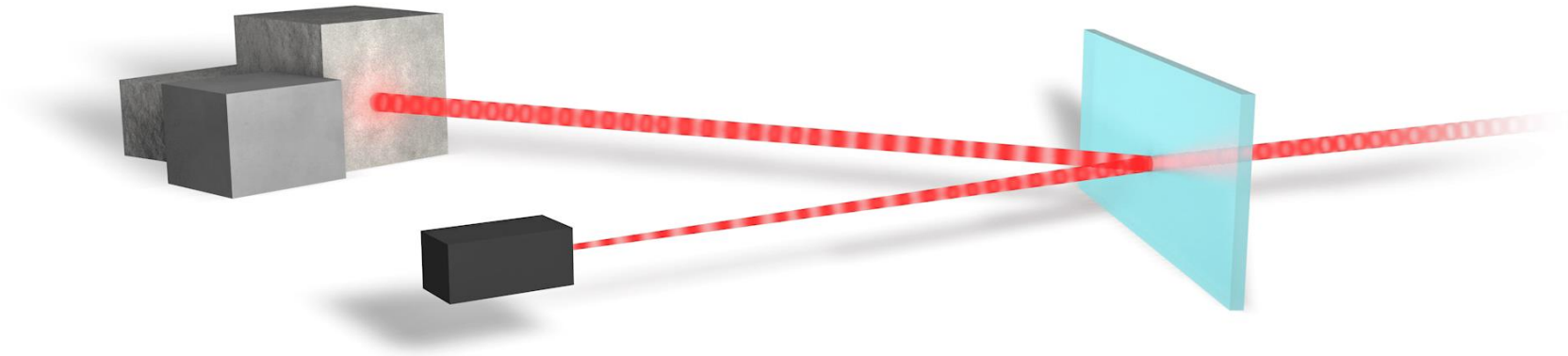
ICRA 2020

Physics-based Simulation of Continuous-Wave LIDAR

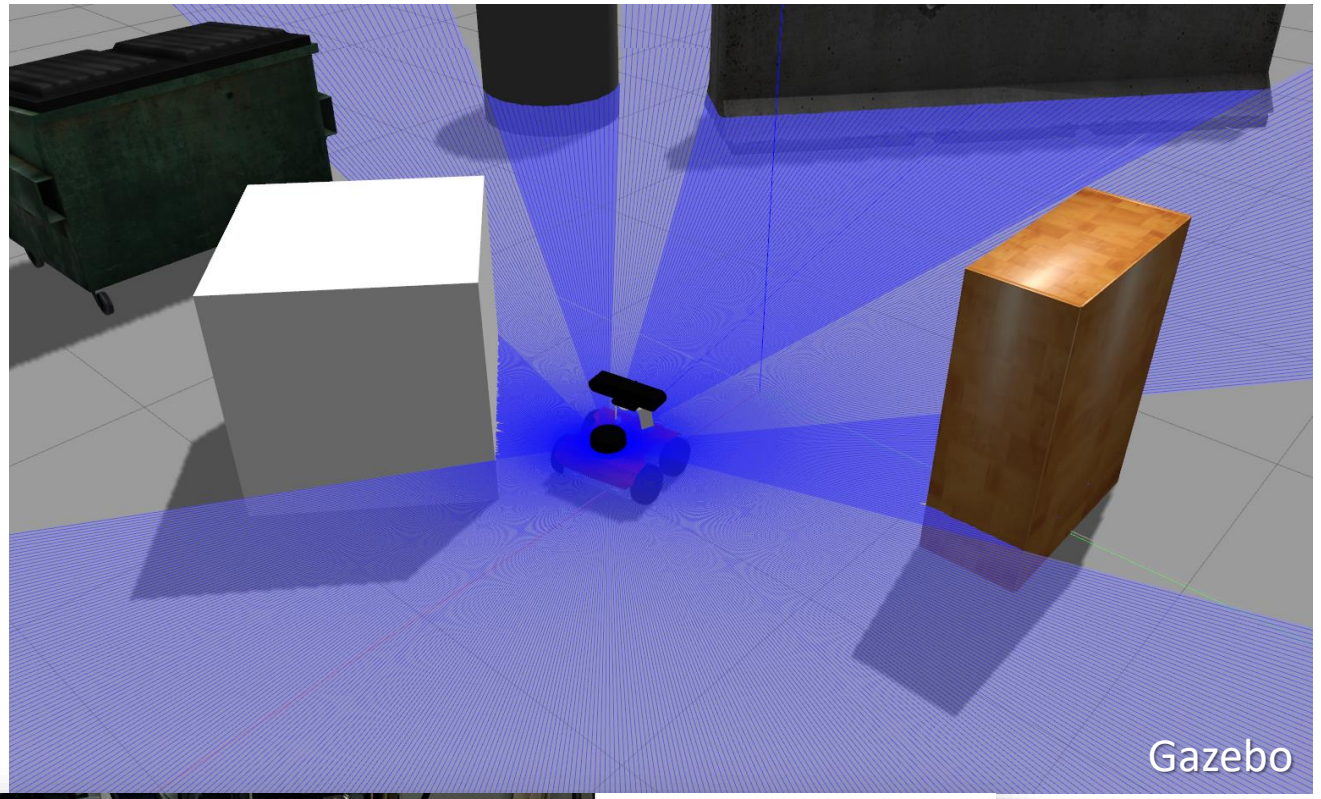
for Localization, Calibration and Tracking

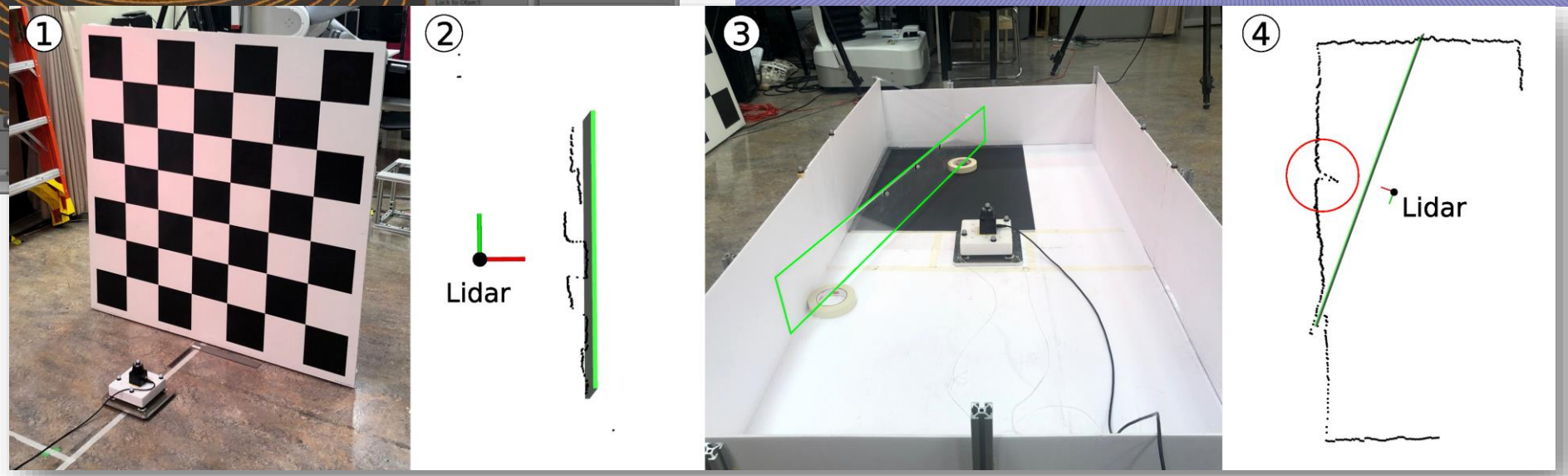
Eric Heiden, Ziang Liu, Ragesh K. Ramachandran, Gaurav S. Sukhatme



University of Southern California, Los Angeles, USA

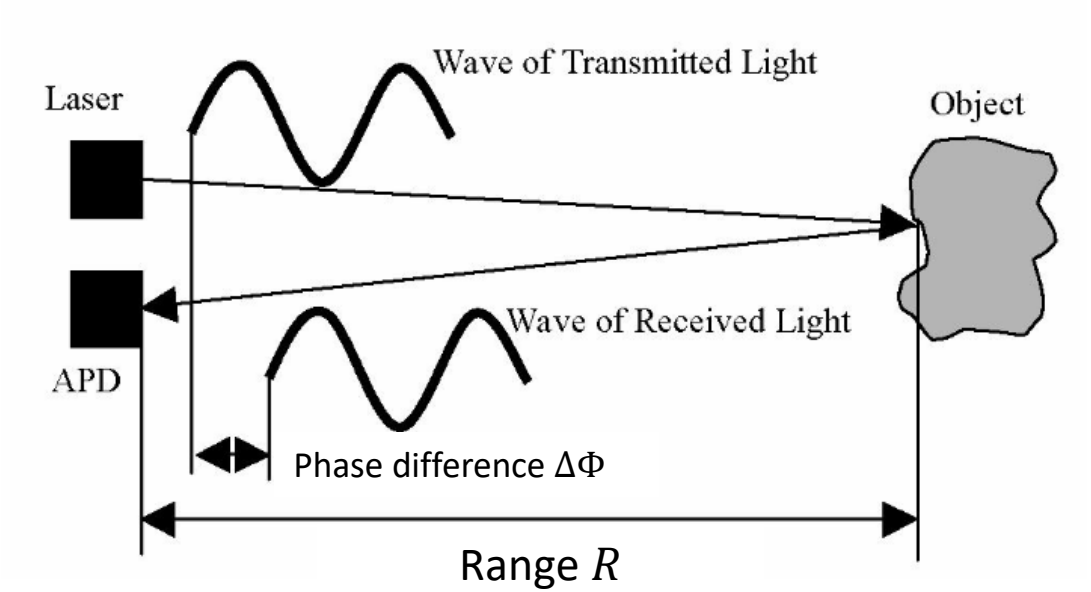
LIDAR simulation state of the art





CW LIDAR Principle

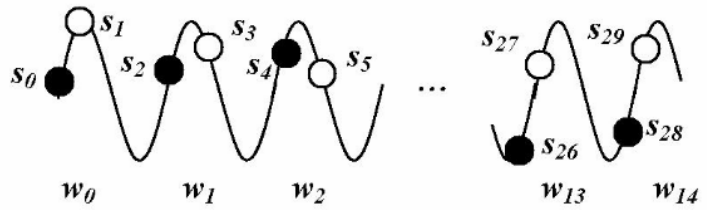
CW LIDARs use phase difference $\Delta\Phi$ between received and transmitted wave to measure range R

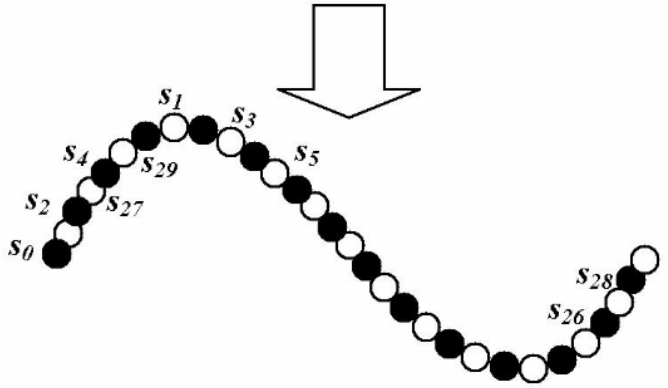


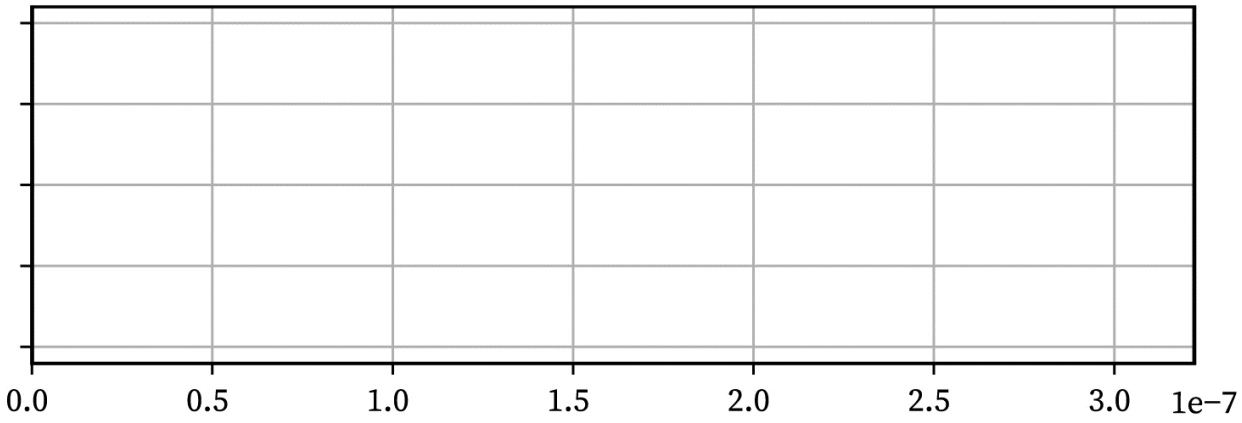
$$R = \frac{1}{4\pi}\frac{c}{f}\Delta\Phi$$

Kawata et al. 2005

CW LIDAR Data Sampling







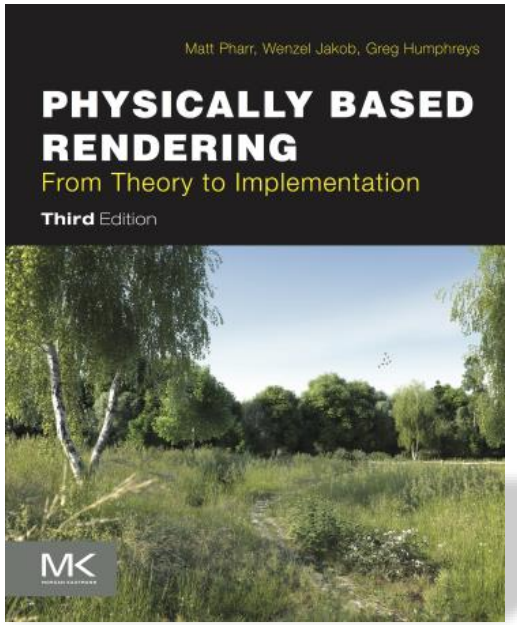
Measure phase for received and transmitted wave $\Phi = \arctan \frac{\sum_i s_i \cos t_i}{\sum_i s_i \sin t_i}$

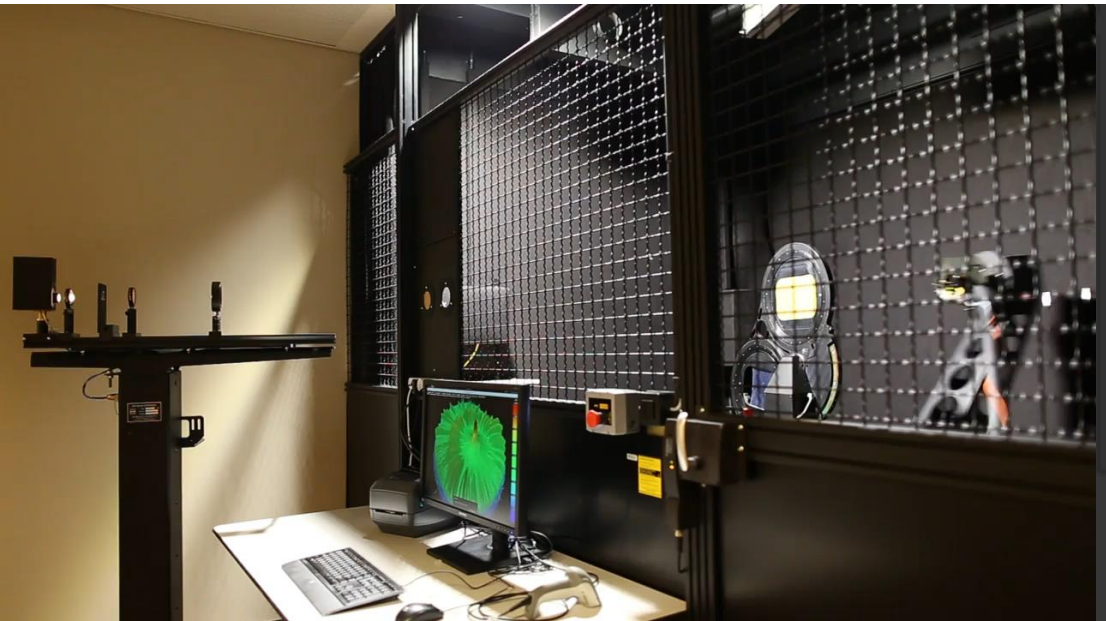
Hokuyo URG04-LX uses peculiar sampling scheme to increase resolution

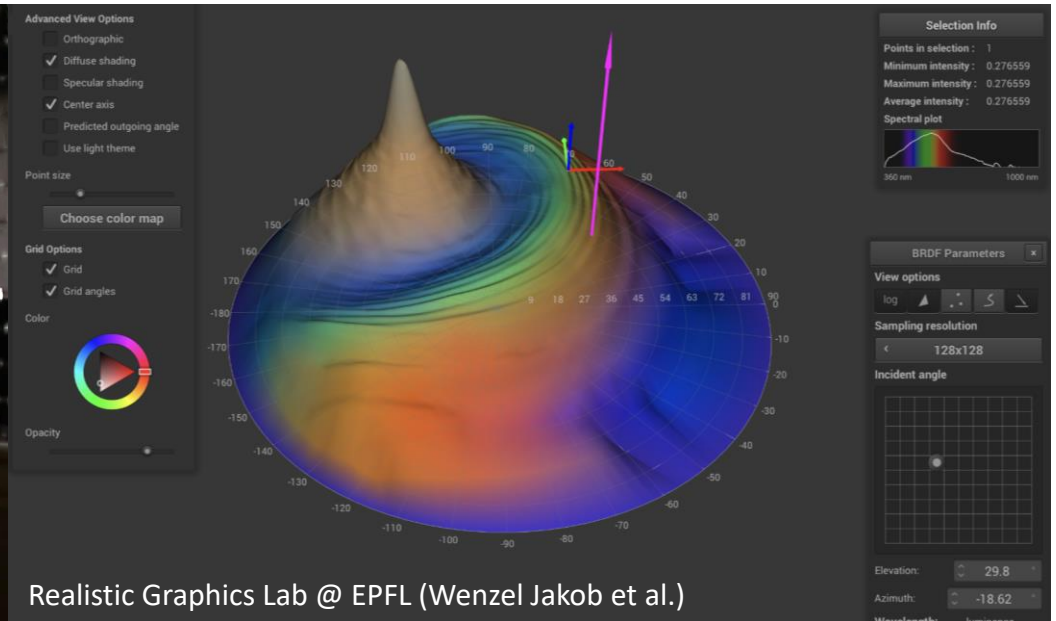
Physically Based Rendering (PBR)

Model interaction between light and various surface types

Followed book by Matt Pharr, Wenzel Jakob, Greg Humphreys and accompanying implementation `pbrt`







Realistic Graphics Lab @ EPFL (Wenzel Jakob et al.)

Rendering Equation

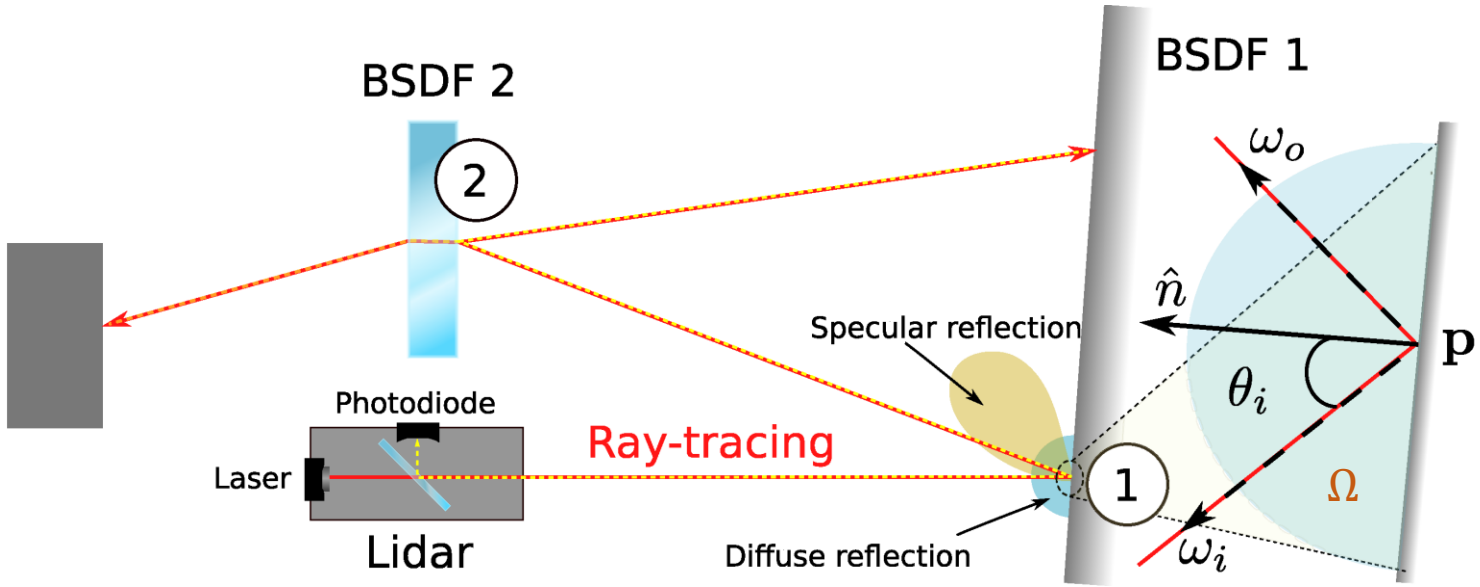
Expresses radiance of light ray with direction ω_o reflected from point $\mathbf{p}$

$$L(\mathbf{p}, \omega_o) = L_e(\mathbf{p}, \omega_o) + \int_{\Omega} f(\mathbf{p}, \omega_o, \omega_i) L_i(\mathbf{p}, \omega_i) |\cos \theta_i| \, \mathrm{d}\omega_i$$

blackbody emission

Bidirectional Scattering Distribution Function (BSDF)

Radiance of light ray with direction ω_i



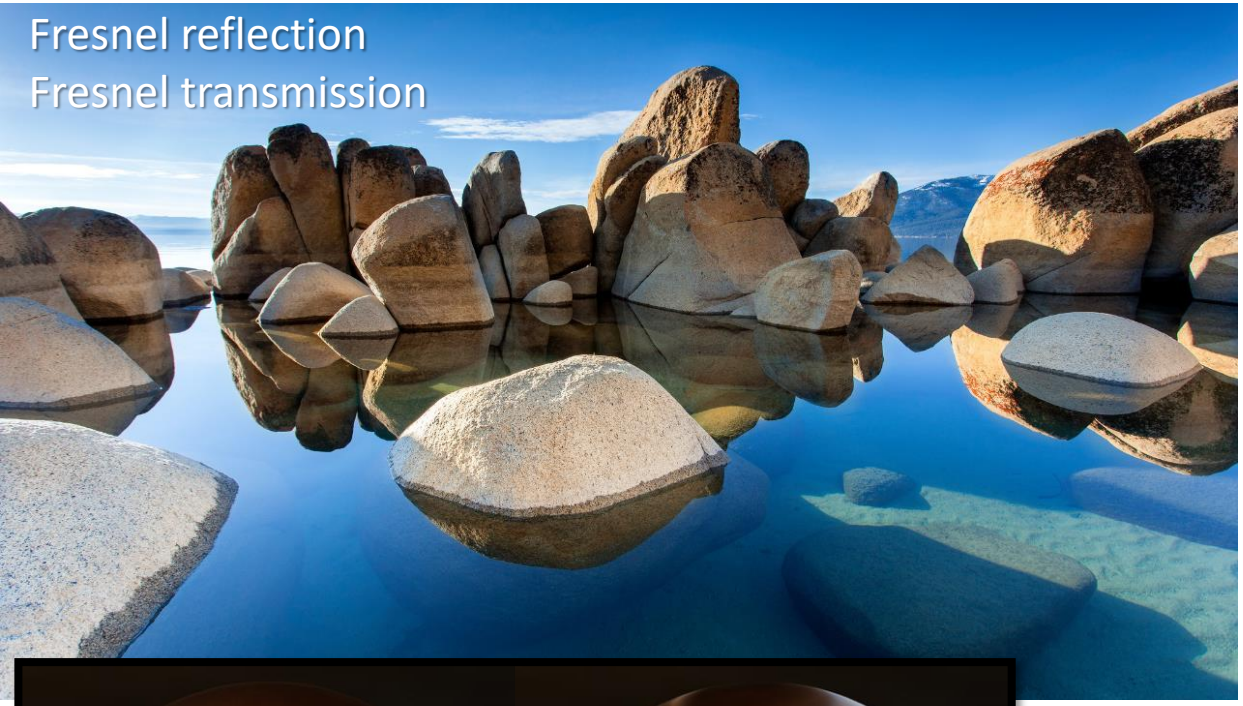
BSDF of Lambertian surface:

$$f(\mathbf{p}, \omega_o, \omega_i) = \frac{k}{\pi}$$

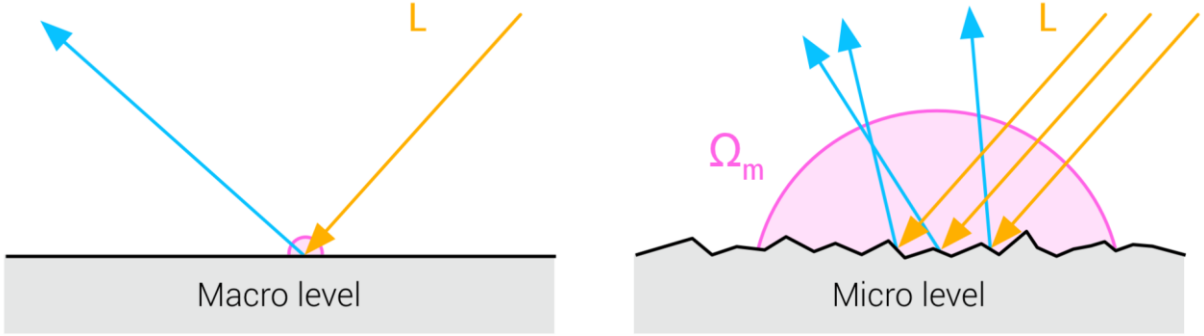
surface normal $\hat{n}$

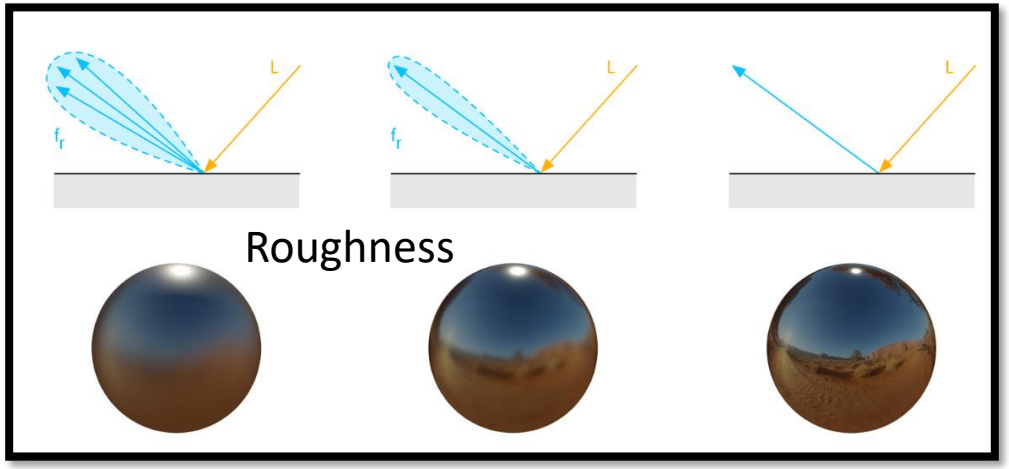
Advanced Surface Properties

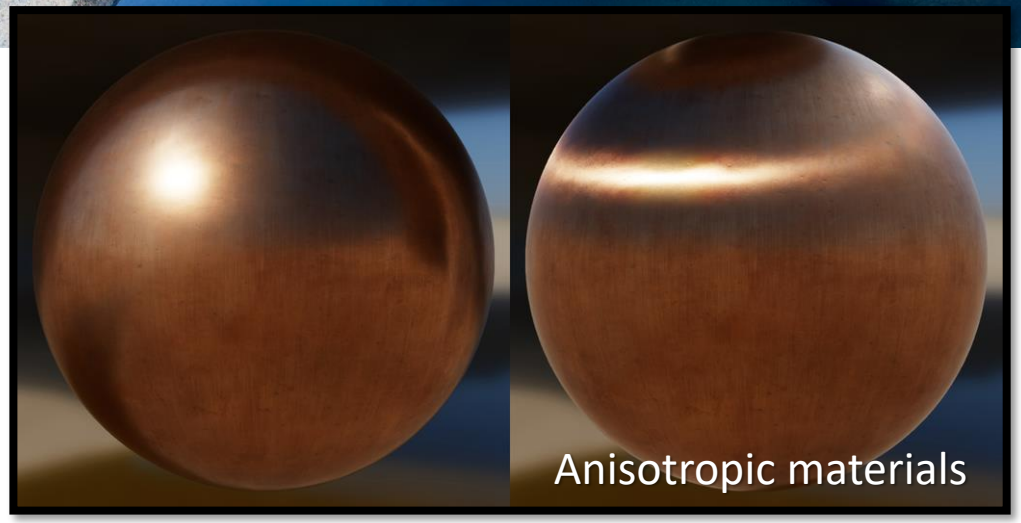
Pictures made by Filament

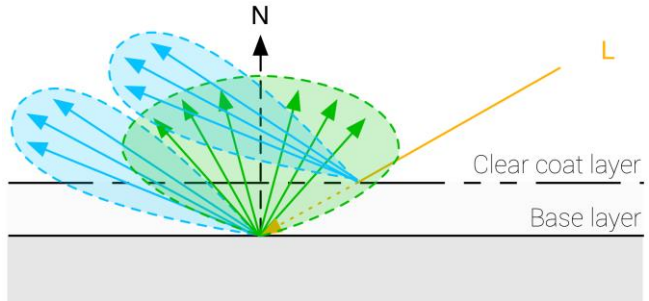


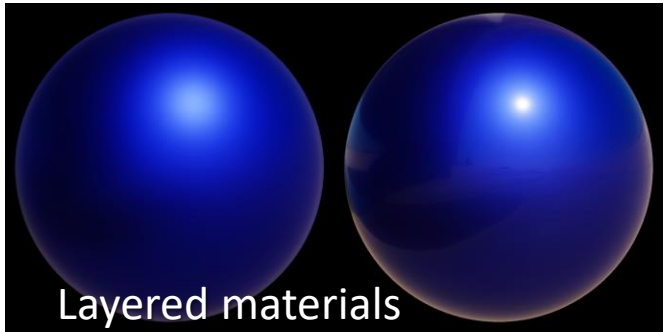
Microfacet distribution







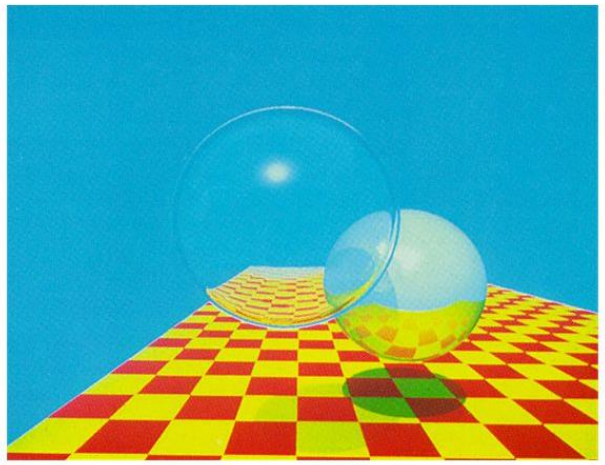




Integration

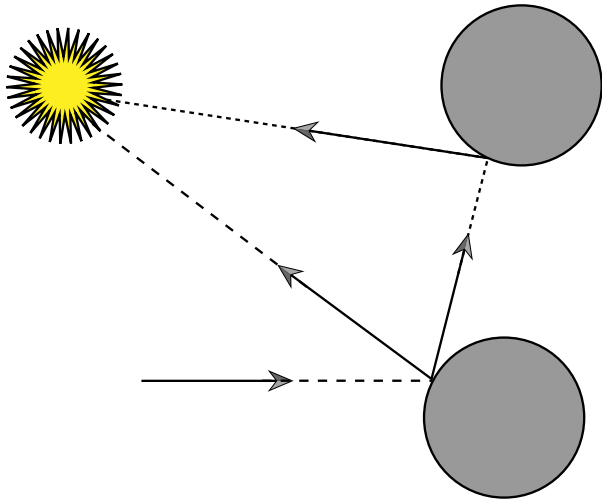
Need to solve integral in $L_e(\mathbf{p}, \omega_o) + \int_\Omega f(\mathbf{p}, \omega_o, \omega_i) L_i(\mathbf{p}, \omega_i) |\cos\theta_i| \, \mathrm{d}\omega_i$

Whitted Raytracing (1980)

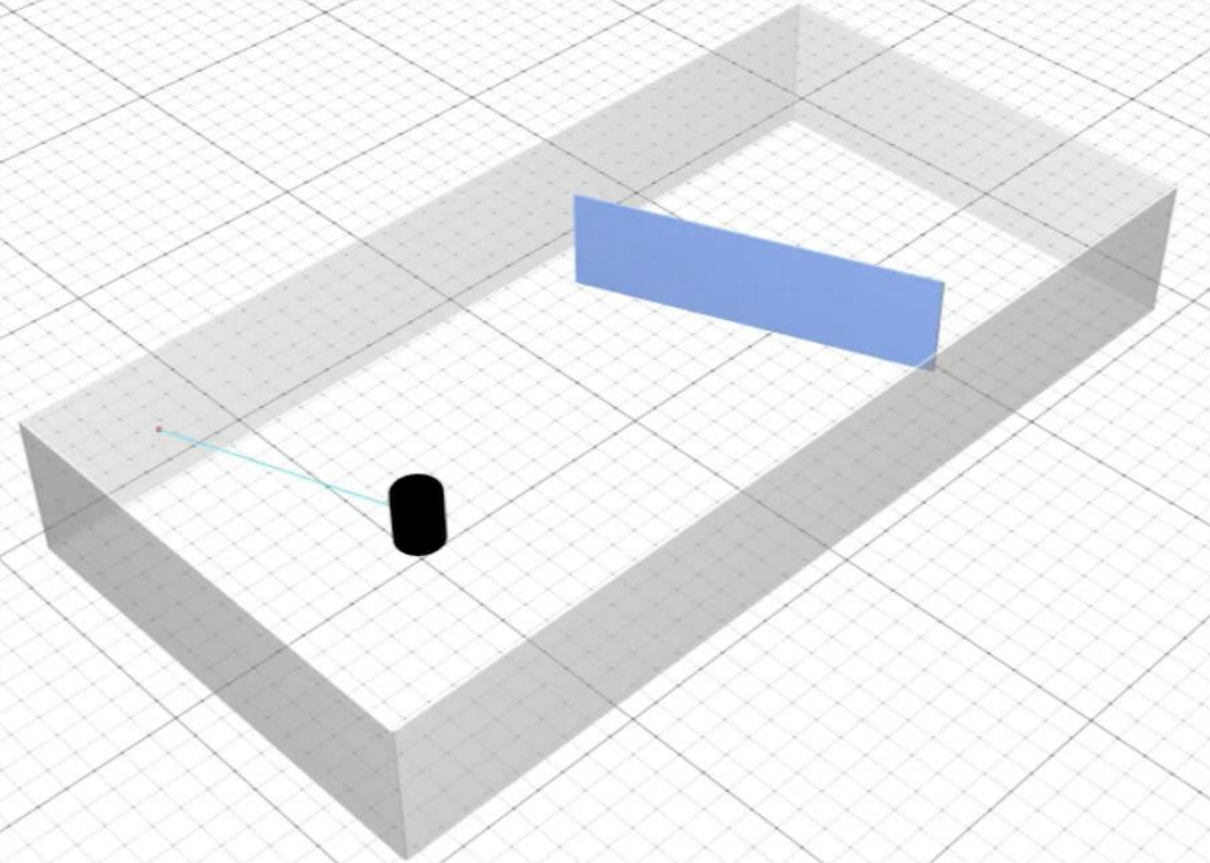


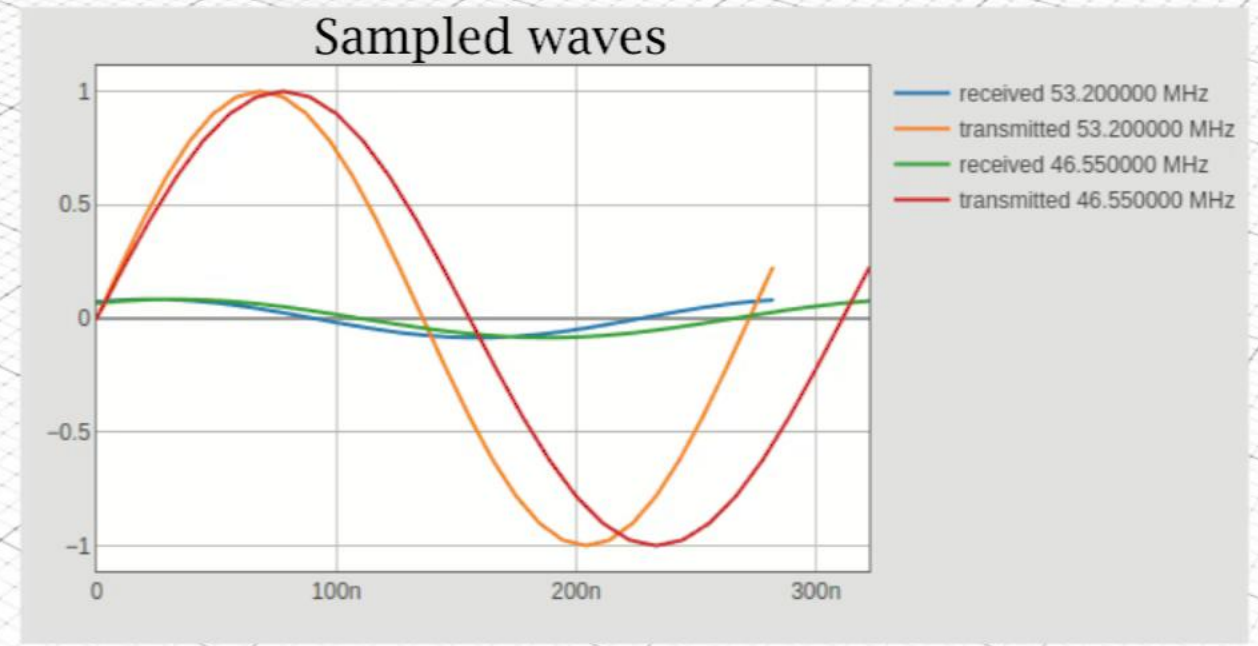
Turner Witted

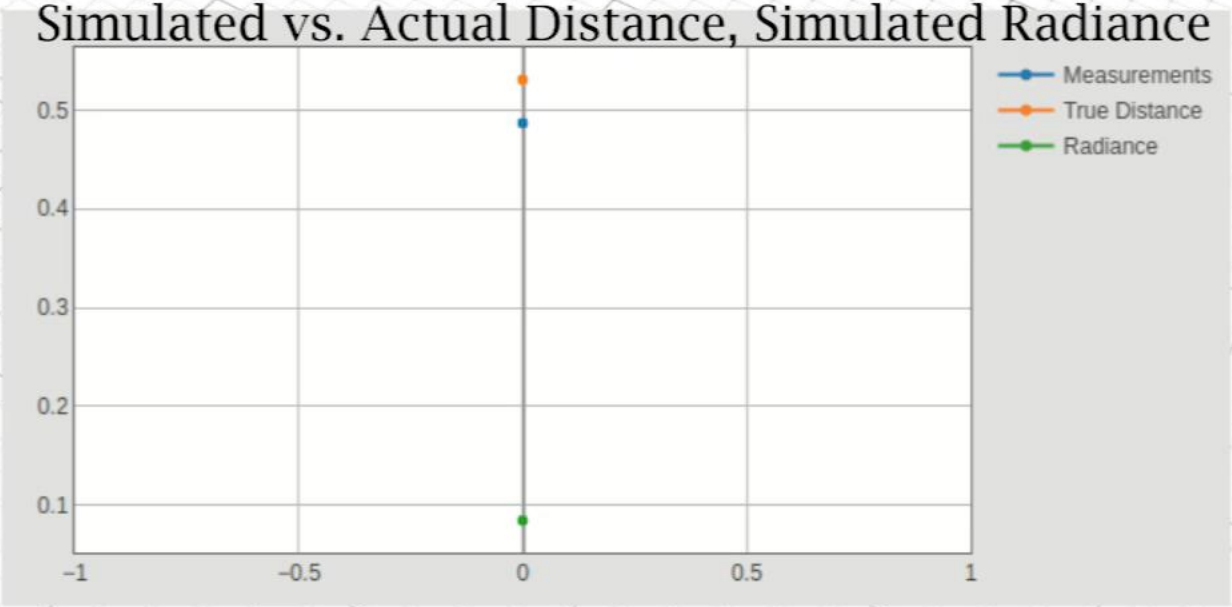
Only considers direct lighting
(1 sample per interaction)



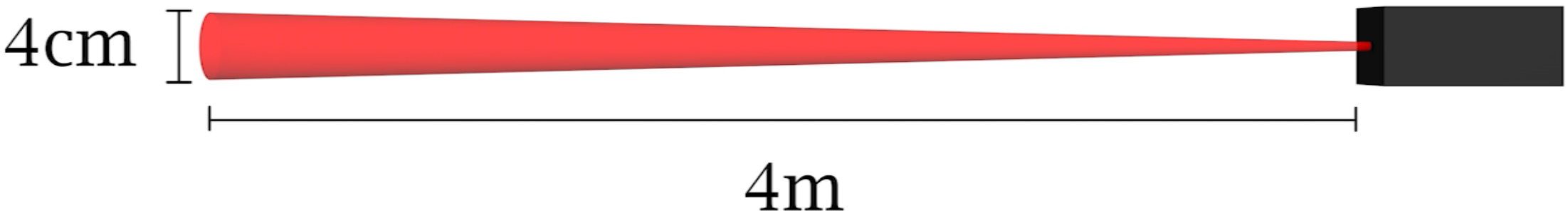
Simulation of Hokuyo URG04-LX with a single measurement







Laser beam divergence in Hokuyo URG04-LX



Scene/LIDAR Parameter Estimation

Solve Nonlinear Least Squares problem for parameter vector θ given true measurements y_i

$$\underset{\theta}{\text{minimize}}(\mathcal{L} = \sum_i \| f_\theta(r_i) - y_i \|_2^2)$$

(sometimes) s.t. $L \leq \theta \leq U$

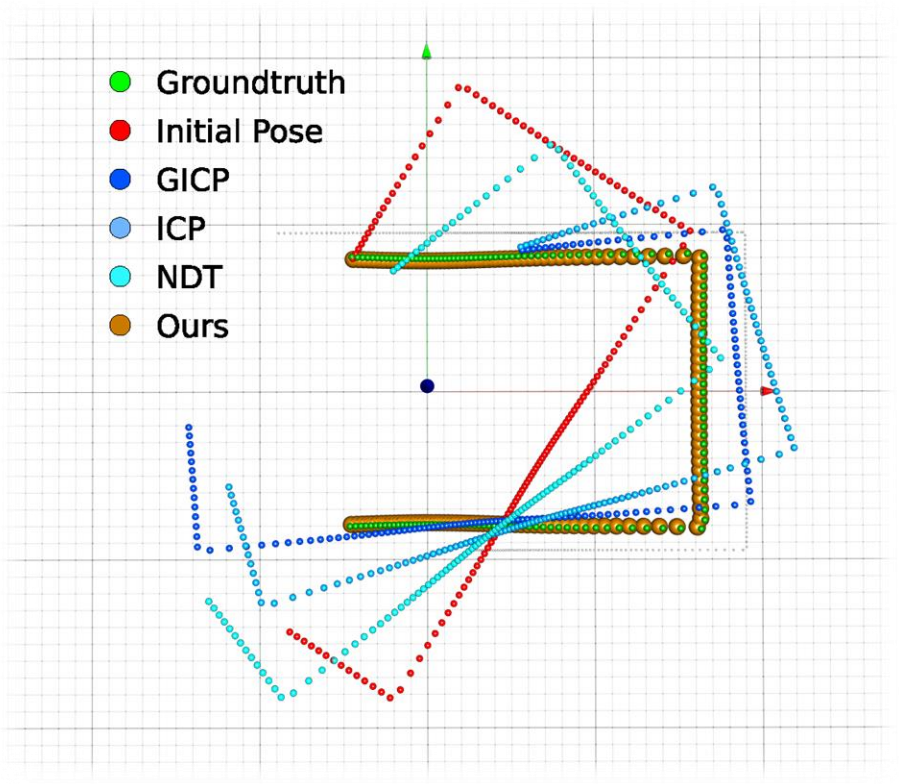
Calculate derivatives $\frac{\partial \mathcal{L}}{\partial \theta_k}$ via automatic differentiation

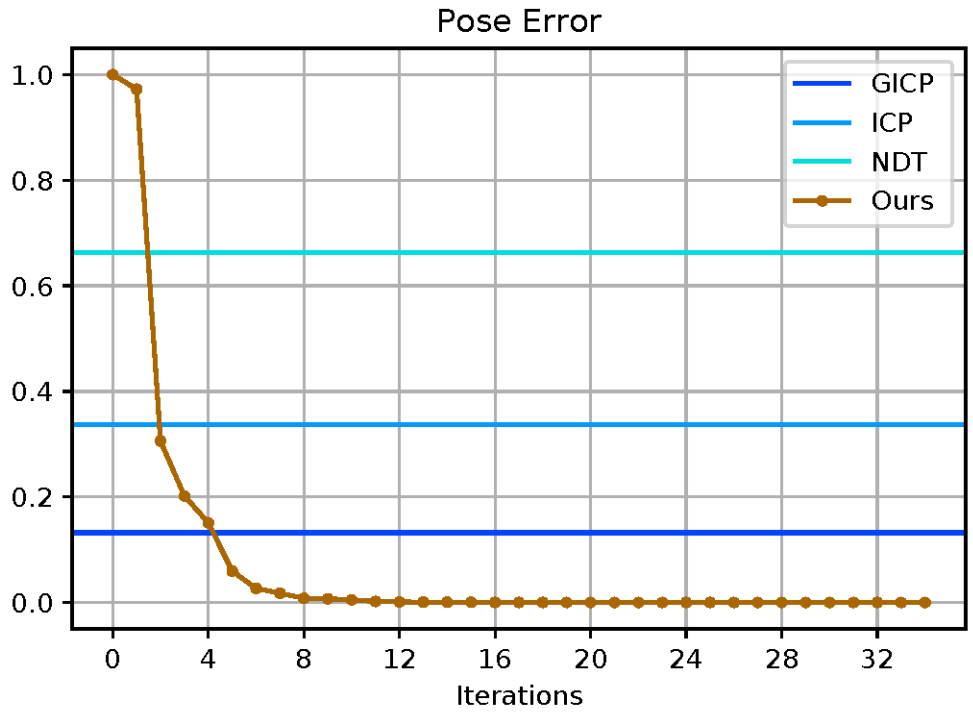
Run Levenberg-Marquardt / L-BFGS with Wolfe line search to solve optimization problem

Experiments

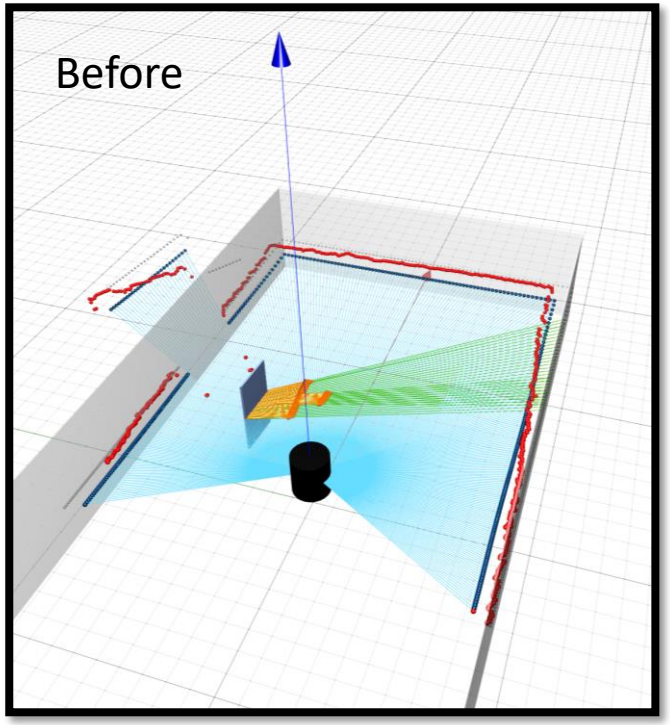
LIDAR Odometry

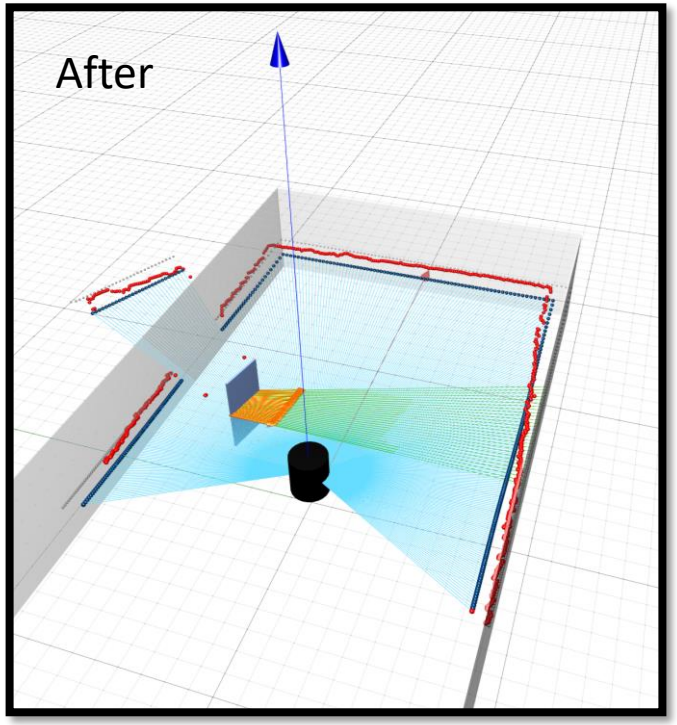
Estimate SE(2) transform of LIDAR frame given 2 scans in cuboid environment

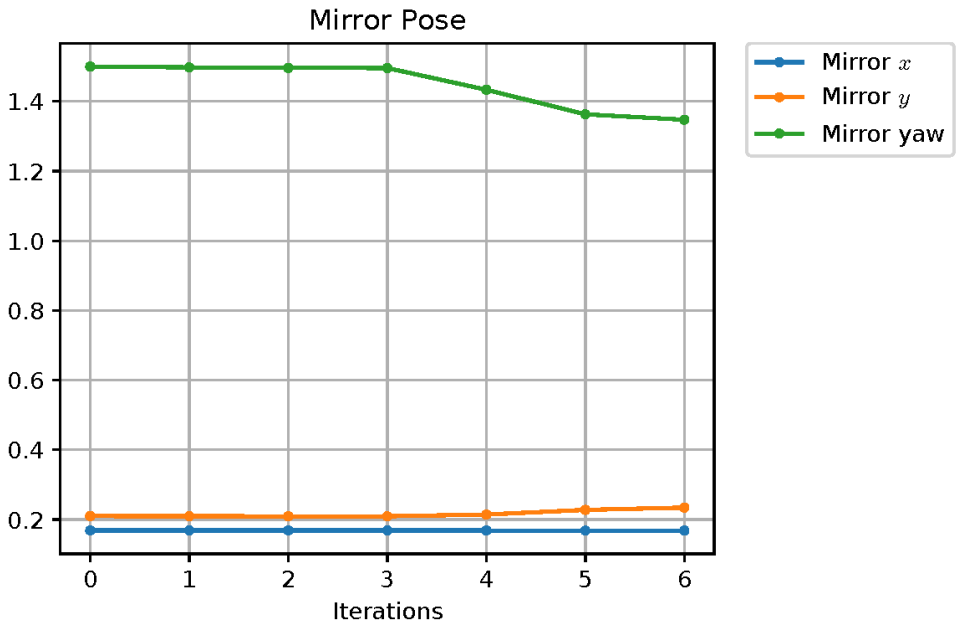




Tracking a mirror in the real world

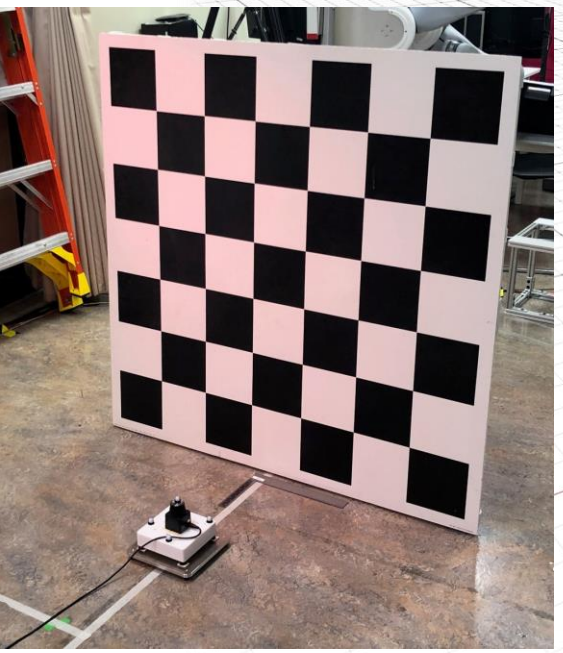


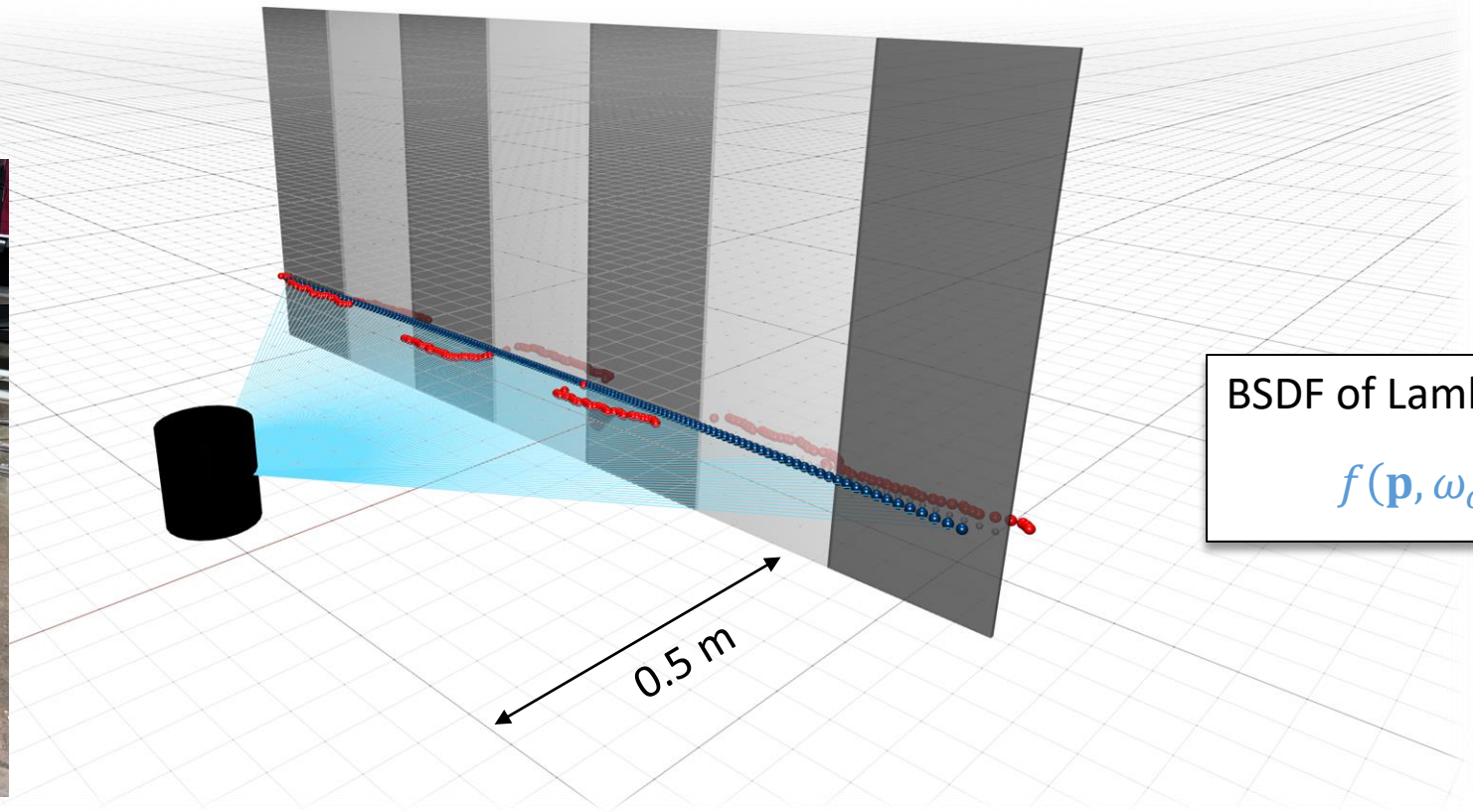




Calibrating APD & Estimate Surface Properties

Before



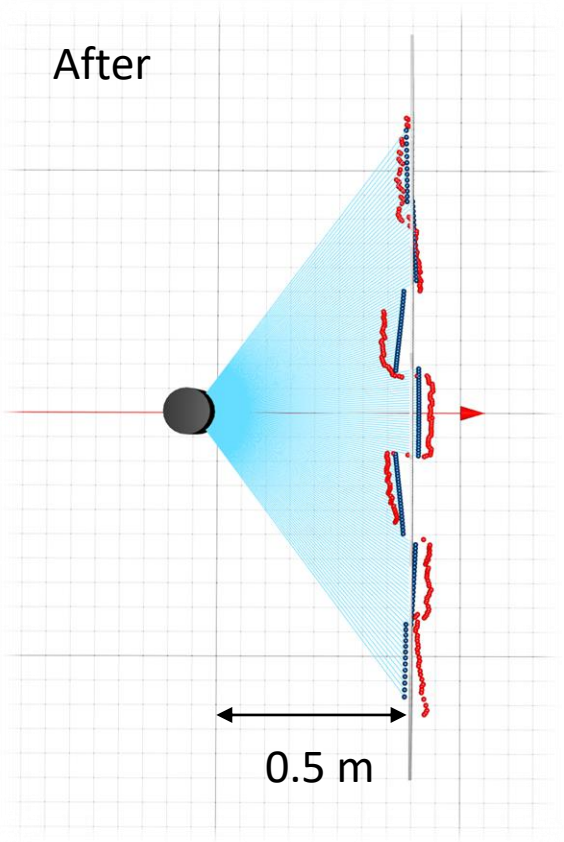


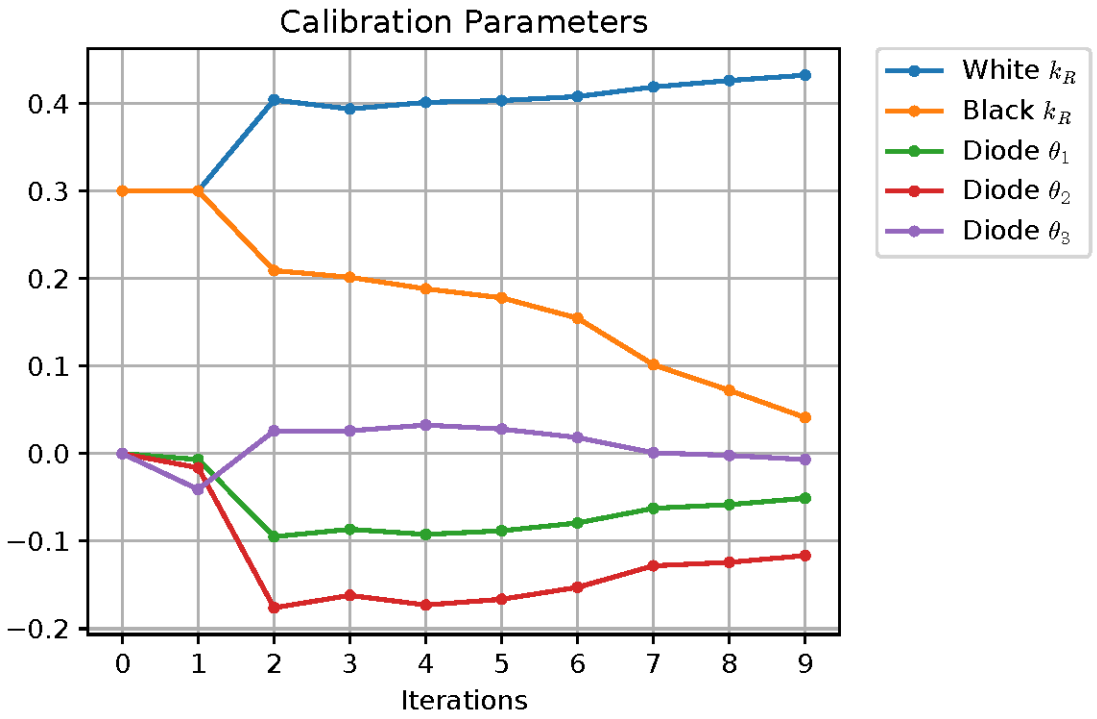
BSDF of Lambertian surface:

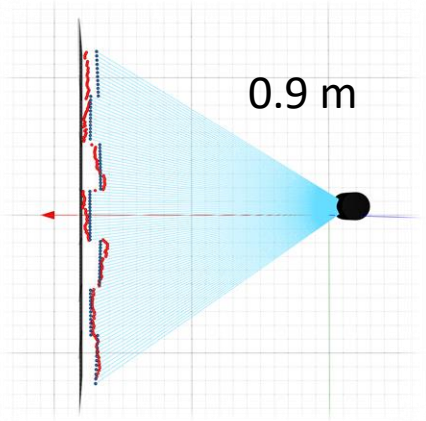
$$f(\mathbf{p}, \omega_o, \omega_i) = \frac{k}{\pi}$$

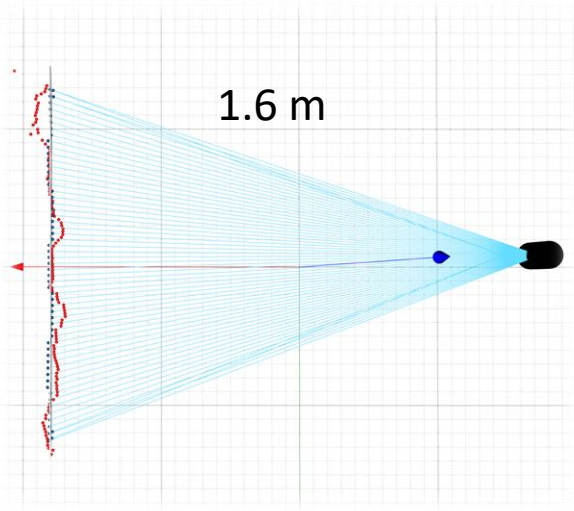
- Brightness/color has significant influence on measured distance
- Estimate this influence by fitting parabola to radiance <-> phase shift relationship:
  $\Delta\Phi' = \Delta\Phi - (\mathrm{aL}^2 + \mathrm{bL} + \mathrm{c})$ for $a, b, c \in \mathbb{R}$
- Assume white/black sections are Lambertian, need to estimate k_{white}, k_{black}

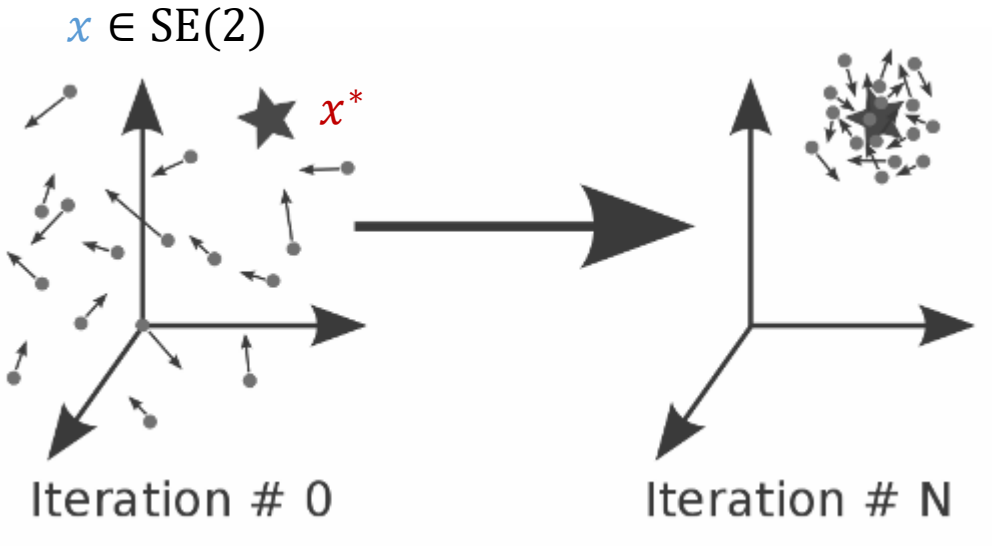
Calibrating APD & Estimate Surface Properties







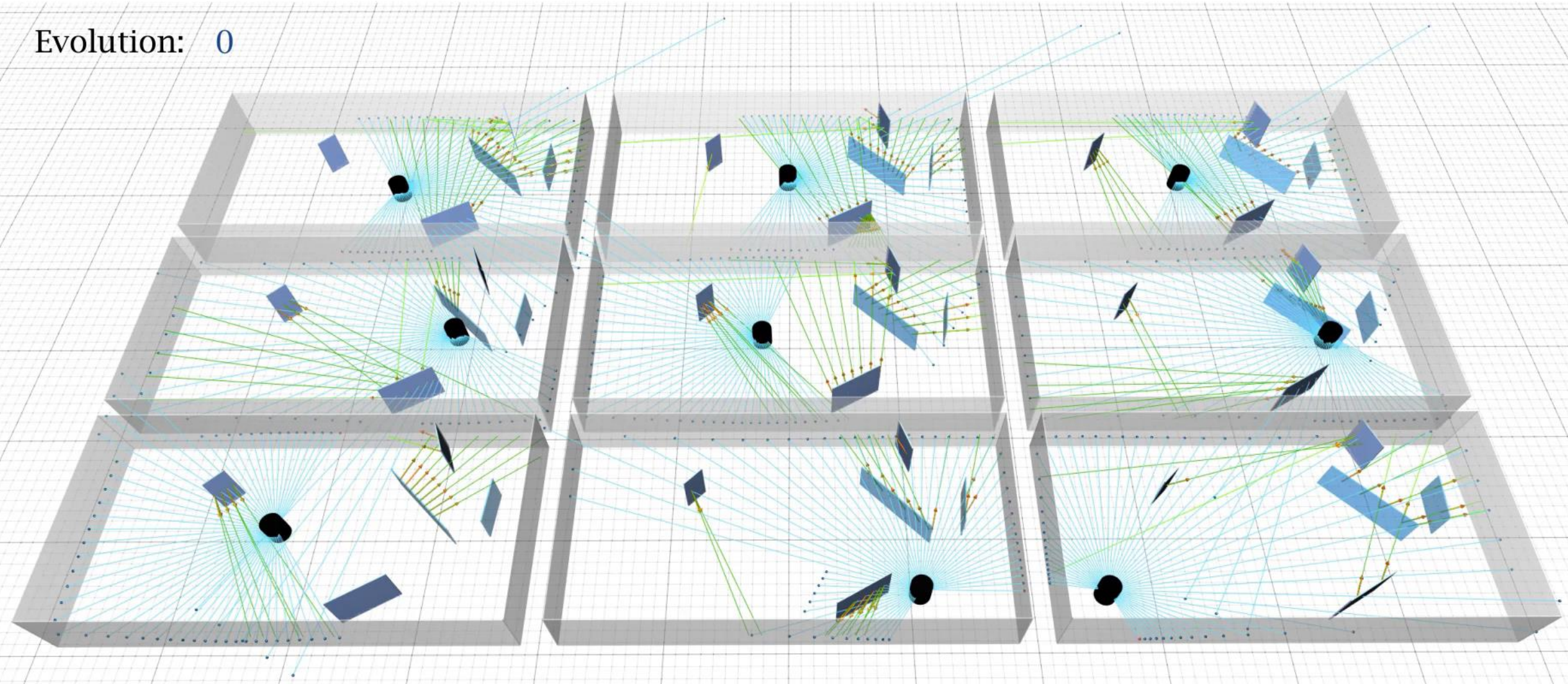




Particle Swarm Optimization

Localization in complex environment through
population-based optimization (gradient-free)

PaGMO (Parallel Global Multiobjective Optimizer)
Izzo et al. 2012



Particle Swarm Optimization: 20 generations, 9 islands à 10 individuals
Shown is the best individual of each island per evolution.

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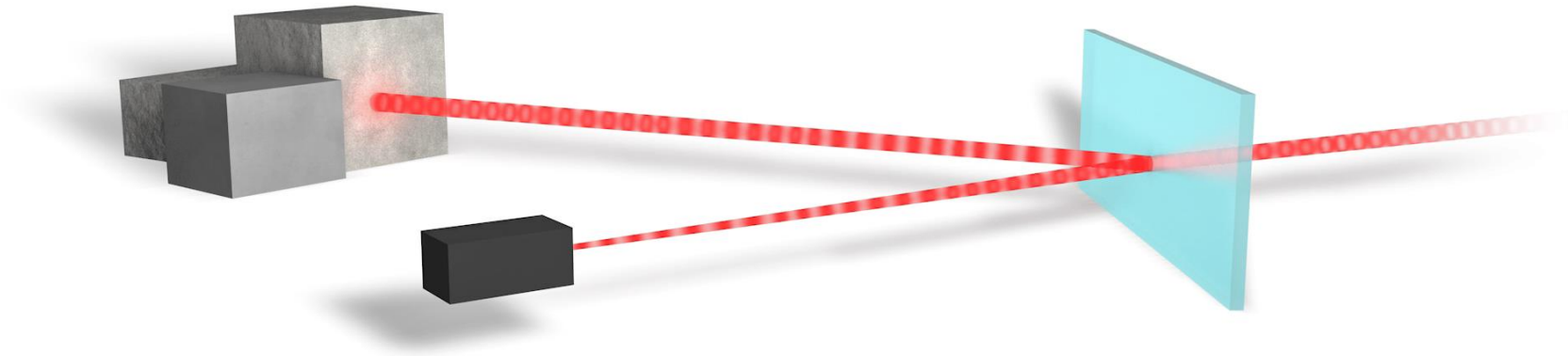

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