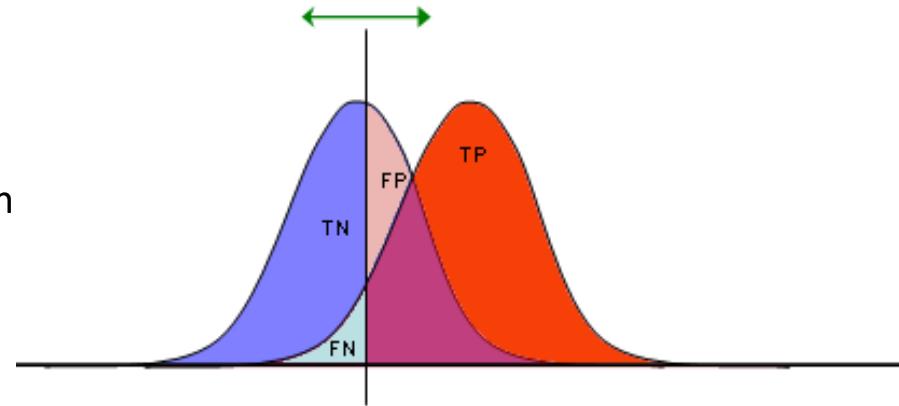
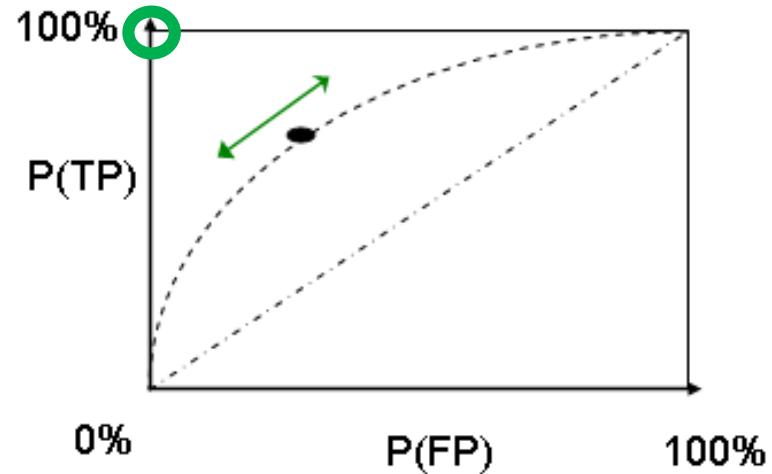
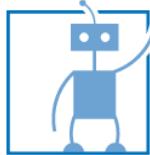


Autonomes Fahren SS 2019

AV Sensor-Sets

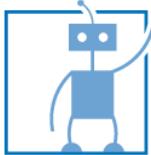




Robust Perception: Key issue for Avs ... and humans



https://en.wikipedia.org/wiki/The_dress

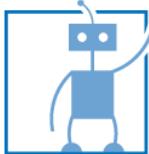


Autonomous Driving will change the world. A solution for many traffic problems.

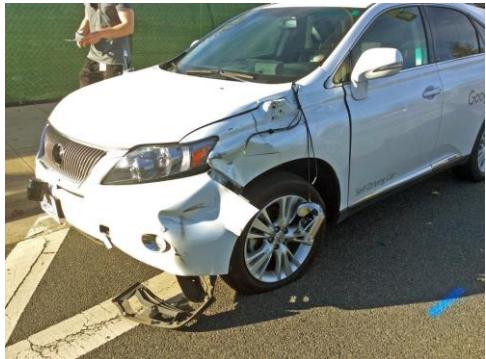


Images of Waymo, Tesla and Uber vehicles

Strong progress has been made since the first AV inventions.



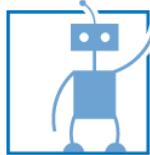
Autonomous Driving will change the world. A solution for many traffic problems.



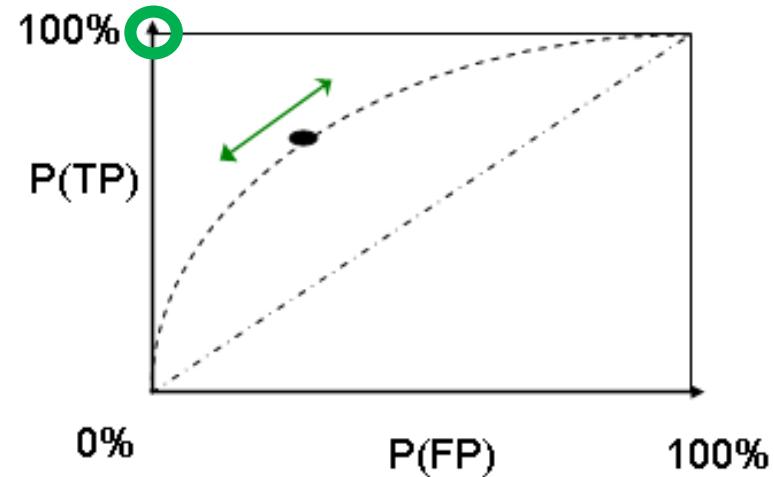
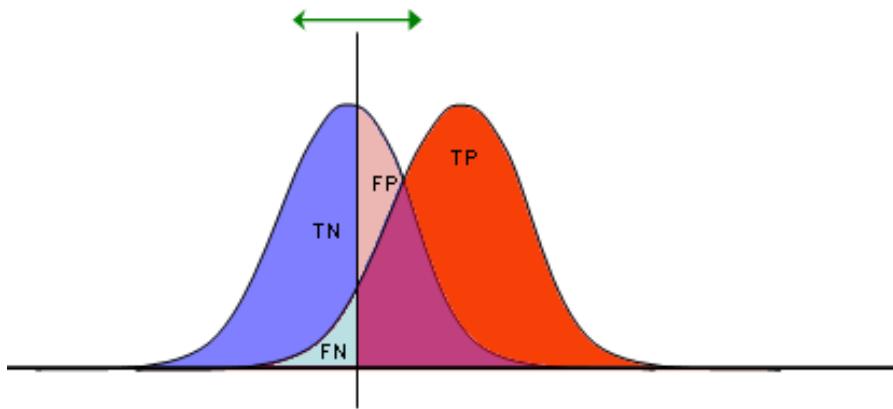
Images of Waymo, Tesla and Uber vehicles

However, many problems still remain.

The highest level of quality is required to achieve reliable autonomy.



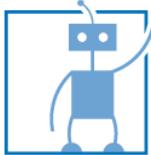
AV technology will never be 100% error-free. Redundancy and safety monitoring are mandatory.



Receiver Operating Characteristic curve (ROC) represents AV challenge in one image.

Top left promises 100% True Positive, 0% False Positive detection, which is wanted, but never reached.

→ Without runtime monitoring, AVs will not work.

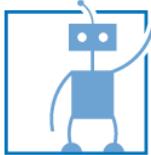


AV Sensor-Sets

- Automated cars require precise self-localization and localization of obstacles, lane markers, etc.
- Different sensors are available: Laser, Radar, Kamera, Ultraschall, GPS, Rain-sensors, thermal imaging...
- Which could you use and how are they different from each other?

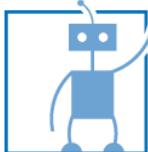


*derivative work: Altair78
(talk) Lexus-LS600h-
L_asia_spec.jpg: Tim Wang
CC BY-SA 2.0, Wiki



AV Sensor-Sets

- Sensor performance depends on the sensors, the signal propagation and the target properties
- This lecture will serve as an introduction to a variety of properties for sensors, targets and propagation, based on public literature
- Examples (lidar) will be used to highlight important aspects



Sensor Categorization

Active or passive Sensors:

- Sensors are often sorted into active and passive sensors

Passive Sensor:

A passive sensor is an instrument designed to receive and measure emissions or reflections.

...Camera, electric field sensing, acceleration measurement...

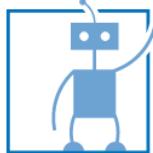
Active Sensor:

An active sensor is an instrument used for measuring signals reflected by the sensor that were reflected, refracted or scattered.

...Radar, Laser, Ultrasound, GPS...

... smart camera with car light?



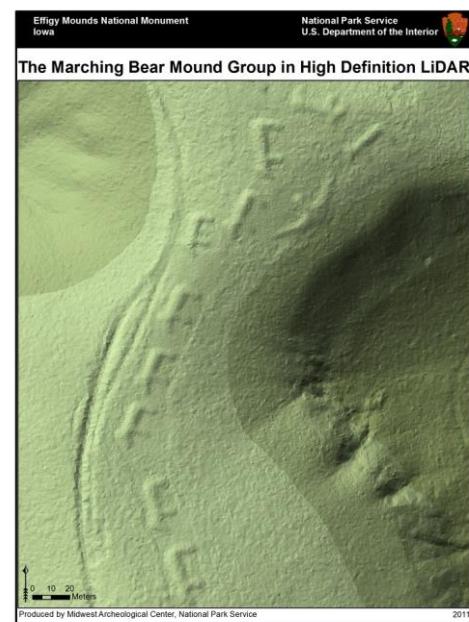
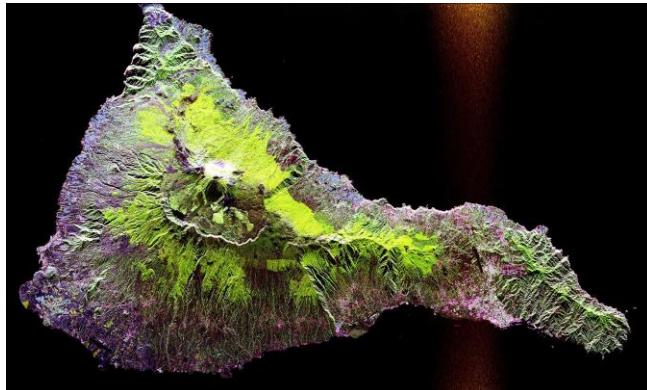


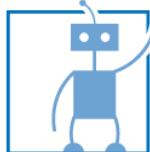
AV Sensor-Sets

Imaging Sensor?

Does the sensor detect and convey the information to form an image? ...Camera...

...Lidar? ...Radar? ...Ultrasound?



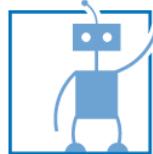


AV Sensor-Sets

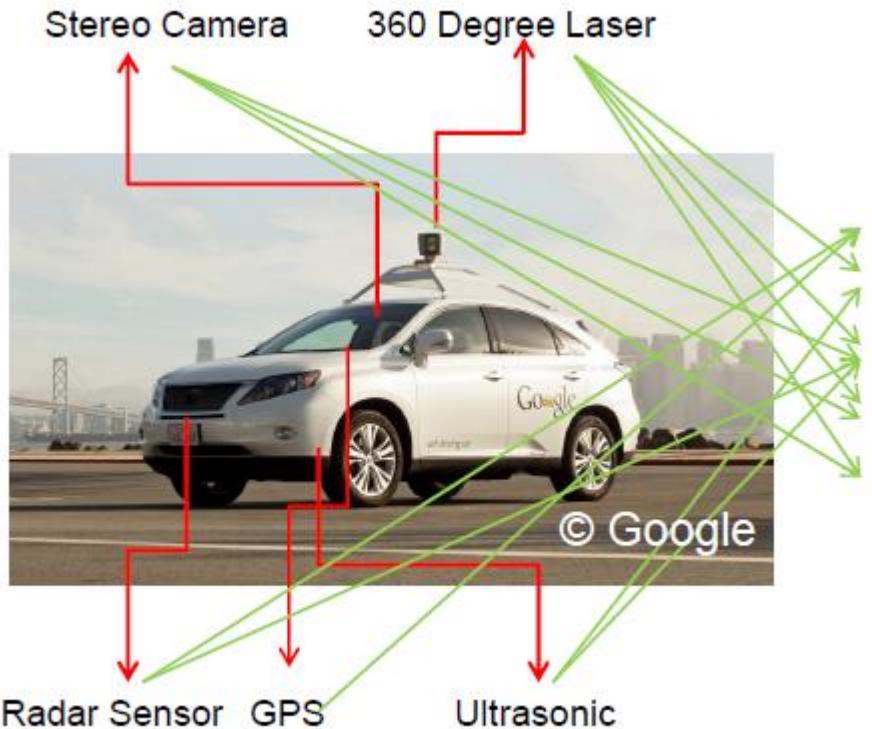
K. Fuerstenberg et al.: "Pedestrian Recognition and Tracking of Vehicles using a vehicle based Multilayer Laserscanner", Intelligent Vehicle Symposium, IEEE (Volume:1), 2002

Segment				
Video image				
Distance	10 m	18 m	42 m	79 m

Example for sensor challenges: Limited angular resolution. Certainty of object type identification decreases with distance. Small objects can be missed between LIDAR beams.

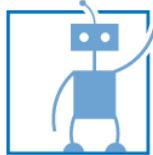


AV Sensor-Sets



Information Extraction-----Useful Features

- ✓ **Location** – “It’s in front of me”
- ✓ **Range** – “It’s really close”
- ✓ **Range rate** – “It’s coming closer”
- ✓ **Size** – “It’s really big”
- ✓ **Classification** – “It’s a semi truck”



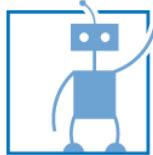
AV Sensor-Sets

- Often thresholds are used to differentiate between detection and none-detection.
- Search for peaks in a detected signal to separate detections from noise
- Note: None-adaptive sensing thresholds regularly cause issues
 - Known accidents due to mismatching stationary vs non-stationary targets
 - Known issues due to false height classification (see curb stone video)

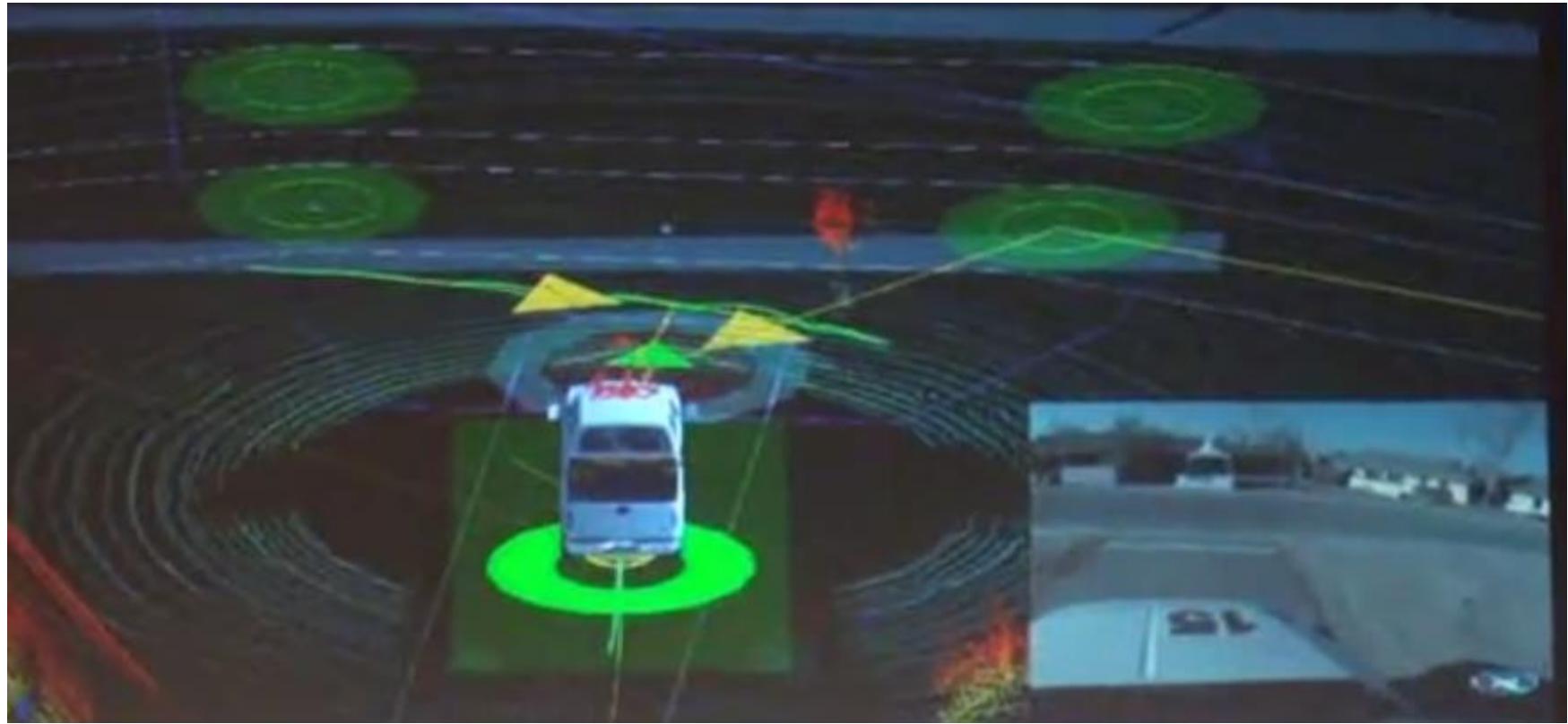
VELODYNE LIDAR IN GRAND CHALLENGE

**FILMED AT NIST
FEBRUARY 13, 2008**

www.SOCIETYOFROBOTS.COM

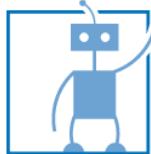


Failed threshold classification

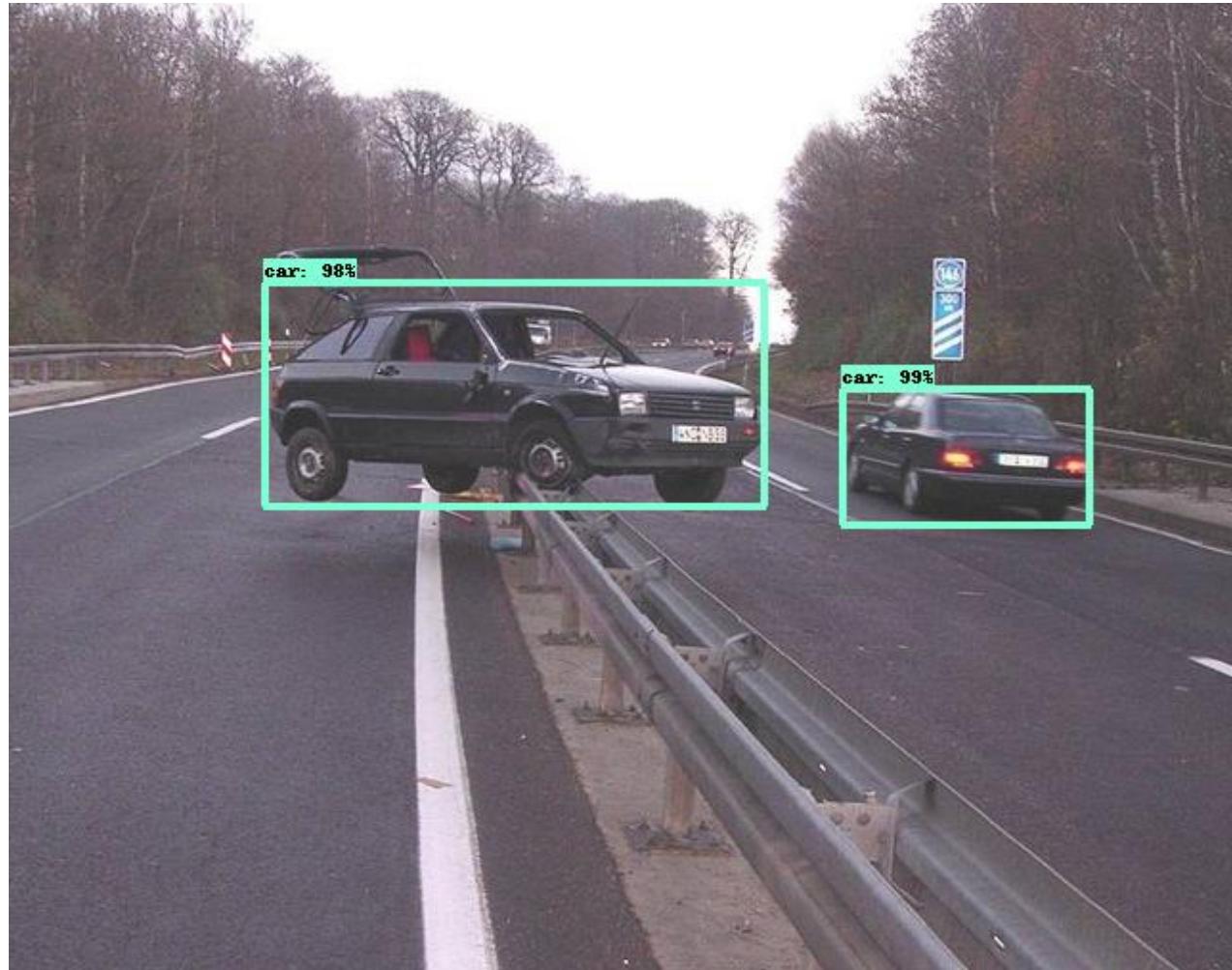


“Rain gutter mistaken for curb stone”

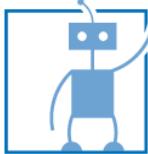
From „Velodyne Lidar in Grand Challenge”, youtube 2008



Assumptions are easily violated



Vehicles can occur in uncommon positions and orientations, but still need to get detected.



Sensor Datasheets

ibeo LUX 8L (Prototype) – Technical facts...

automotive

Laser

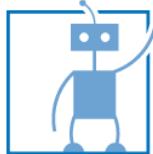
- Laser class: Class 1, Eye safe
- Wave length: 905 nm
- Technology: Time of flight
Output of distance and echo pulse width
- Range: 200 m (average target, 0 deg view direction)

Measurement

- Horizontal field of view: 110 deg (50 deg to -60 deg)
- Vertical field of view: 6.4 deg (0 deg view direction)
- Multi layer: 8 layers (2 pairs of 4 layers)
- Multi echo: Up to 3 distance measurements per laser pulse
(allow measurements through atmospheric clutter like rain and dust)
- Data update rate: 6.25/ 12.5/ 25 Hz, valid for both alternate scanning pairs of layers
- Operating temperature range: -40 to 85 deg C/ -40 to 185 deg F
- Accuracy (distance independent): 10 cm/ 3.9 in
- Angular resolution: H orizontal: up to 0.125 deg
- Vertical: 0.8 deg
- Distance resolution: cm/ 1.57 in

Software (embedded)

- Raw data pre processing: All measurements will be classified and tagged as valid/ ground/ clutter (available @ 6.25 Hz only)
- Real time object tracking: Object properties: position, size, speed (available @ 6.25 Hz only)
- Ego motion compensation: Vehicle ego motion data via CAN required



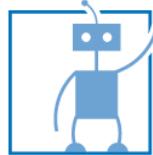
Sensor Datasheets

Mechanical/ Electrical

- Power supply: 9 to 27 V
- Power consumption: 8 W (average), < 10 W (max)
- Dimensions (W x D x H): 164.5 x 93.2 x 88 mm³/ 6.47 x 3.67 x 3.46 in³
- Protection class: IP 69 K (IEC 60529, DIN 40050-9
(using protected plug connectors))
IP 68 (IEC 60529 (2 m, 24 h))

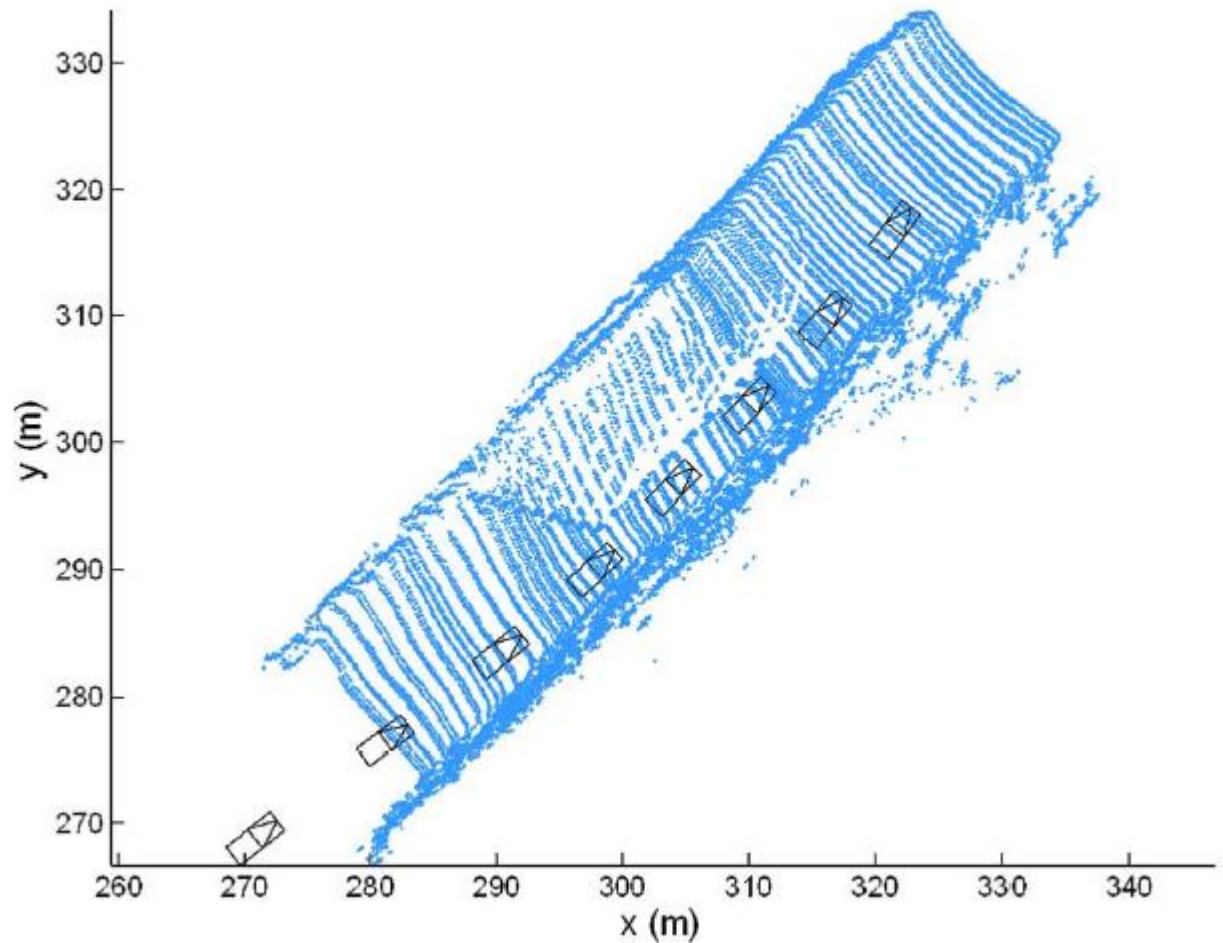
Data I/O

- 100 MBit Ethernet:
Output: Raw- and object data
Input: Configuration/ time sync via NTP server
- CAN:
Output: Object data
Input: Ego motion data
- RS232:
Sync

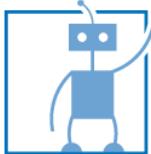


Sensor Artifacts

Lines typical sign of lidar image



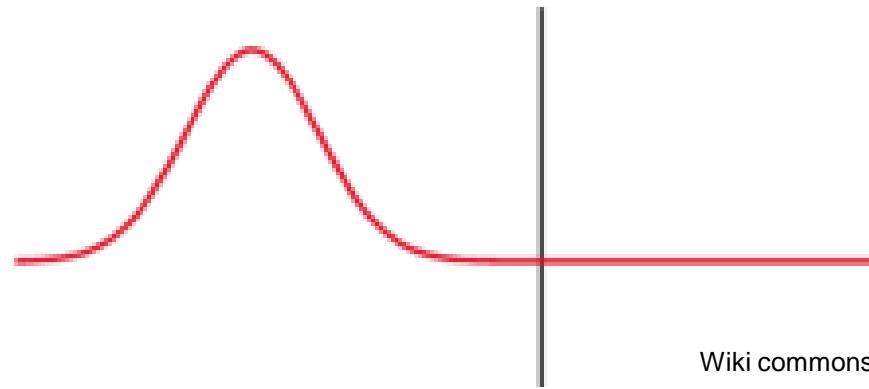
Jaehyun Han, Dongchul Kim, Minchae Lee, and Myoungho Sunwoo,
„Enhanced Road Boundary and Obstacle Detection
Using a Downward-Looking LIDAR Sensor”, IEEE TRANSACTIONS ON
VEHICULAR TECHNOLOGY, VOL. 61, NO. 3, MARCH 2012



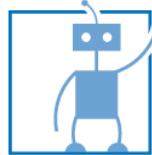
Introduction to sensor physics

Signal propagation:

- Refraction
- Reflection
- Scattering
- Absorption
- Transmission
- Diffraction
- Attenuation



Wiki commons



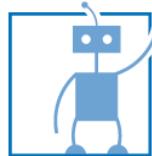
Introduction to sensor physics

- Refraction: wave crossing from one medium into another, experiencing a change in direction, while continuing to travel through the new medium.

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}.$$

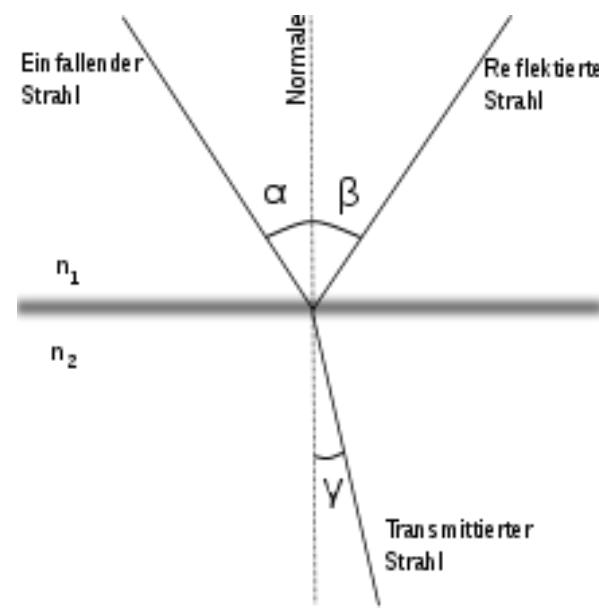
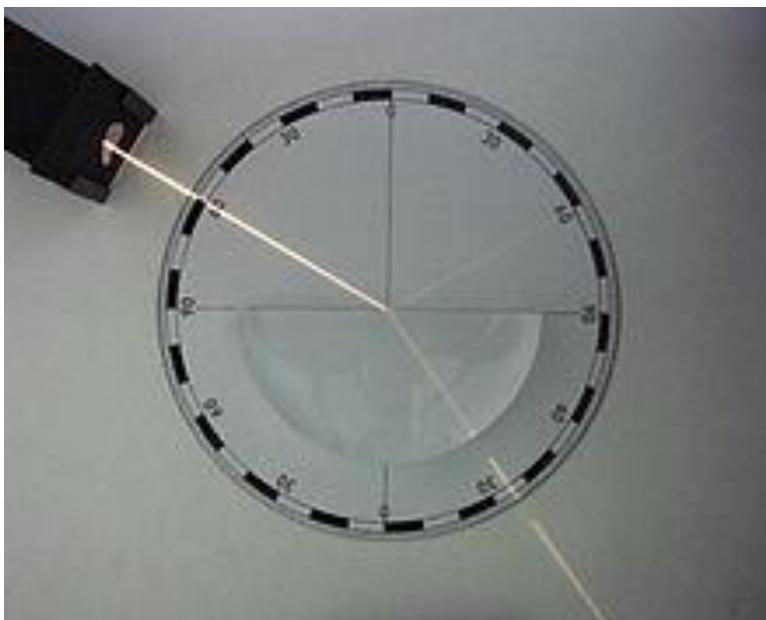


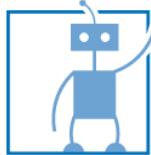
<https://commons.wikimedia.org>



Introduction to sensor physics

- Reflection: Change in direction of a wave, between two different media, with outgoing angle equal to the incident angle on the other side of the surfaces normal.

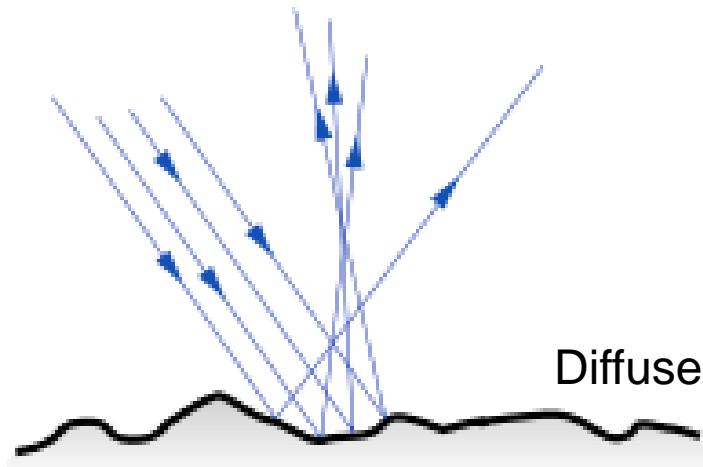




Introduction to sensor physics

Diffuse or specular reflection?

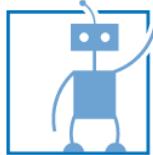
Depending on surface roughness
and signal wave length



Specular

Diffuse

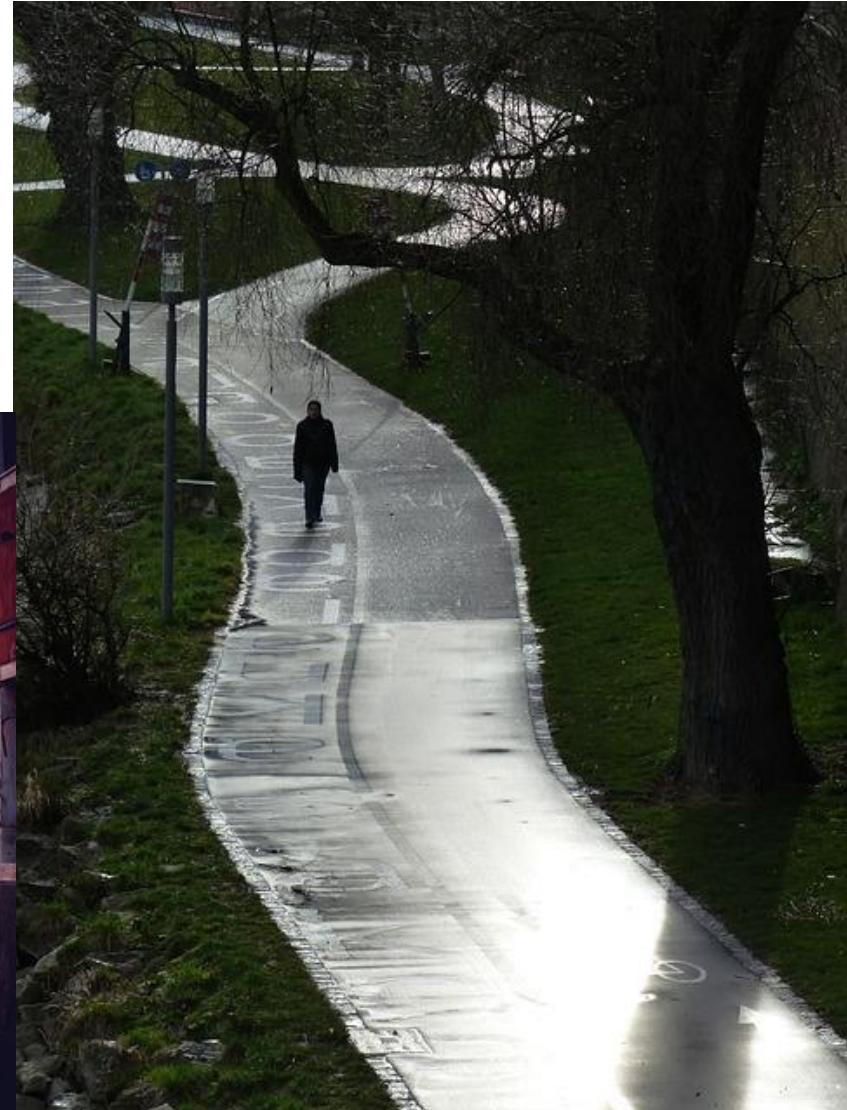


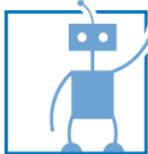


Introduction to sensor physics

Actual reflections depend on specific scenario.

Comparison of dry and wet street





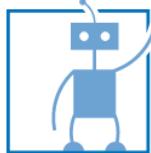
Introduction to sensor physics

- Scattering: radiation such as light being forced to deviate from straight path due to localized non-uniformity in propagation medium

For example because of droplets or surface roughness (scattering centers)

Zodiacal light: glow originating from scattering of sunlight due to dust located between planets





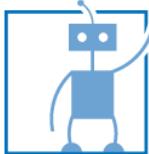
Introduction to sensor physics

- Absorption: Loss of energy of propagating wave while traveling through a medium

e.g. conversion into thermal energy in damping material (Ultrasound: foam; Light: carbon black) depends on depth, absorption coefficient...

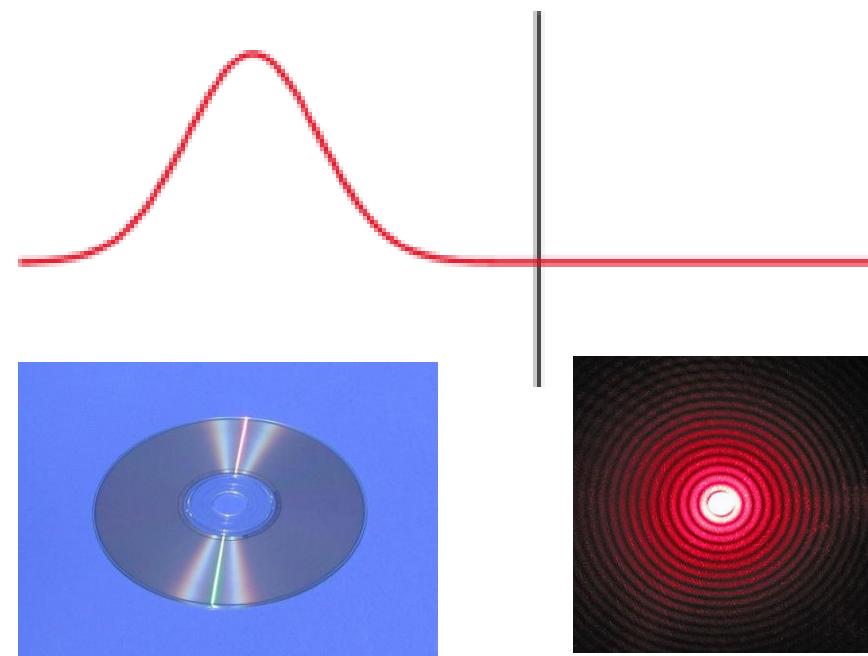


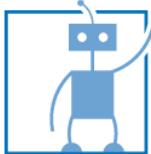
Carbon black, by FK2051 wiki commons



Introduction to sensor physics

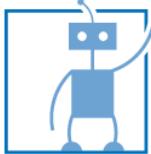
- Attenuation describes all losses in signal intensity, including scattering and absorption.
- Transmission: Propagating wave crosses from one medium into another and is transmitted through the medium
- Diffraction: Change of direction and intensities of waves, passing an obstacle or an aperture with size approximately the wavelength of the waves.





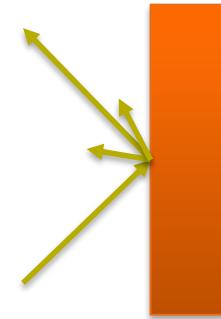
AV Sensor-Set Design Questions

- What do you want to measure and why?
- How do you measure it and why this way? Are there alternatives?
- How will you know if the measurement will be or was successful (metrics)? How accurate are your measurements?
- Do you have additional sensors for redundancy?
- Documentation of reasoning, simulations, analysis and measurements
- Validate and verify (Do you have to correct requirements for the sensors? Do the sensors work as they are supposed to?)
- Does your approach fulfill norms for certification?



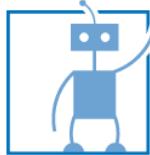
AV Sensor-Set Detection Range

Detection Range?

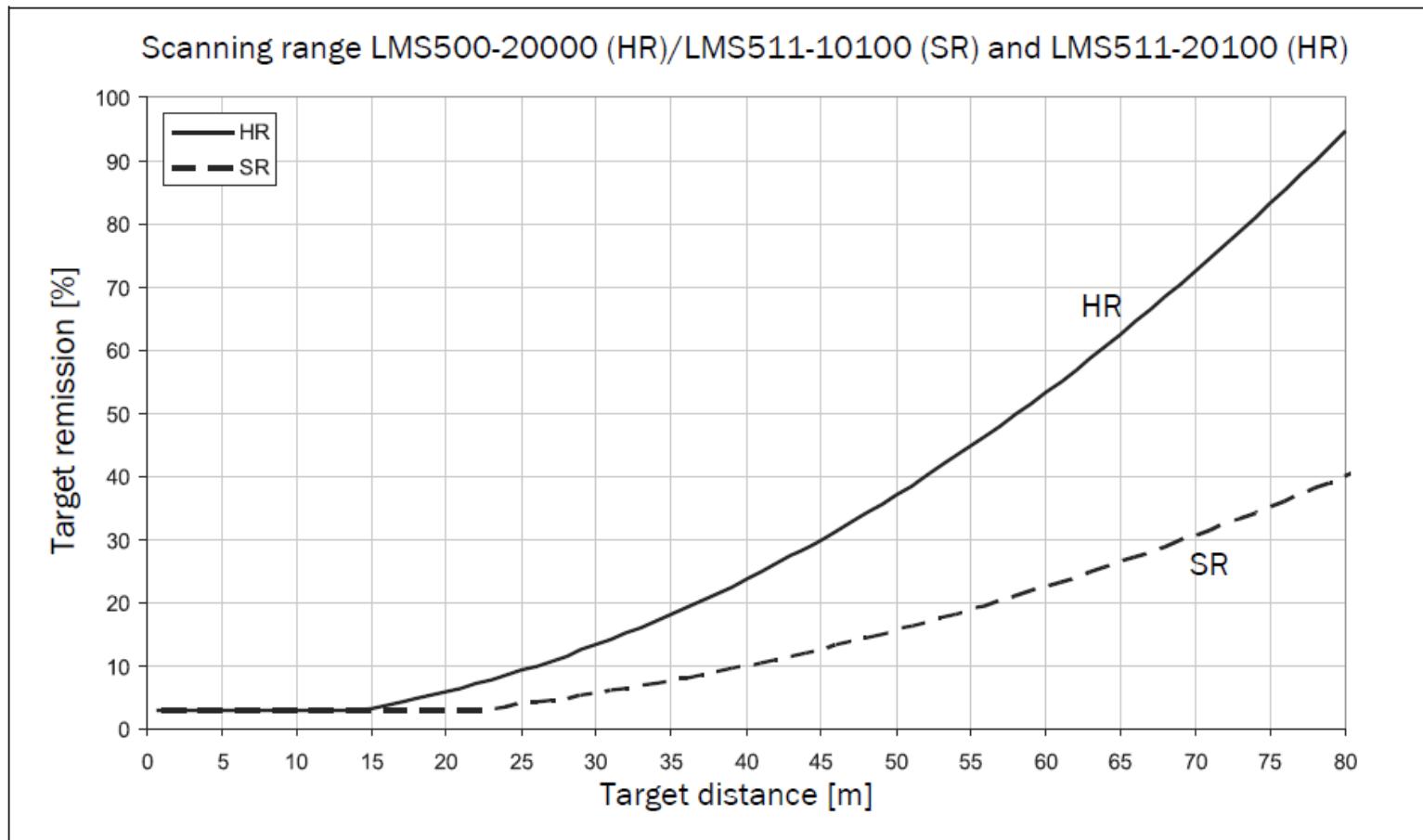


..90% Remission? Range can depend on target and scenario.

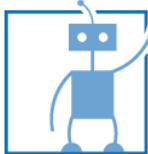
Radar	SMS UMRR (type 29 antenna model)	SMS UMRR (type 30 antenna model)	SMS UMRR (type 31 antenna model)	Delphi ESR Long Range	Delphi ESR Middle Range	Bosch Mid-Range Radar	Bosch Long- Range Radar (LRR3)	ARS 3XX Radar (Continental)	SRR 2XX Radar (Continental)
Mnimum and maximum range	1 to 160 m	1 to 90 m	1 to 45 m	1 to 174 m	1 to 60 m	1 to 160 m (front); 1 to 100 m (rear)	0,5 to 250 m	0,25 to 200 m	1 to 50 m
Lidar	ibeo LUX	ibeo LUX HD	ibeo LUX 8L	ibeo miniL LUX	SRL 1 Lidar Continental	UTM-30LX/EW Hokuyo	UXM- 30LX- EW Hokuyo	UXM-30LXH-EWA Hokuyo	LD-MRS Series Sick
Distance range	200 m (average)	90 m (@ 90% remission)	200 m	40 m	10.0 m (13.5 m expanded distance)	30 m	30 m	0.1 to 80m @ 90% remission	0.02-5.6 m



AV Sensor-Set Detection Range



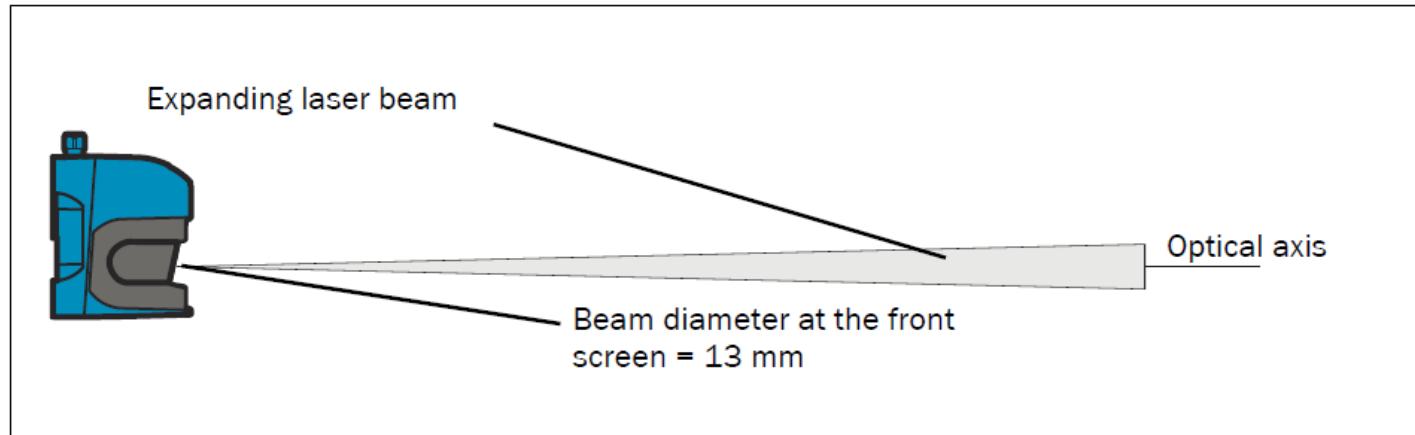
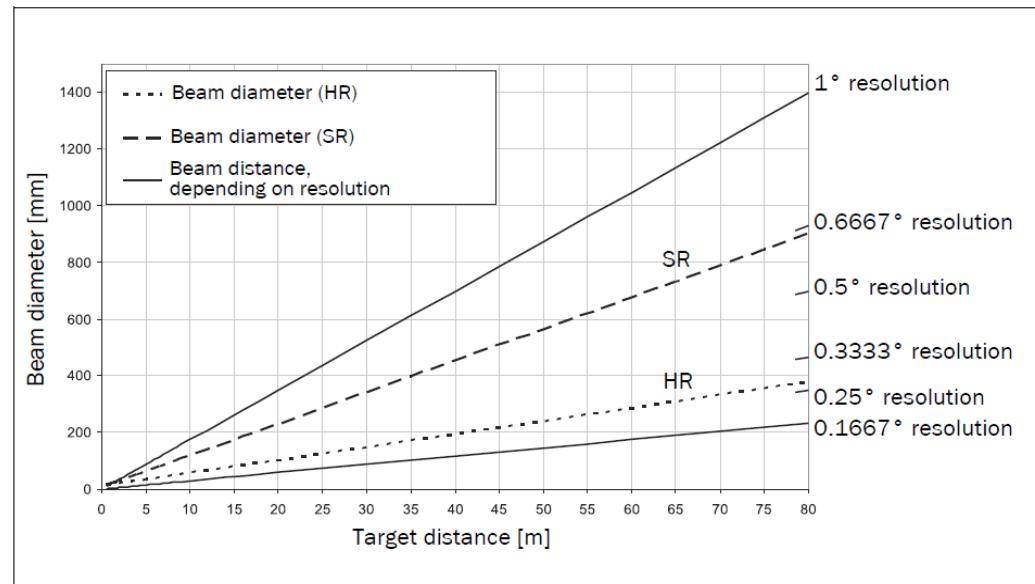
Example of how detection range depends on target remission for a LMS5xx Laser Measurement Sensors – Sick, 2015



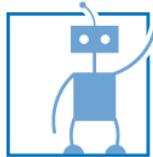
AV Sensor-Set Detection Range

Errors often result from false assumption.

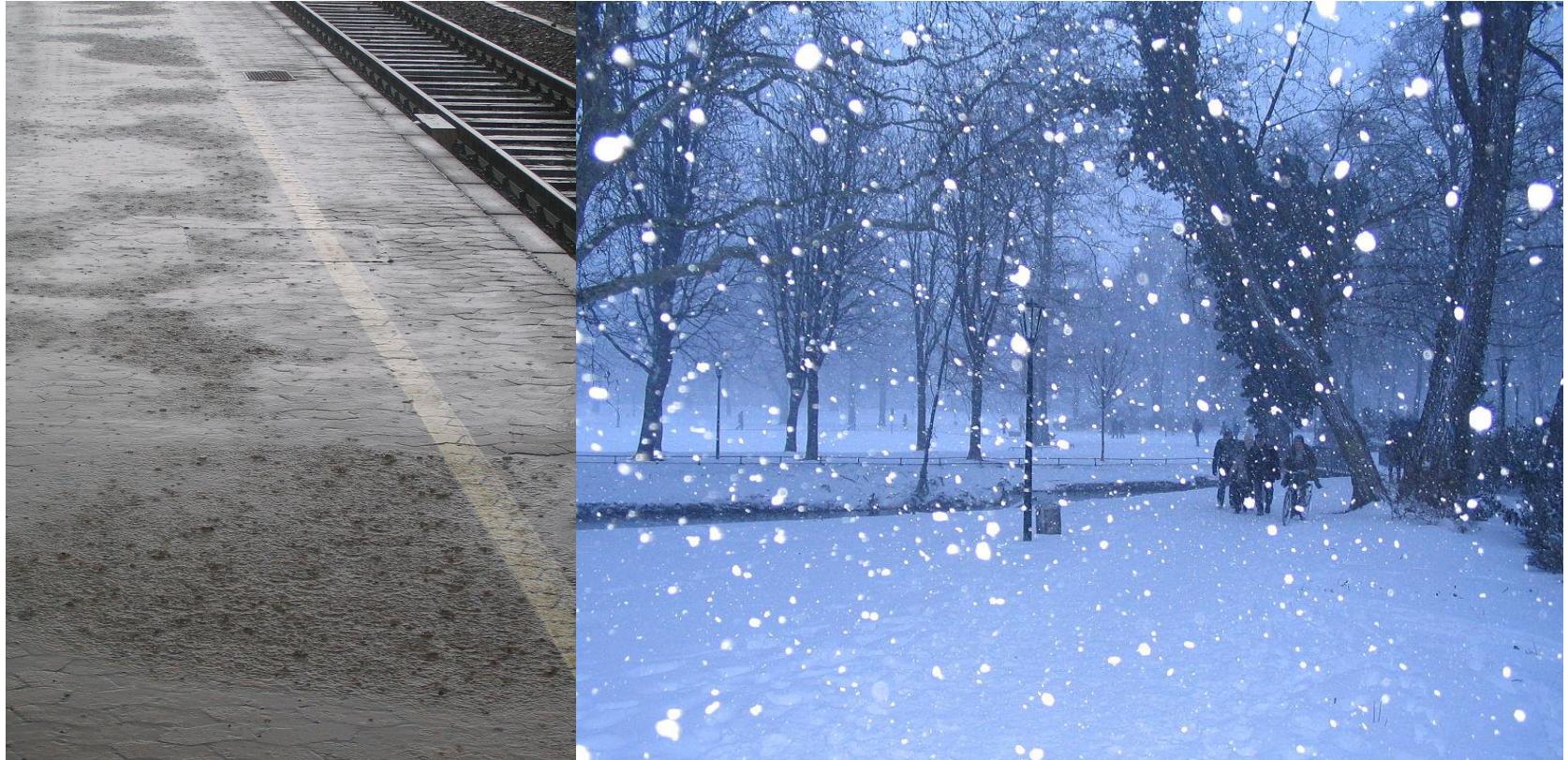
Example: Falsely assuming that a LIDAR beam is a “dot”.



LMS5xx Laser Measurement Sensors –
Sick, 2015

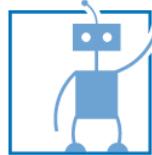


AV Sensor-Set Weather Impact



Reinhard Dietrich, CC BY-SA 3.0





AV Sensor-Set Lidar Multi-Echo Technology

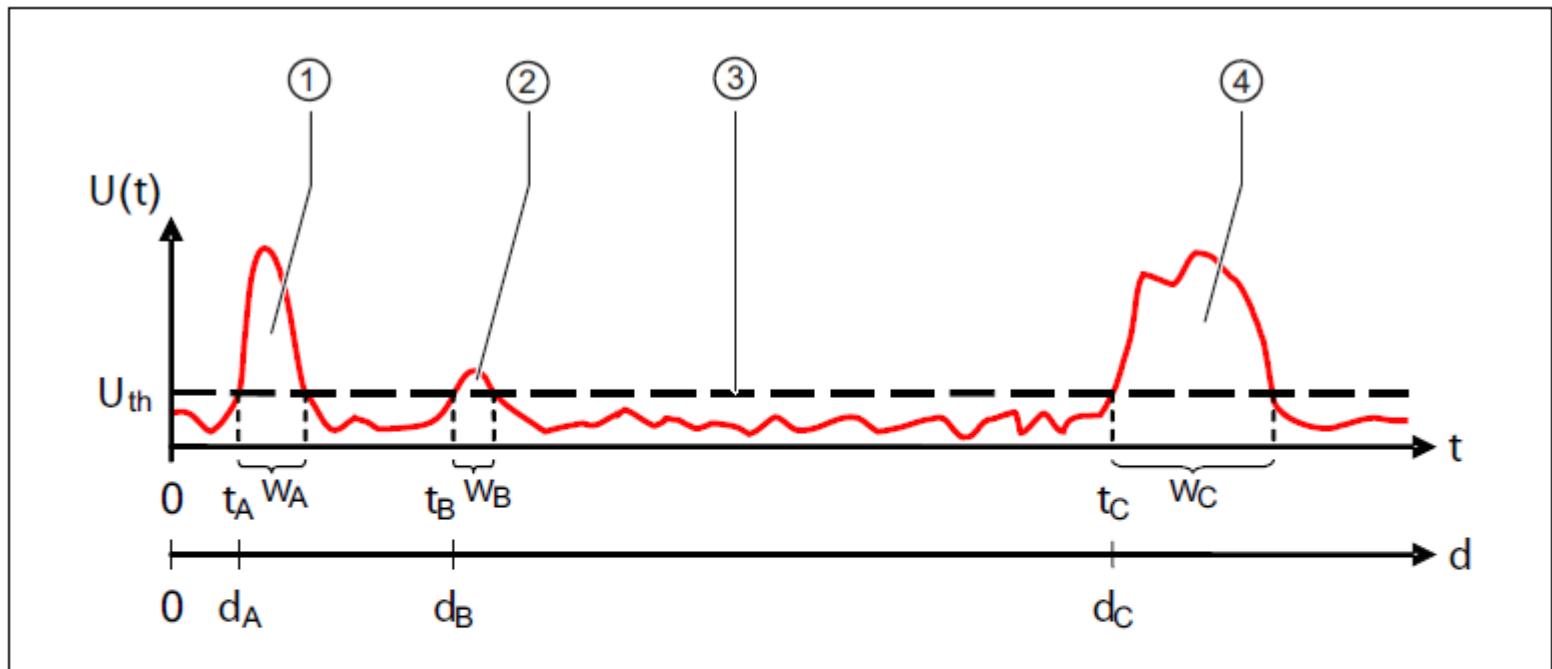
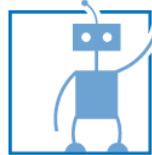


Abb. 3-3: Multi-Echo-Fähigkeit

Legende:

- ① Beispiel Echo Glasscheibe
- ② Beispiel Echo Regentropfen
- ③ Schwellenspannung
- ④ Beispiel Echo Gegenstand

- 1) Glas
- 2) Rain drop
- 3) Noise
- 4) Vehicle

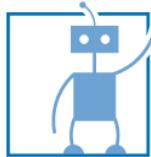


AV Sensor-Set Lidar Multi-Echo Technology



Characteristics	Riegl laser LD-3100HS	SICK laser LMS-220
Type	telemeter	laser stripe
Wavelength	900 ± 100 nm	920 nm
Beam divergence	3 mrad max.	7 mrad
Information recorded	Distance (12 bits) Energy returned (8 bits) Temperature	Distance (13 bits)
Theoretical range	50 to 150 m	50 m
Accuracy (mean value)	± 20 mm	± 20 mm in single scan mode
Operation Temperature	$-30..+50^\circ\text{C}$	$-30..+70^\circ\text{C}$

Preliminary Results on the use of
Stereo, Color Cameras
and Laser Sensors in
Antarctica
Nicolas Vandapel, Stewart
J. Moorehead, William
Whittaker, 2000



AV Sensor-Set Lidar Multi-Echo Technology

Target at 11m, moderate snow, increased standard deviation

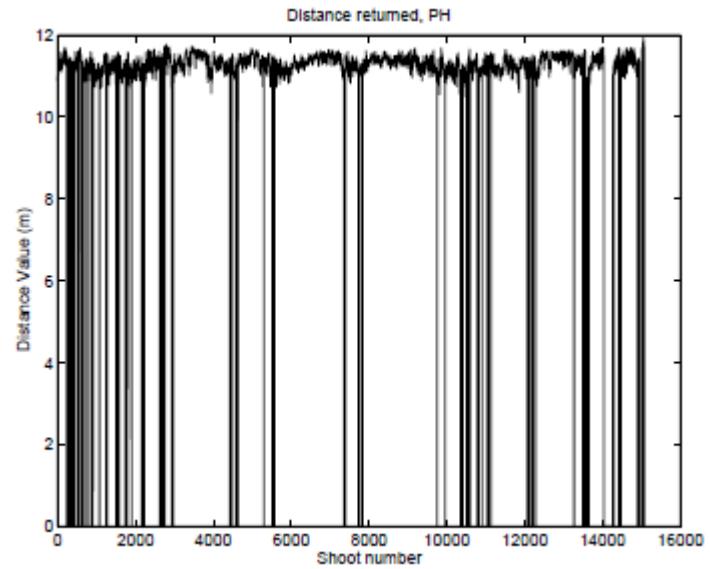
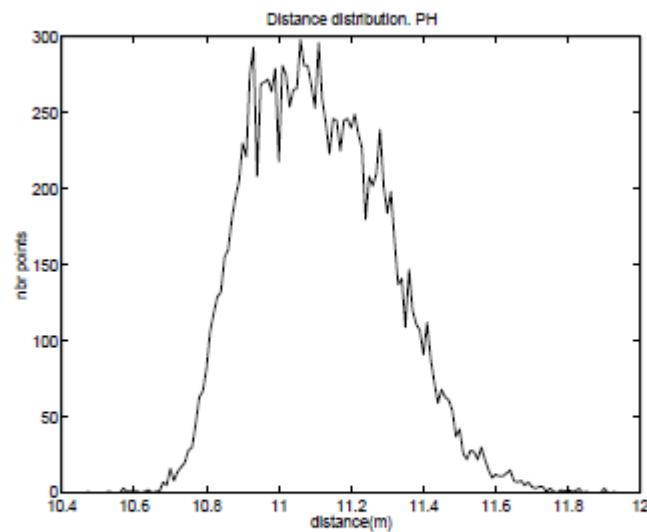
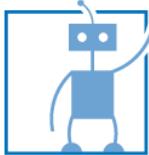


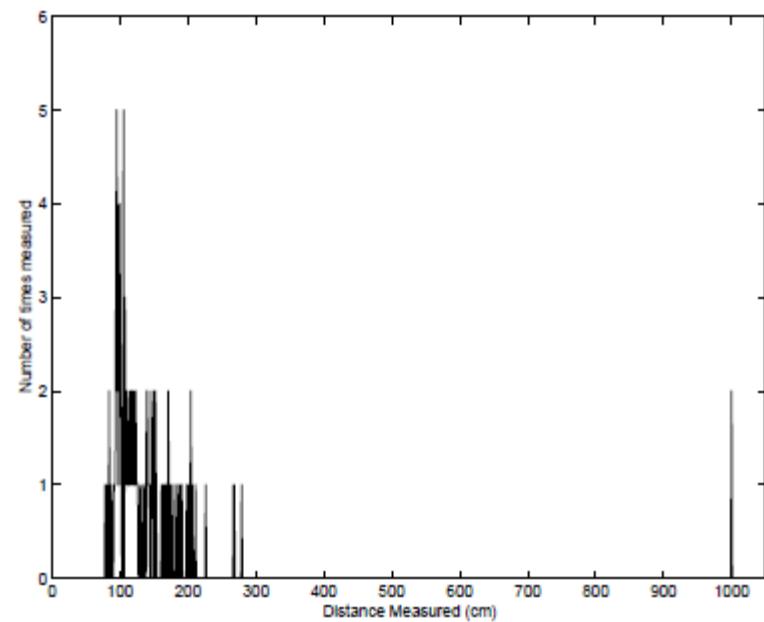
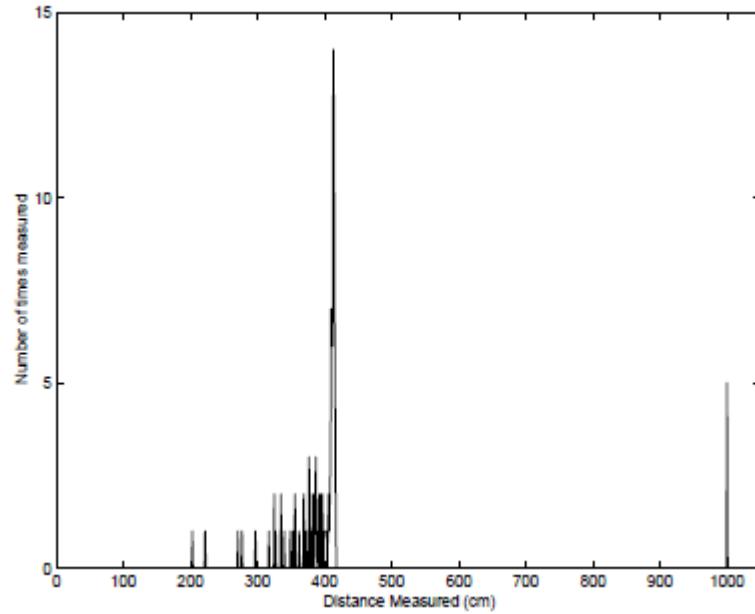
Figure 11. Distance Distribution

Preliminary Results on the use of
Stereo, Color Cameras and Laser
Sensors in Antarctica
Nicolas Vandapel, Stewart J.
Moorehead, William Whittaker, 2000

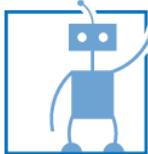


AV Sensor-Set Lidar Multi-Echo Technology

Moderate(left) and heavy snow(right), target at 4m



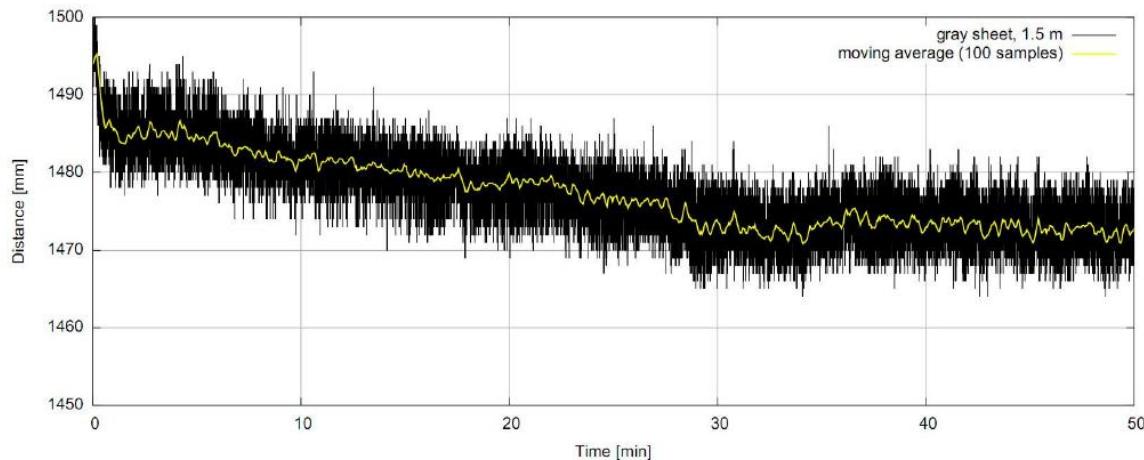
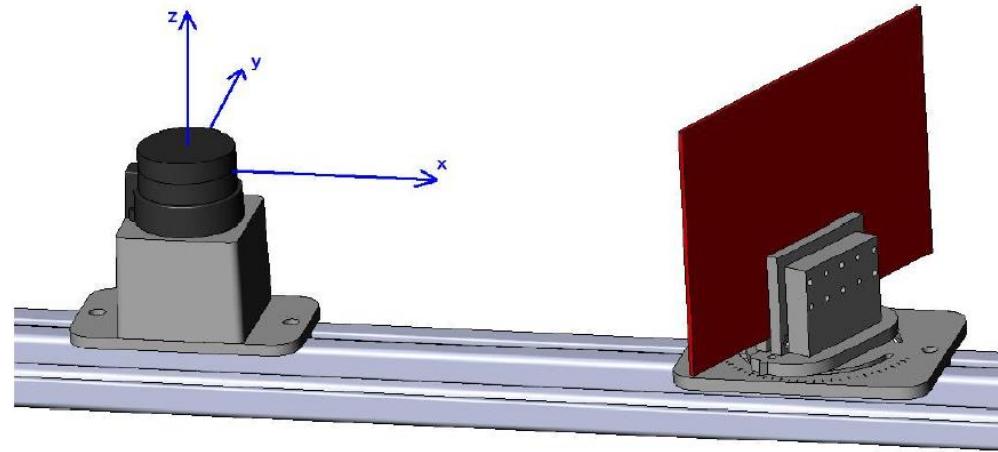
Preliminary Results on the use of
Stereo, Color Cameras and Laser
Sensors in Antarctica
Nicolas Vandapel, Stewart J.
Moorehead, William Whittaker, 2000



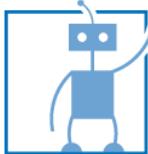
Exemplary scenario sensor performance impacts

Measured
Distance
(Lidar):

Measured distance
over time
(heat dissipation
of the sensor)



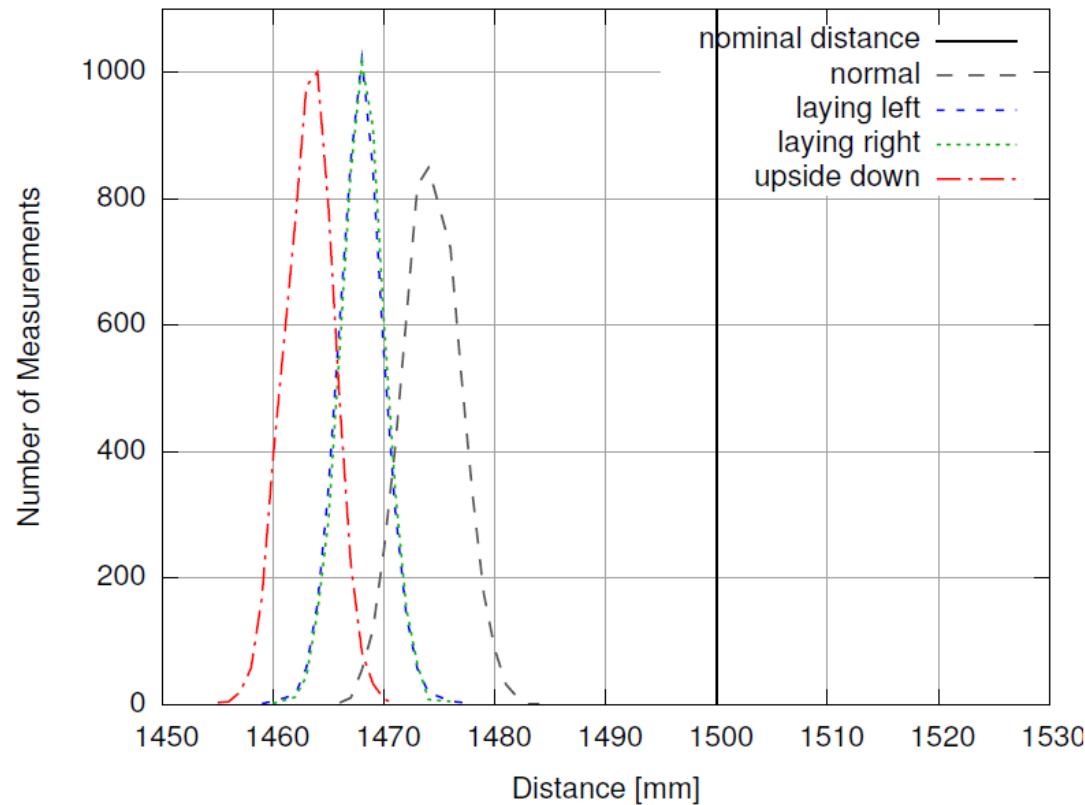
Laurent Kneip, Fabien Tache, Gilles Caprari, and Roland Siegwart,
*"Characterization of the compact Hokuyo URG-04LX 2D laser range
Scanner"*, IEEE International Conference on Robotics and Automation, 2009



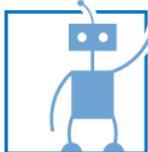
Exemplary scenario sensor performance impacts

Measured Distance (Lidar):

Measured distance
and sensor
orientation?



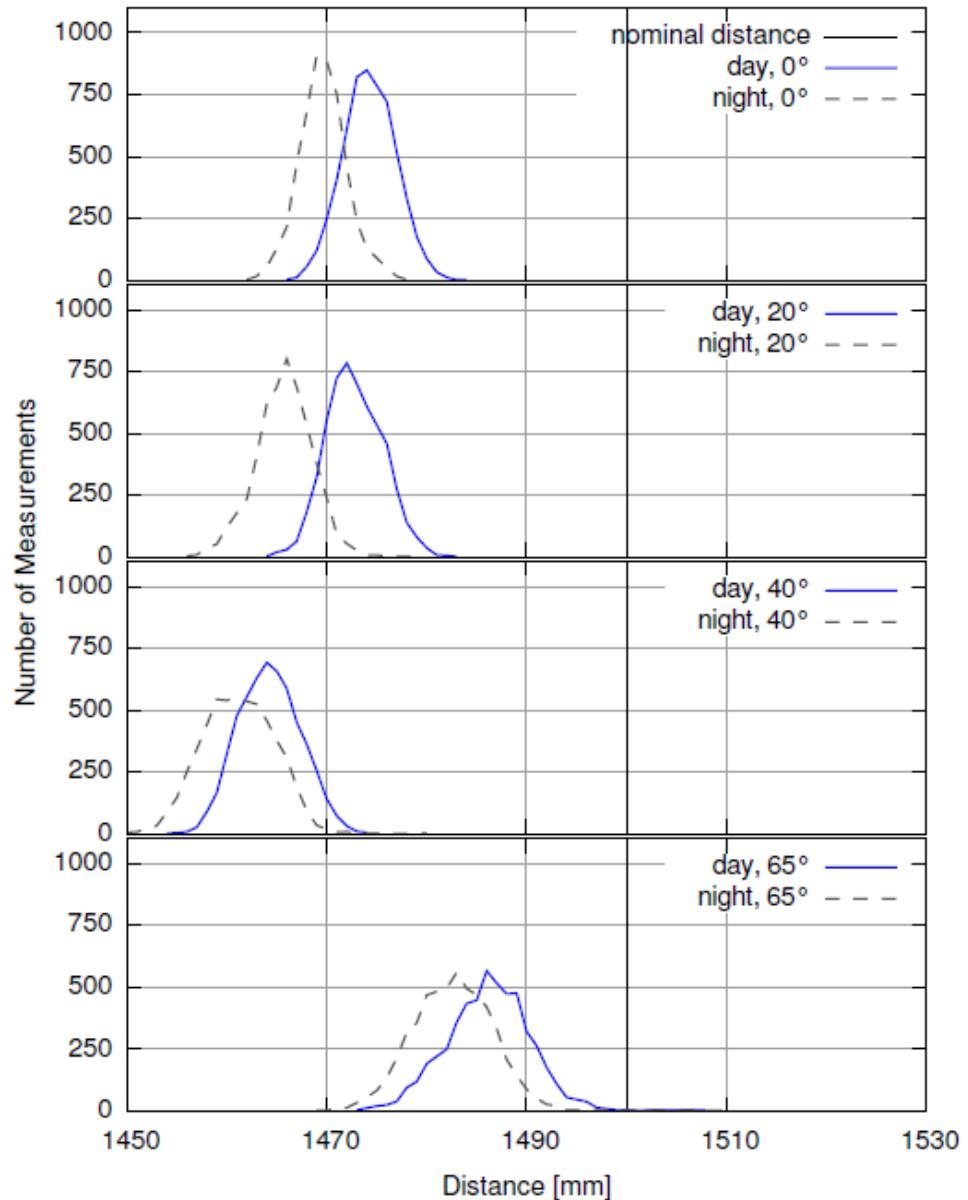
Laurent Kneip, Fabien Tache, Gilles Caprari, and Roland Siegwart,
*"Characterization of the compact Hokuyo URG-04LX 2D laser range
Scanner"*, IEEE International Conference on Robotics and Automation, 2009



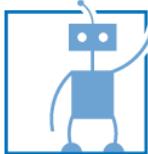
Exemplary scenario

Measured Distance (Lidar):

Measured distance,
day or night?



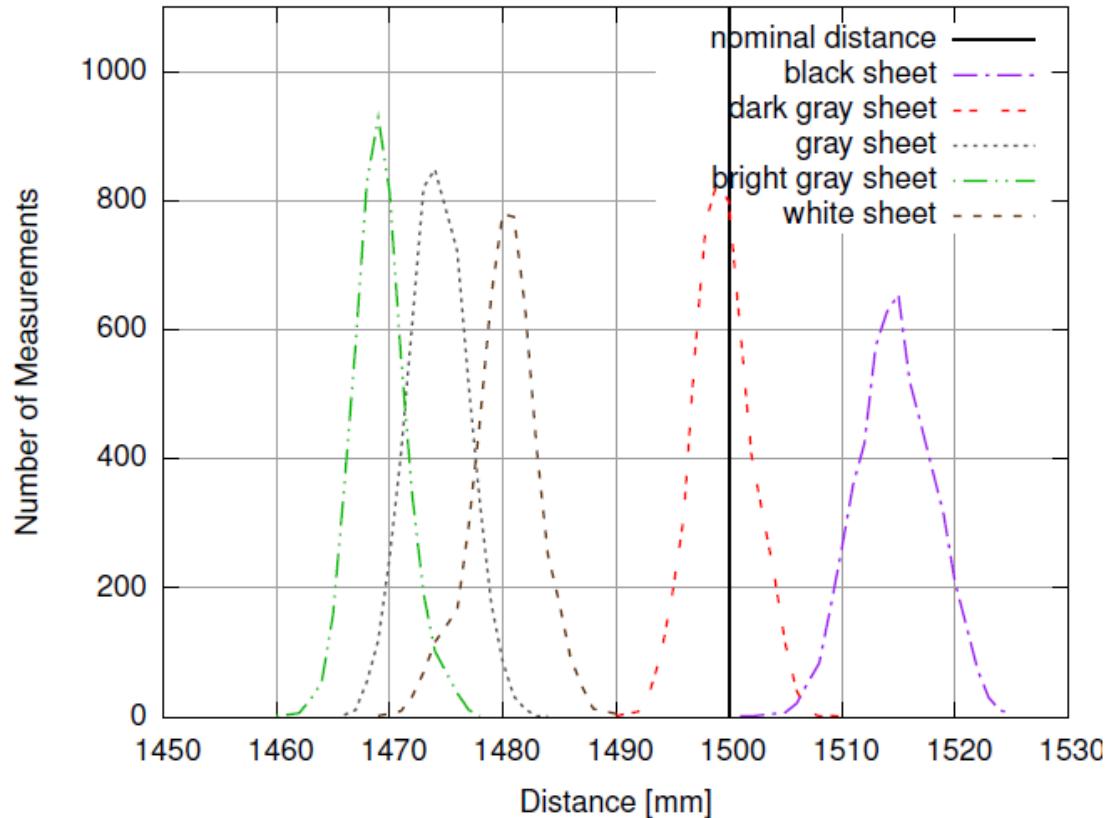
Laurent Kneip, Fabien Tache, Gilles Caprari, and Roland Siegwart,
*"Characterization of the compact Hokuyo URG-04LX 2D laser range
Scanner"*, IEEE International Conference on Robotics and Automation, 2009

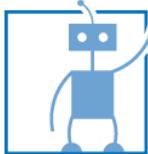


Exemplary scenario sensor performance impacts

Measured Distance (Lidar):

Measured distance
and surface
brightness
or color?

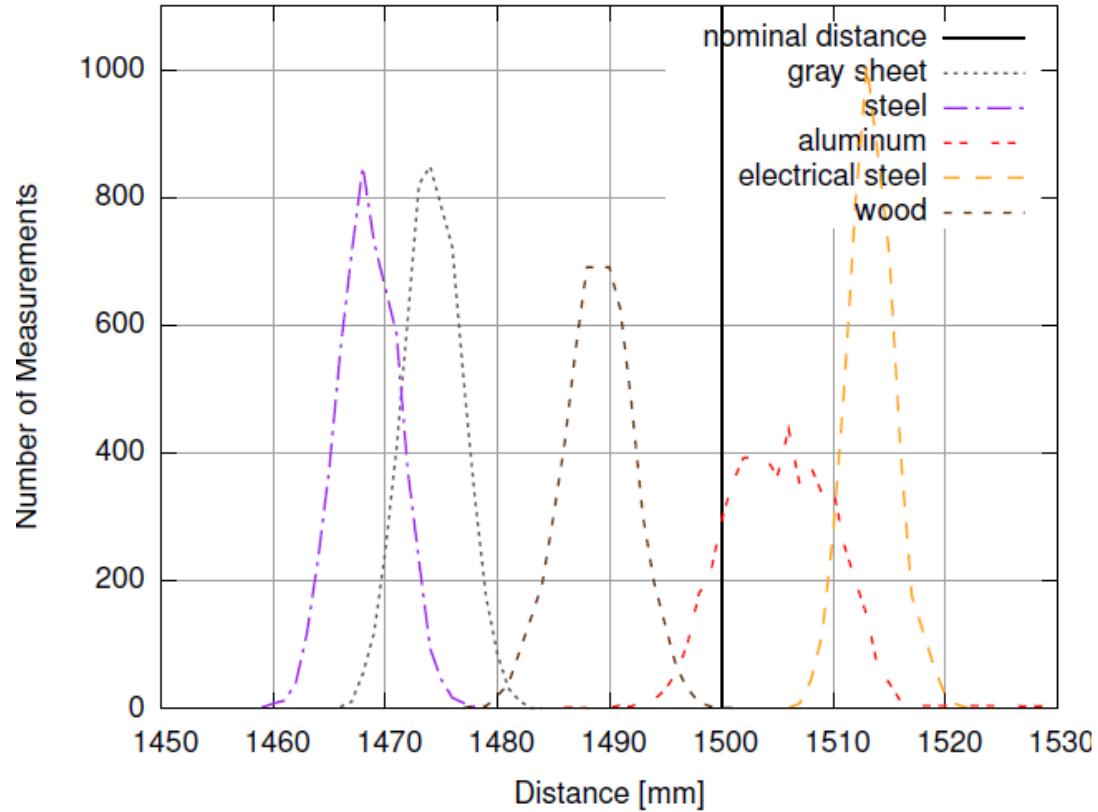


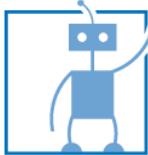


Exemplary scenario sensor performance impacts

Measured Distance (Lidar):

Measured distance
and target material?

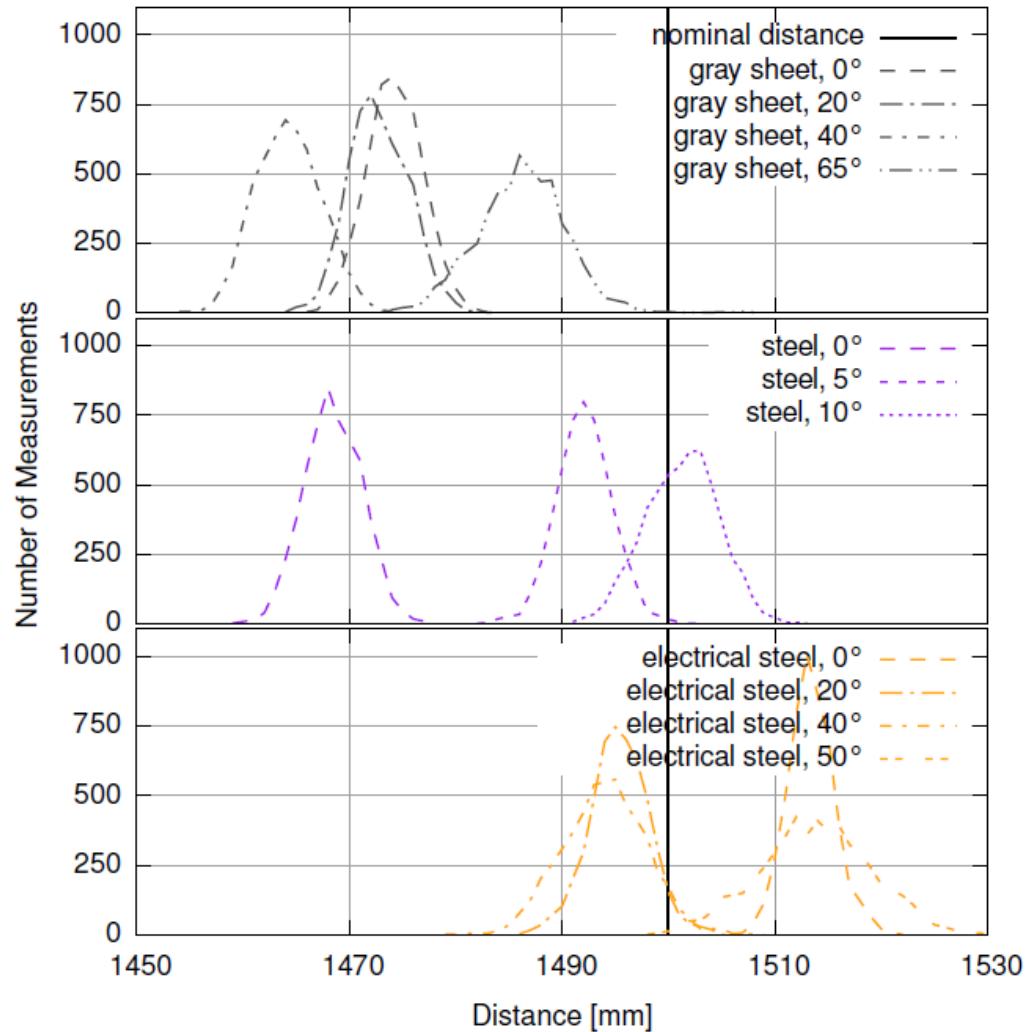




Exemplary scenario sensor performance impacts

Measured Distance (Lidar):

Measured distance
and incident angle?





Tesla Autopilot tried to kill me!



RockTreeStar



Subscribe

60

1,347,405

28





Light rain, failing to stay on road + failed curve prediction



Accidentally exiting highway, failure to understand road exit



Leaves on curbstone, failing to follow curve



Widening of road, failure to understand and follow road



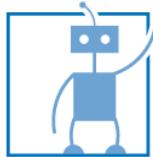
Failure to detect small traffic cones on the road / failure to stop timely in front of cones



Failure to timely stop in front of barrier

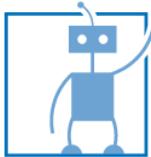


Road contrast light/dark patch, strong curve



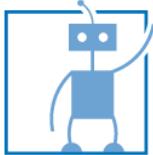
Fog/Steam and manhole cover – two sources of false positives





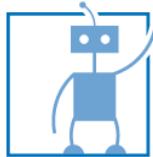
Lack of camera features





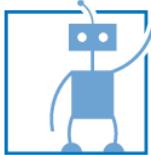
Pot holes filled with water are difficult to detect





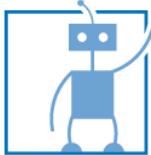
Another smoke scenario





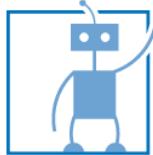
Water spray can limit surrounding sensor performance





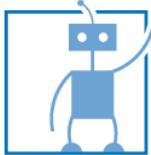
Crocodiles everywhere!





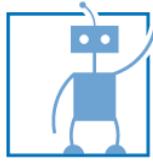
Sun exposure – Blindness. IR Comparison.





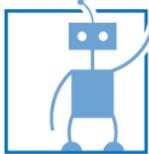
Optical variations. Apperance example speed bumps





Example of fog detection distance reduction



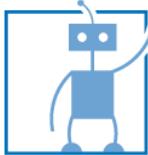


Example of fog detection distance reduction

Mission 7. Fog Zone - Success

The dashboard view shows the interior of a car with a KAIST logo on the rearview mirror. The monitoring interface includes:

- Coordinates: x_icc: -10.5415, y_icc: -199.928, Heading: 209.82, 208.92, lat: 37.240997314, lon: 126.77424623, latdev: 0.72, londev: 0.72, sats: 12, 0, 0, 0.
- A map showing the vehicle's path with the text "slow mode".
- A 2D lidar or sensor map showing the surrounding environment with red and green highlights.
- Distance and pedestrian count controls: 34 dist (2.7), 56 dist (10), ped count limit (15), Ped count (1).
- A speedometer-like gauge with a needle at 40, and a digital display showing 13.071.



Example of fog detection distance reduction



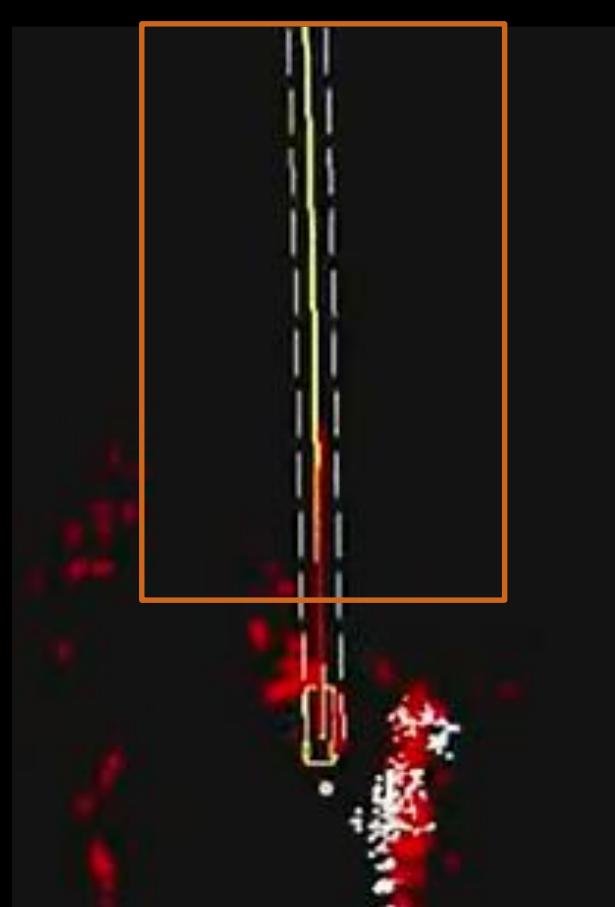
Mission 7. Fog Zone - Success



Fog



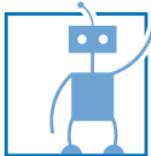
No View



Passed Fog



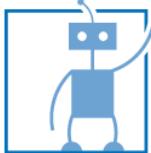
Fog impact on sensor performance



Snow on the ground

- Bicycle driver may fall to ground
- Traffic lights are barely visible
- Dirt on sensors can reduce their performance
- Lanes are hidden
- ...





Art as a risk.

- “Traffic Light Tree is a public sculpture in London, England, created by the French sculptor Pierre Vivant following a competition run by the Public Art Commissions Agency. **Originally situated on a roundabout near Canary Wharf**, at the junction of Heron Quay, Marsh Wall and Westferry Road, it is now located on a different roundabout, near Billingsgate Market.”



Traffic light tree was relocated... if it would have been included in backend maps, the map would have needed to be updated



Suchbegriff

TIPPS-TERMINE-TICKETS

Freitag, 22. Januar 2016

[START](#) | [LOKALES](#) | [NACHRICHTEN](#) | [SPORT](#) | [MEINUNG](#) | [FREIZEIT](#) | [RATGEBER](#)

Freiburg | Breisgau | Emmendingen | Ortenau | Schwarzwald | Lörrach & Dreiland | Waldshut

SONNENSTRÄHLEN

Fassade der Freiburger UB blendet zu sehr – Banner müssen aufgehängt werden

Im Frühjahr und Herbst wird die Hi-Tech-Fassade der Freiburger Uni-Bibliothek an der Südostseite verhüllt werden müssen. Der Grund: Steht die Sonne tief, spiegelt sie sich so heftig in der Fassade, dass Autofahrer geblendet werden.



Suchbegriff

TIPPS-TERMINE-TICKETS

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INNENSTADT

Fassade blendet wieder: XXL-Banner an der Unibibiothek

Es ist ein Anblick, an den man sich erst wieder gewöhnen muss: Ein riesiges schwarzes Banner verdeckt die Fassade der neuen Freiburg Universitätsbibliothek. Sie würde sonst Autofahrer blenden.





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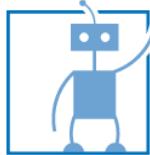
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Only happens 2 times per year:

- 20 minutes per day
- approximately at 9 o'clock (autumn and spring)
- Blinding strong enough to cause temporary black spots for driver vision
- Difficult to find during random tests, but blinding is a known effect and can be tested

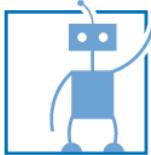




Detection of overhanging objects / cliffs

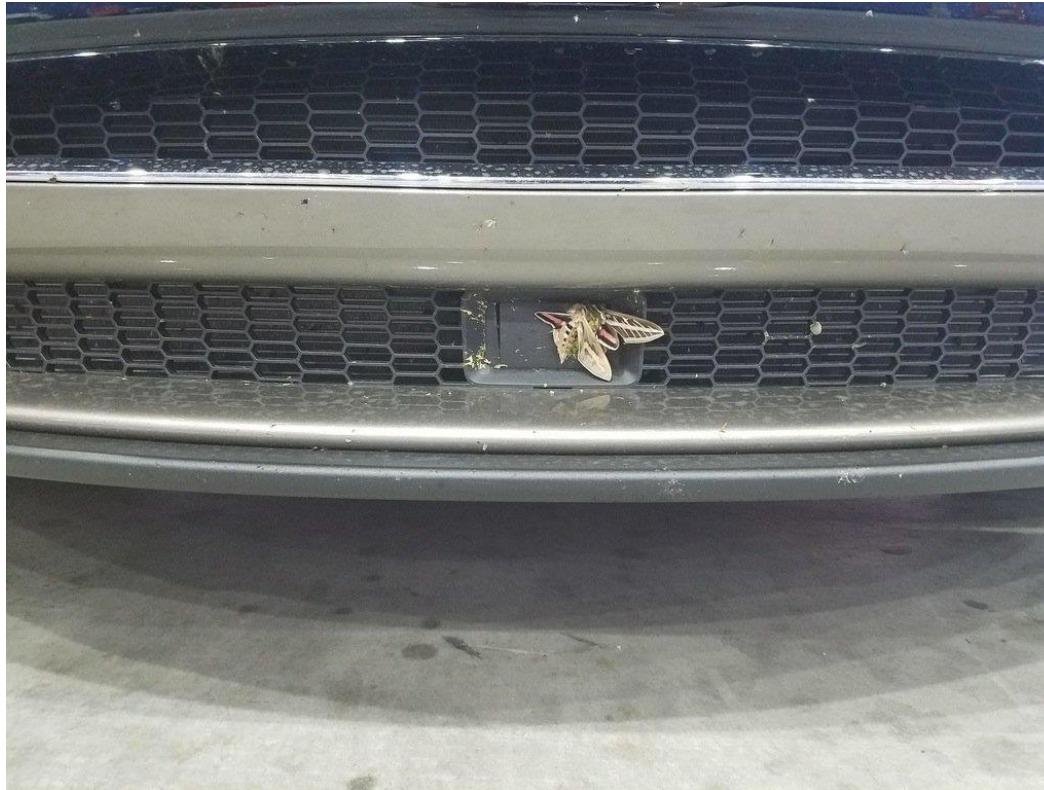
- Model S software supposedly crashes car. Tesla blames the driver?
- Overhanging objects are a challenge anyway.



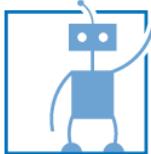


Sensor performance limited by insects / dirt

- Tesla knocked out by bug



<http://www.techinsider.io/tesla-autopilot-knocked-out-by-moth-2016-5>

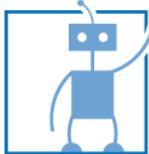


More bugs.

- Traffic infrastructure can be fully covered by insects.



<http://bilder.bild.de/fotos-skaliert/es-summt-und-brummt-als-die-bienen-sich-um-ihre-koenigin-scharen-und-dabei-leider-auch-die-ampel-bloc-44876528-40704156/2,w=650,c=0.bild.jpg>

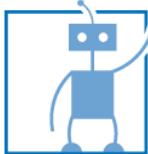


AV debugging

- Traffic infrastructure can be fully covered by insects.



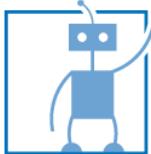
<http://bilder.bild.de/fotos-skaliert/der-imker-ist-da-mit-schutzkleidung-und-eimer-sammelt-er-die-bienen-ein--die-feuerwehr-hat-ihm-dafue-44880764-40706842/2,w=559,c=0.bild.jpg>



„Following“ into false lanes due to loss of information

- False classification of cars, loss of lanes, challenges with following other cars
- Easy to accidentally switch lane and mess up logic.





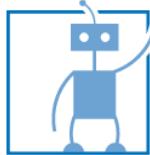
AV Sensor-Set performance impact on comfort

- “(With the Mercedes), during our test, in stop and go traffic, **it felt like we were a drunk drivers**. The vehicle ahead of us was either in a real hurry or on his phone and was weaving all over the lane crossing lines on both sides. The Mercedes followed him, as it should based on how the programming works. When a normal driver was in front of us, **the Mercedes would meander from one side of the lane to the other like a pinball**. If there was a crown in the road, the car would pull to the same side until it reached the road marking, correct and then meander to the same side again. **I can't say it is confidence building.**”

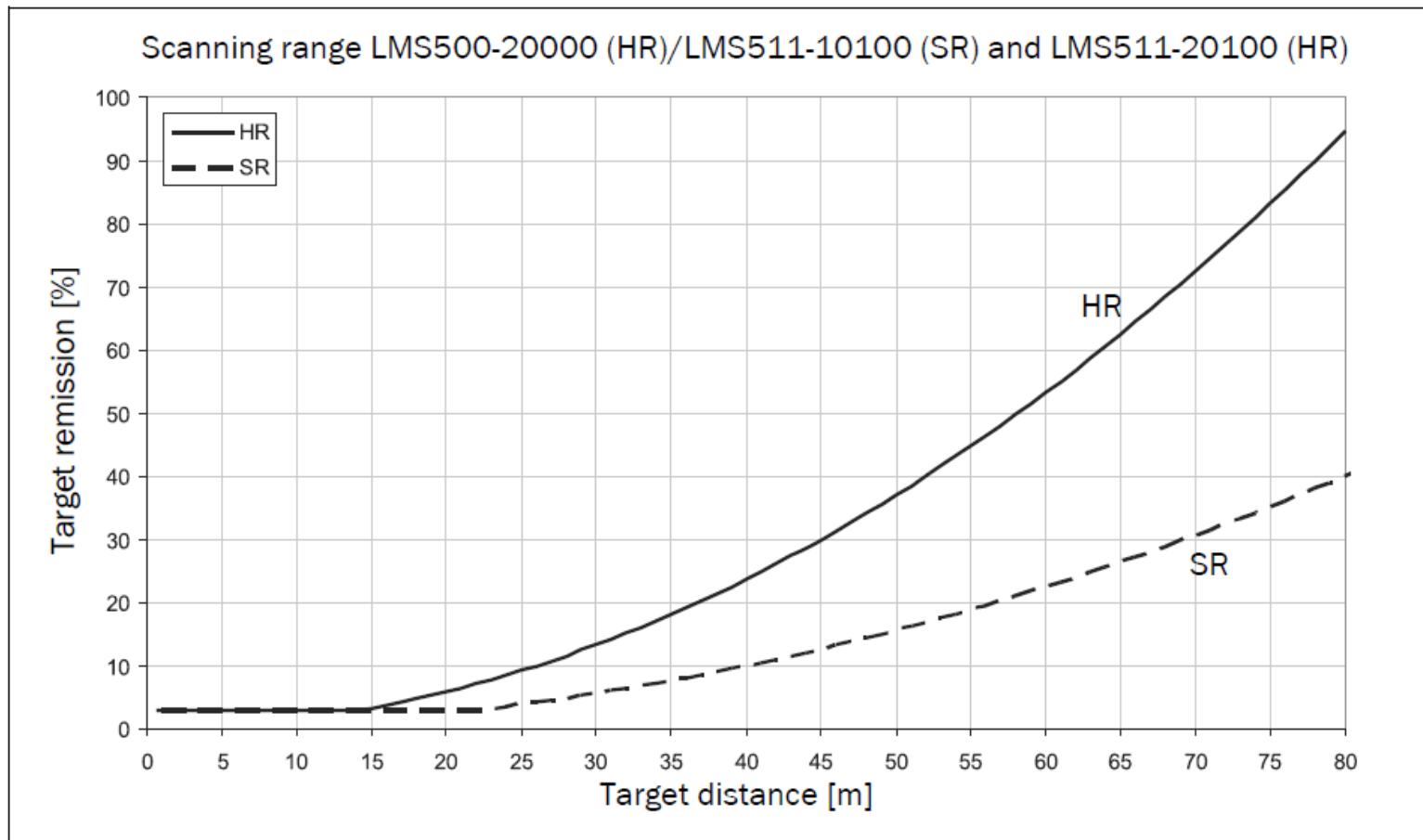
Cause	Sep 2014	Oct 2014	Nov 2014	Dec 2014	Jan 2015	Feb 2015	Mar 2015	Apr 2015	May 2015	Jun 2015	Jul 2015	Aug 2015	Sep 2015	Oct 2015	Nov 2015	Total	
disengage for weather conditions during testing	0	0	0	0	1	5	0	6	0	0	0	0	0	0	0	1	13
disengage for a recklessly behaving road user	1	0	1	1	1	3	3	7	0	0	0	2	1	0	3	23	
disengage for hardware discrepancy	0	1	0	0	2	1	0	1	0	5	8	1	8	8	4	39	
disengage for unwanted maneuver of the vehicle	0	3	6	14	15	1	3	2	1	0	3	2	0	3	2	55	
disengage for a perception discrepancy	1	2	3	18	19	2	20	30	4	4	8	0	4	3	1	119	
disengage for incorrect behavior prediction of other traffic participants	0	2	2	0	1	0	2	0	0	0	0	0	1	0	0	8	
disengage for a software discrepancy	0	11	9	9	14	2	1	5	8	2	9	2	3	1	4	80	
disengage for construction zone during testing	0	0	0	1	0	0	1	0	0	0	1	0	0	0	0	3	
disengage for emergency vehicle during testing	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	
Total	2	19	21	43	53	14	30	51	13	11	29	7	16	16	16	341	

- Large variety of error sources

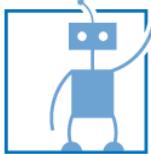
Google disengagement report 2015, <https://static.googleusercontent.com/media/www.google.com/en//selfdrivingcar/files/reports/report-annual-15.pdf>



AV Sensor-Set Detection Range



Example of how detection range depends on target remission for a LMS5xx Laser Measurement Sensors – Sick, 2015

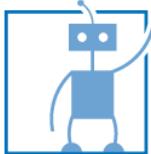


Lidar Simulation

- Lidar Range Measurement:
 - $R = ct/2$
 - R: Range; c: Lightspeed; t: time;
- Lidar Angular Measurement:
 - Sharply limited beam, which only illuminates limited area; measure outgoing angle

Extended simulation base material source:

Influences of weather phenomena on automotive laser radar systems. R. H. Rasshofer¹, M. Spies², and H. Spies. BMW & Spies
<https://www.adv-radio-sci.net/9/49/2011/ars-9-49-2011.pdf>

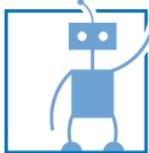


Lidar Simulation – Lidar Range Equation

- Lidar Range Equation for non-elastic scattering, as convolution between transmit signal P_T and spatial impulse response $H(R)$:

$$P_R(R) = C_A \int_{t'=0}^{2R/c} P_T(t') H(R - ct'/2) dt'$$

- $P_R(R)$: Received Power as function of target range
- System constant C_A : $C_A = c\eta A_R/2$
- A_R : Aperture Area of optical receiver
- η : Losses in receiver optic



Lidar Simulation – Transmit Pulse Modeling

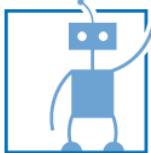
- Dirac-shaped transmit pulse with total pulse energy E_P :

$$P_{T\delta}(t) = E_P \delta(t)$$

- Integrated into Lidar Range Equation:

$$\begin{aligned} P_{R\delta}(R) &= C_A \int_{t'=0}^{2R/c} E_P \delta(t') H(R - ct'/2) dt' \\ &= C_A E_P H(R). \end{aligned}$$

- Only valid for $R \gg c\tau$, with τ : duration of transmit pulse (typically 10 to 20 ns) ($c\tau$ typically 3m to 6m)



Lidar Simulation – Transmit Pulse Modeling

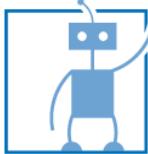
- More realistic pulse model to improve applicable range:

$$P_T(t) = \begin{cases} P_0 \sin^2\left(\frac{\pi}{2\tau_H} t\right) & 0 \leq t \leq 2\tau_H \\ 0 & \text{else} \end{cases}$$

- P_0 : Peak power of laser pulse
- τ_H : half-power pulse width
- Resulting in total energy:

$$E_P = P_0 \tau_H$$

- Typically P_0 up to 80W



Lidar Simulation – Spatial Impulse Response Function

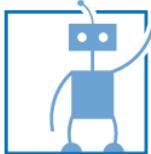
- Spatial Impulse Responses of optical channel H_C and spatial impulse response of target H_T : $H = H_C * H_T$, with:

$$H_C(R) = \frac{T^2(R)}{R^2} \xi(R)$$

- $T(R)$: Total one-way transmission loss in transmission medium

$$T(R) = \exp\left(- \int_{r=0}^R \alpha(r) dr\right)$$

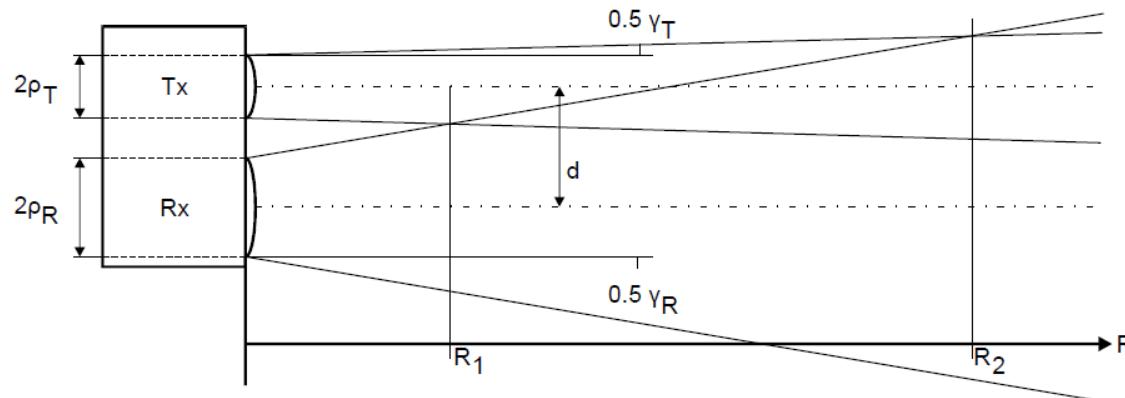
- $\alpha(R)$: Local extinction coefficient
- $\xi(R)$: Crossover function



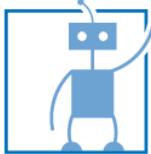
Lidar Simulation – Crossover function

- $\xi(R)$: Crossover function as ratio between area A_T illuminated by transmitter and area A_R observed by receiver

$$\xi(R) = \begin{cases} \frac{A_R(R) \cap A_T(R)}{A_T(R)} & \text{if } A_R(R) \cap A_T(R) < A_T(R) \\ 1 & \text{else.} \end{cases}$$



- Depends on sensor type. Constant for coaxial transmit/receive optics.



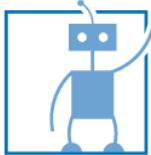
Lidar Simulation – Crossover function

- For bistatic beam configuration using circular illumination and detection areas with parallel optical axis and displacement d , R_1 of first contact between transmit and reception is given by:

$$R_1 = \frac{d - \rho_T - \rho_R}{\tan(\gamma_T/2) + \tan(\gamma_R/2)}$$

- ρ_T, ρ_R : aperture radius
- γ_T, γ_R : Opening angle

$$R_2 = \frac{d - \rho_R + \rho_T}{\tan(\gamma_R/2) - \tan(\gamma_T/2)}$$



Lidar Simulation – Crossover function

- Defining:

$$r_T = R \tan(\gamma_T/2) + \rho_T$$

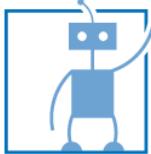
$$\phi_T = 2 \arccos \left(\frac{r_T^2 - r_R^2 + d^2}{2dr_T} \right)$$

$$r_R = R \tan(\gamma_R/2) + \rho_R$$

$$\phi_R = 2 \arccos \left(\frac{r_R^2 - r_T^2 + d^2}{2dr_R} \right)$$

- Gives the crossover function:

$$\xi(R) = \begin{cases} 0 & \text{if } R \leq R_1 \\ \frac{r_T^2(\phi_T - \sin\phi_T) + r_R^2(\phi_R - \sin\phi_R)}{2\pi r_T^2} & \text{if } R_1 < R < R_2 \\ 1 & \text{if } R \geq R_2 \end{cases}$$



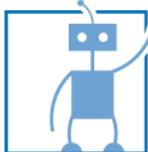
Lidar Simulation – Spatial Impulse Response Function

- For Laser Radar Pulses reflected at plain surfaces of solid objects that don't change the time signature of the laser pulse (hard targets) (target at R_0 , with target area A_{TA})

$$H_{T\delta}(R) = \begin{cases} \beta_0 \delta(R - R_0) & \text{if } A_{TA} \geq A_T(R_0) \\ \beta_0 \delta(R - R_0) \frac{A_{TA}}{A_T} & \text{if } A_{TA} < A_T(R_0) \end{cases}$$

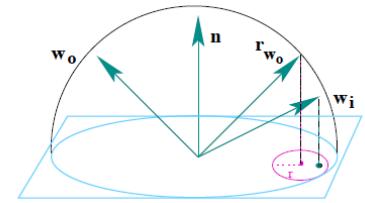
- $A_T(R_0)$: Describes cross-section area of transmit beam at R_0
- β_0 : Differential reflectivity of target. Simple Lambert reflection model based on reflectivity from 0 to 1:

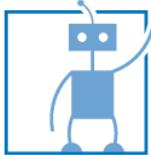
$$\beta_0 = \Gamma / \pi.$$



Lidar Simulation – Target Reflectivity; BRDF

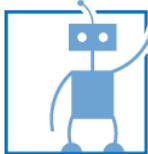
- Bidirectional Reflectance Distribution Function (BRDF)
- **Empirical Model:** Provide simple formulation to mimic specific kind of reflection. Low computational cost, adjustable by parameters, without consideration of physics.
- **Theoretical Model:** Accurately simulate light scattering by using physics laws. Complex expression. High computational effort.
- **Experimental Model:** Measure BRDF with gonioreflectometer varying light sources and sensor positions. Slow. Limited data. Limited resolution.





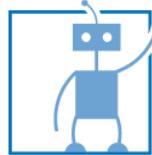
Lidar Simulation – Target Reflectivity; BRDF

- Bidirectional Reflectance Distribution Function (BRDF)
- **Physical-based Reflectance Models:**
 - Ideal reflection: light incoming from a given direction is reflected in a single direction following law of reflection.
 - Other models: Torrance-Sparrow BRDF Beard-Maxwell BRDF; Cook-Torrance BRDF; Kajiya BRDF; Poulin-Fournier BRDF; He-Torrance-Sillion-Greenberg BRDF...

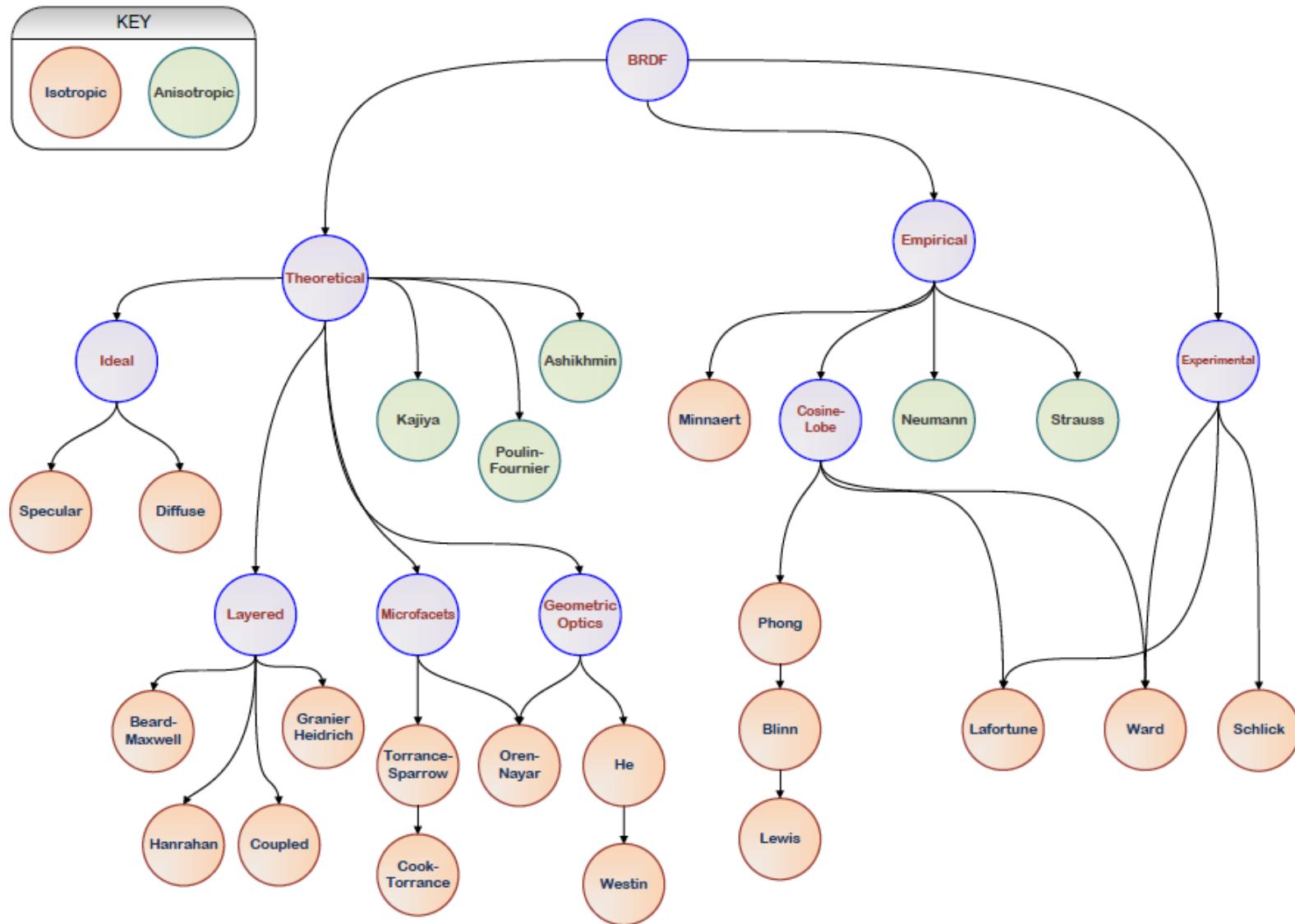


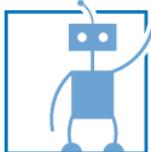
Lidar Simulation – Target Reflectivity; BRDF

- Bidirectional Reflectance Distribution Function (BRDF)
- **Empirical Models**
 - Phong BRDF; Blinn BRDF; Lewis BRDF; Neumann-Neumann BRDF; Strauss BRDF...
- **Experimental models Models**
 - Ward BRDF, Schlick BRDF, Lafourture BRDF..



Lidar Simulation – Target Reflectivity; BRDF





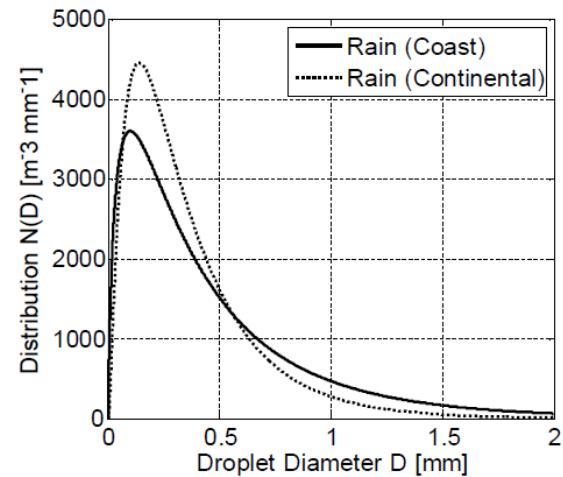
Lidar Simulation – Influence of rain and fog

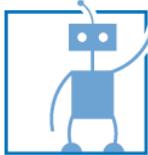
- Extinction coefficient:

$$\alpha = \frac{\pi}{8} \int_{D=0}^{\infty} D^2 Q_{\text{EXT}}(D) N(D) dD$$

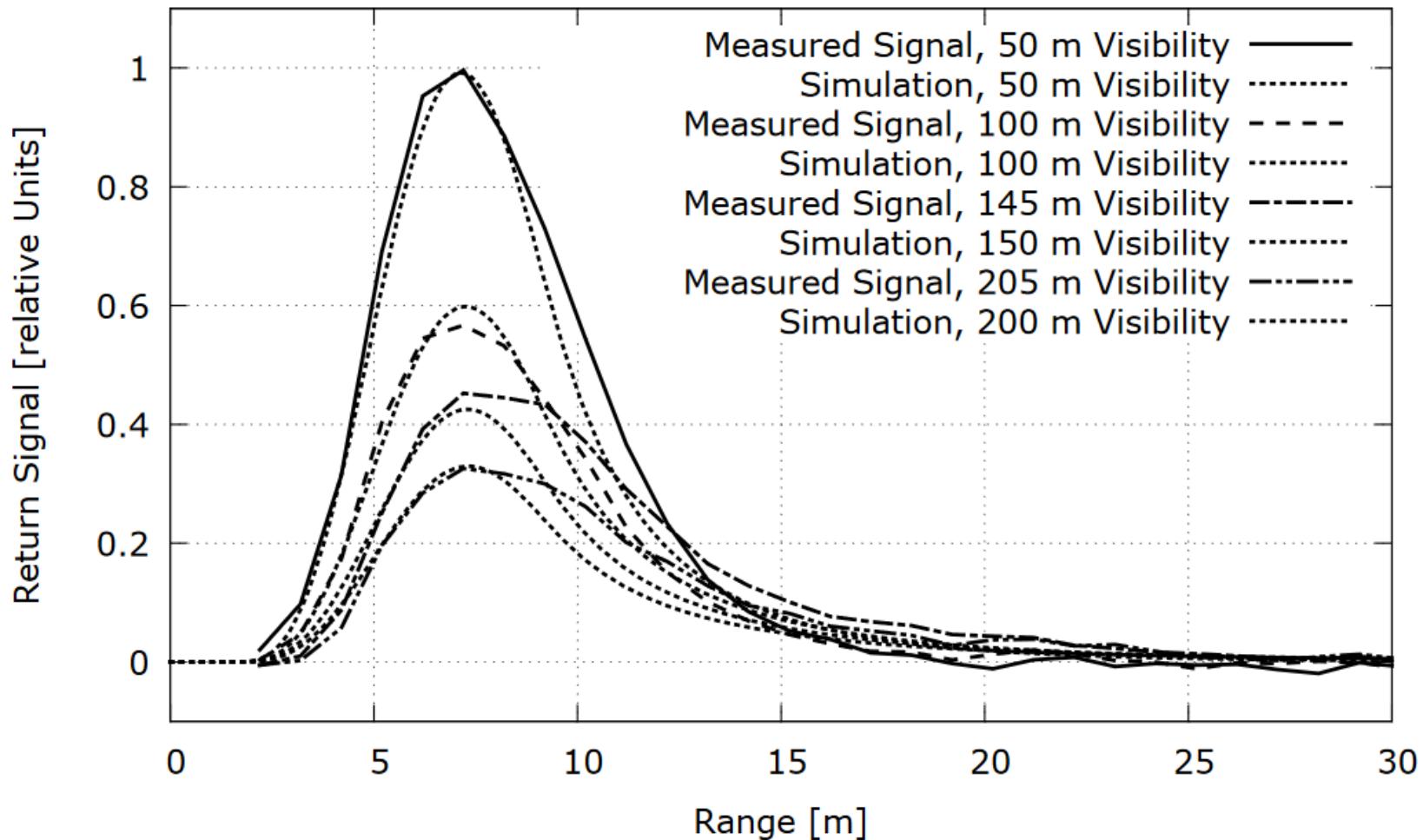
- Q_{EXT} : Extinction efficiency
- $N(D)$: Probability to hit a droplet of diameter D
- Backscattering coefficient:

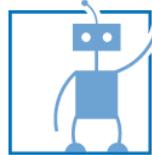
$$\beta = \frac{\pi}{8} \int_{D=0}^{\infty} D^2 Q_B(D) N(D) dD$$





Lidar Simulation – Influence of rain and fog



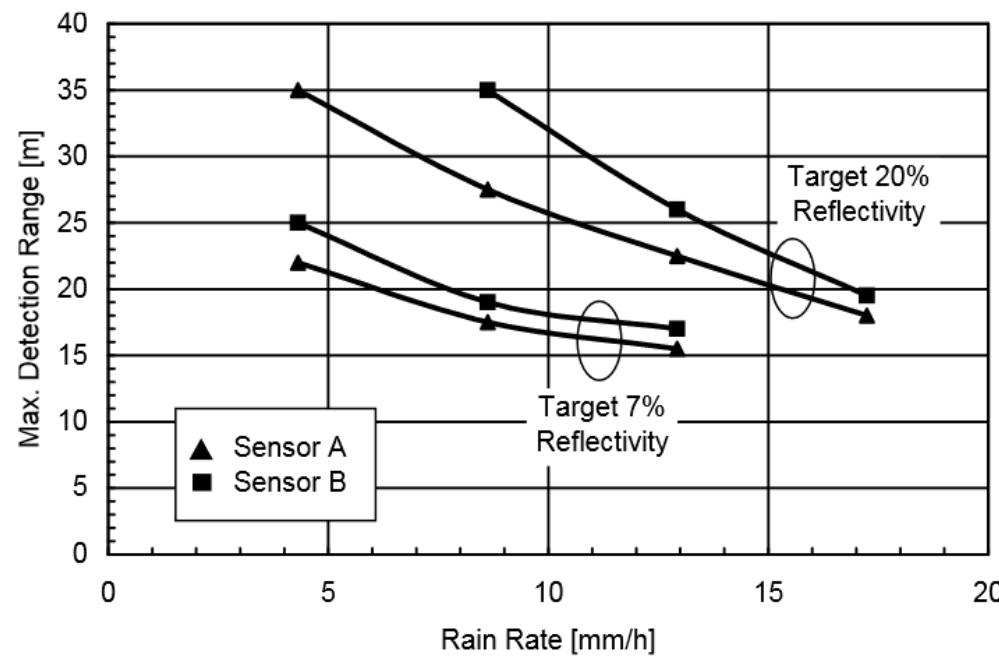


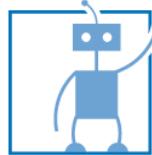
Lidar Simulation – Influence of rain and fog

Standard Target
Range 20m
Reflectivity 7%
Size 0.8m²

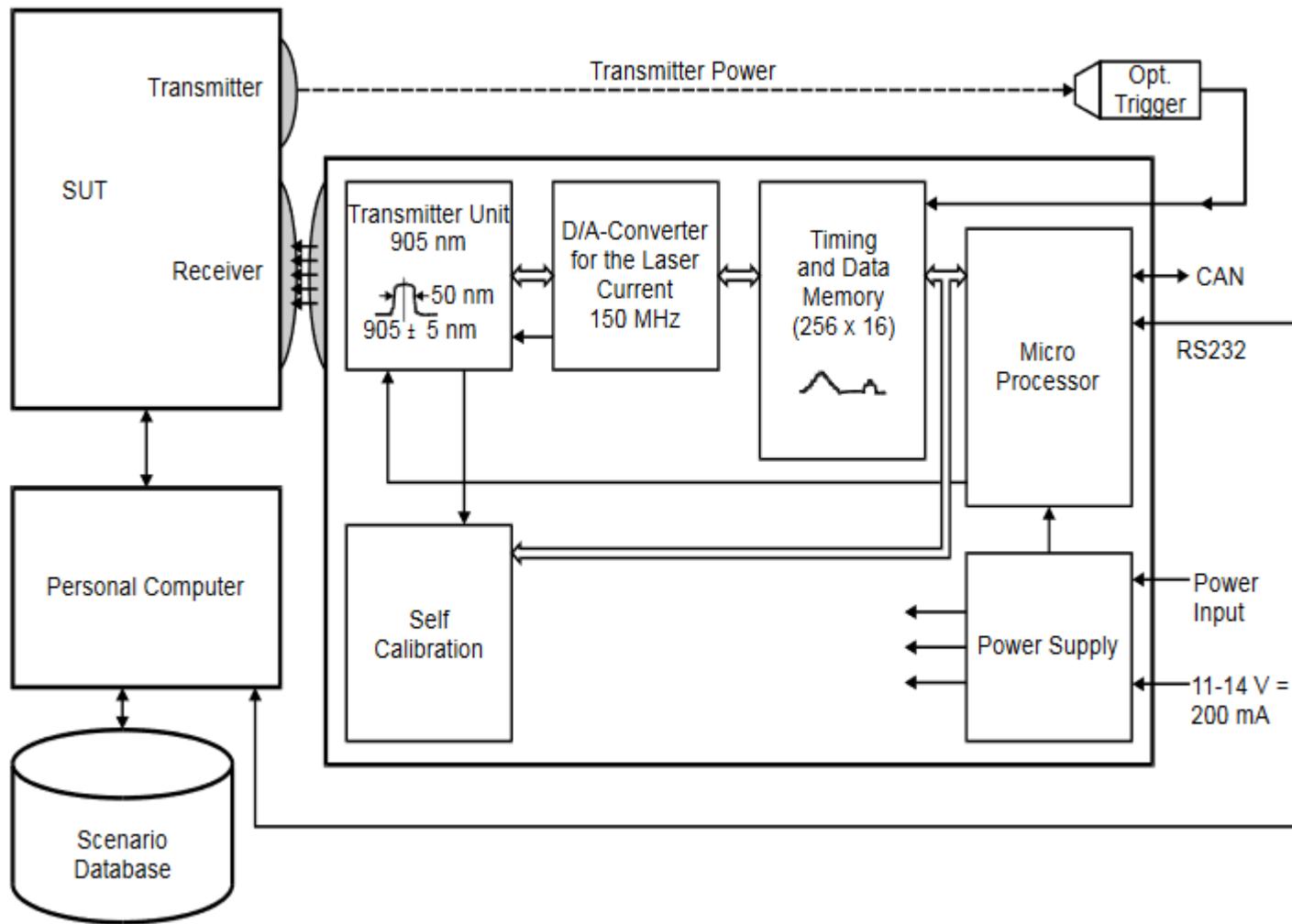


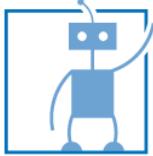
Standard Target
Range 20m
Rain Rate 10mm/h





Lidar Simulation – Influence of rain and fog





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