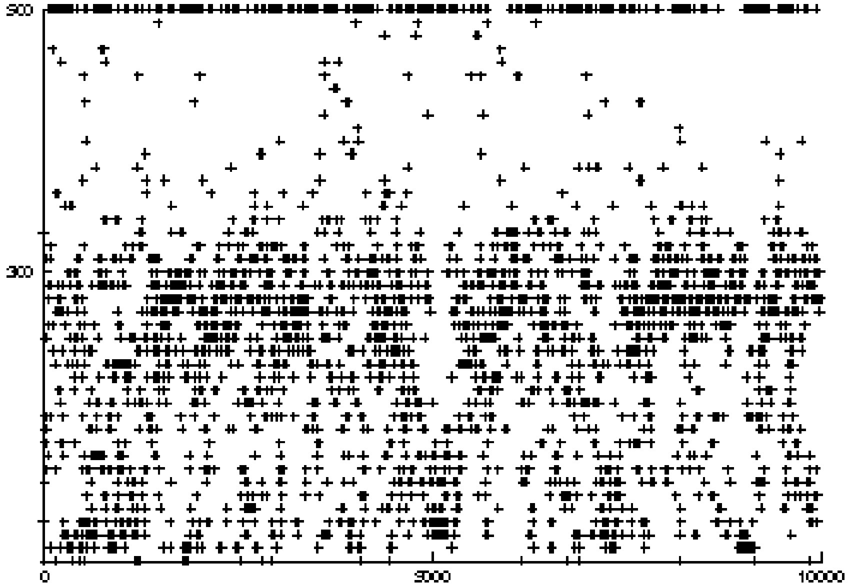


$$P(z \mid x, m) = \begin{pmatrix} \alpha_{\text{hit}} \\ \alpha_{\text{unexp}} \\ \alpha_{\text{max}} \\ \alpha_{\text{rand}} \end{pmatrix}^T \cdot \begin{pmatrix} P_{\text{hit}}(z \mid x, m) \\ P_{\text{unexp}}(z \mid x, m) \\ P_{\text{max}}(z \mid x, m) \\ P_{\text{rand}}(z \mid x, m) \end{pmatrix}$$

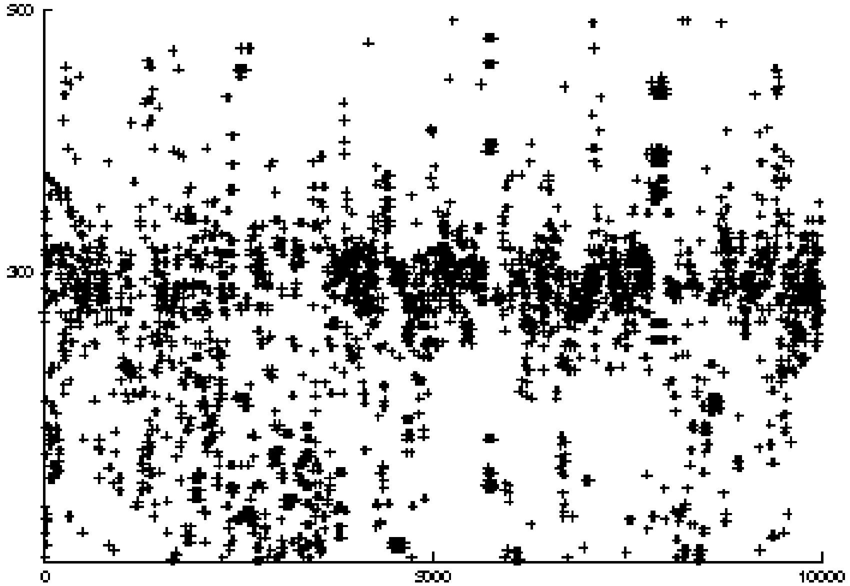
The model parameters can be learned from data

Learning the Model Parameters from Real Sensor Data

Measured distances for expected distance of 300 cm.

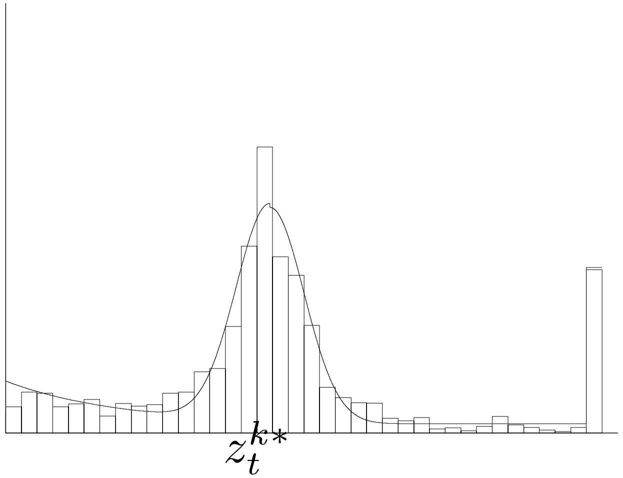


Sonar

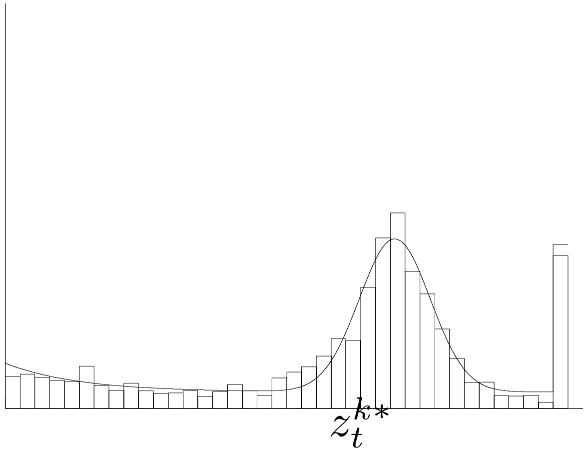


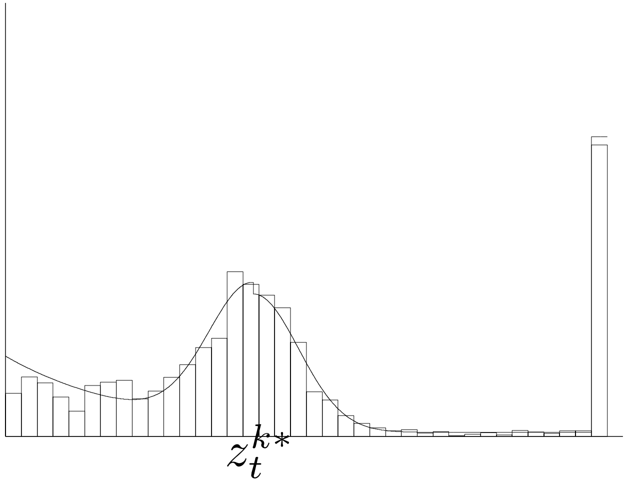
Laser

Learned Models

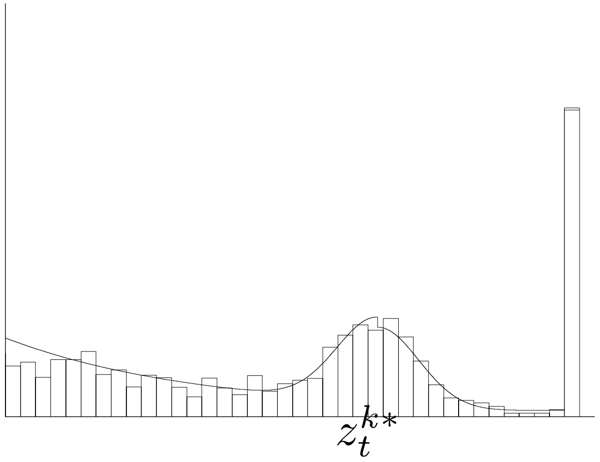


Laser





Sonar



300cm

400cm