Automotive LIDAR

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Abstract

Light Detection And Ranging (LIDAR) is an optical measurement principle to localize and measure the distance of objects in space. Basically it is similar to a RADAR-system, but instead of using microwaves LIDAR uses ultraviolett, infrared or beams within the visible light spectrum. Besides distance measurements, which is the basic task, LIDAR sensors can be used for a limited visual detection of objects by analyzing the light intensity, visibility measurement by analyzing the shape of the reflected LIDAR pulse, day/night detection as background illumination is significantly different between day and night, pollution detection and speed estimation. As several research vehicles for autonomous driving vehicles like e.g. Google car use LIDAR as basis sensor technology for scanning the environment there is an increase in development activities for LIDAR sensors meeting automotive requirements (cost, performance, reliability).

Parking Assistance are systems which support the driver during parking manoeuver. This is achieved either by providing distance information to relevant obstacles, camera images or additionally by steering assistance. For the different system configurations requirements regarding sensors, signal processing, HMI, interfaces to the vehicle network need to be met. While first parking systems only provided informations to the driver, recent systems provide lateral steering support and current plus next gerneration parking systems will take more and more both lateral and longitudinal controll of the vehicle during the parking manoeuver. In the near future Valet Parking systems will be available, where the system searches for a suitable parking slot and performs the entire parking process automatically.

1 Function, Basic Principles

1.1 Terminology

LIDAR: Light Detection and Ranging is an optical measurement principle to localize and measure the distance of objects in space. Basically, it is similar to a RADAR system, but instead of using microwaves, LIDAR uses ultraviolet, infrared, or beams within the visible light spectrum (see Fig. 1).

1.2 Measurement Method Distance Sensor

There are several distance measurement methods when using infrared sensors. Most common in automotive is “time-of-flight distance measurement.” The time elapsed between transmitting and receiving of the light (laser) pulse is directly proportional between the measurement system and detected object.

With “time-of-flight measurement,” one or several light pulses are transmitted; they are reflected by a possible existing object. The elapsed time until reflected

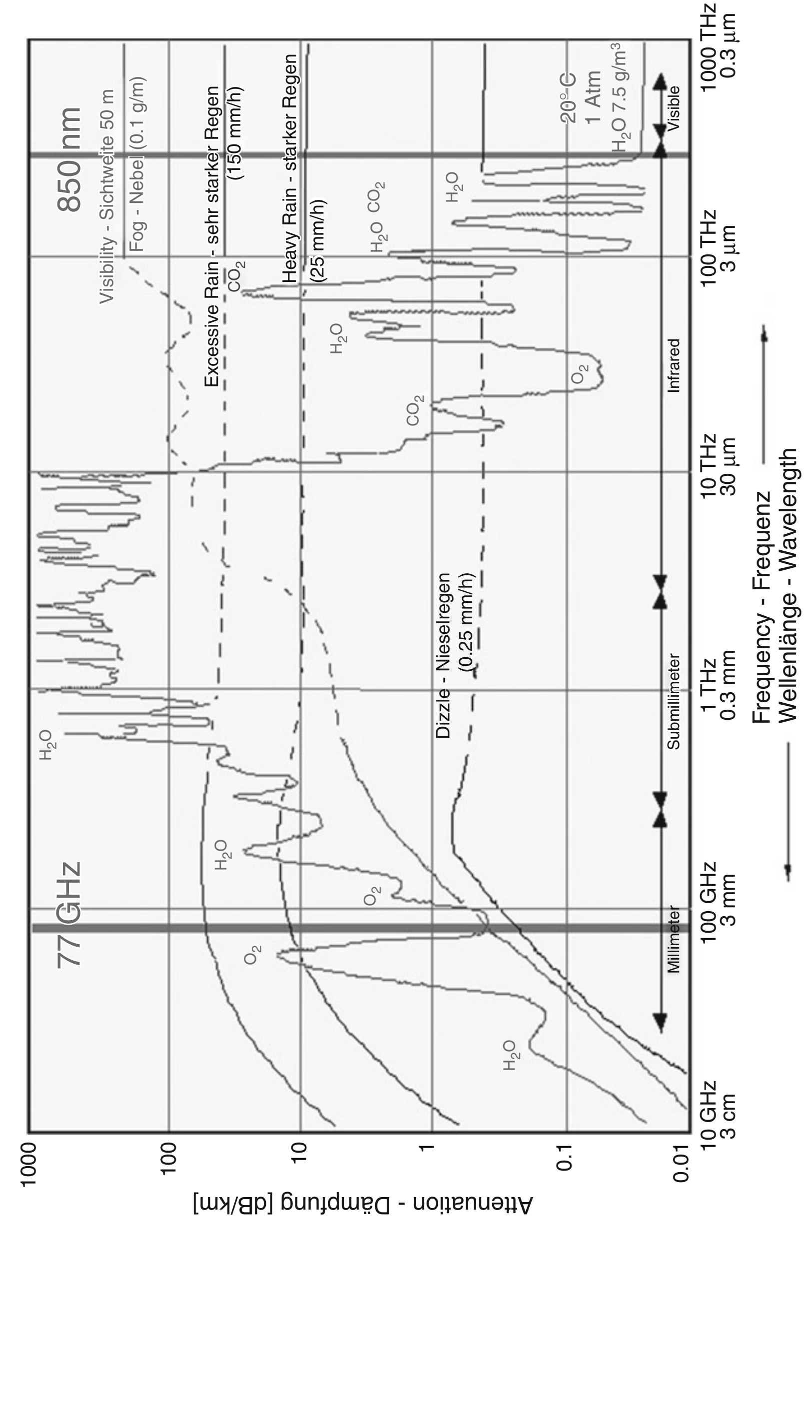


Fig. 1 Frequency spectrum

signal is received is proportional to the distance. With a speed of light of 300,000 km/s (in air), the time to be measured with an object at a distance of 50 m is approx. 3×10^{-7} s or 333 ns. This is a typical driving situation where "speed = 100 km/h and distance = half tachometer" (see Fig. 2):

$$d = \frac{c_0 \cdot t}{2} \tag{1}$$

d = distance in m
c_0 = speed of light (300,000 m/s)
t = time in s

A reflected pulse of a fixed and single object (e.g., vehicle) has the shape of a Gaussian curve.

Since the emitted light pulse travels twice the distance between the sensor and obstacle, the elapsed time between sending and receiving represents twice the distance to the object (see Figs. 2 and 3).

If there are several objects in the detection area of the sensor and therefore in the measurement channel, they can be recorded with an appropriate evaluation if the distance between the obstacles is sufficiently large enough. This is called multi-target capability of the system (see Fig. 4).

If there is an increased attenuation of the atmosphere due to fog, rain, etc., then individual pulses are reflected on the water droplets in the air (see Fig. 5). Depending on the optical design of the system, this can lead to saturation behavior in the receiver. A measurement is no longer possible.

But state-of-the-art sensors work with a dynamic adjustment of the sensitivity, and together with the multi-target capability of the measurement channel, obstacles within or behind "soft" atmospheric disturbances can be measured. With "soft" objects, like fog, many signals are recorded from different distances. This leads to a merge of the single pulse responses, and the total signal response is a flat and extended echo (see Fig. 6). Thus, both the elapsed time of the received pulse response (a single Gaussian curve in the simplest case) and the shape of the echo are used for a more detailed analysis on the kind of the detected echoes and the environmental conditions.

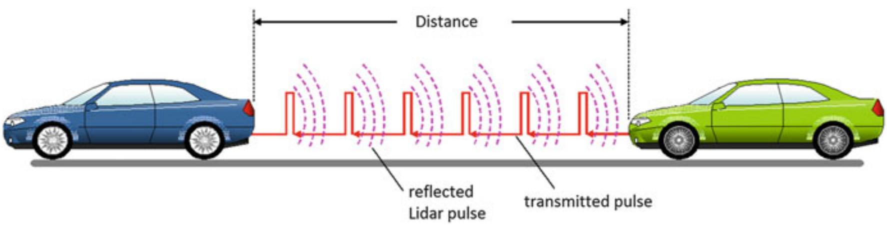


Fig. 2 Travel time measurement

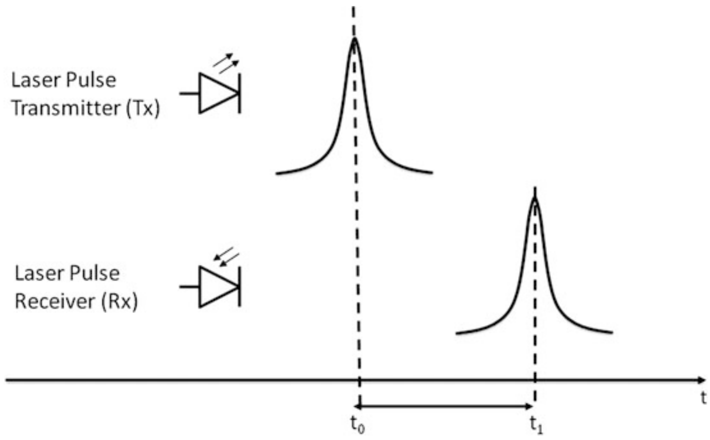


Fig. 3 Impulse response of an object

Fig. 4 Impulse response of two objects

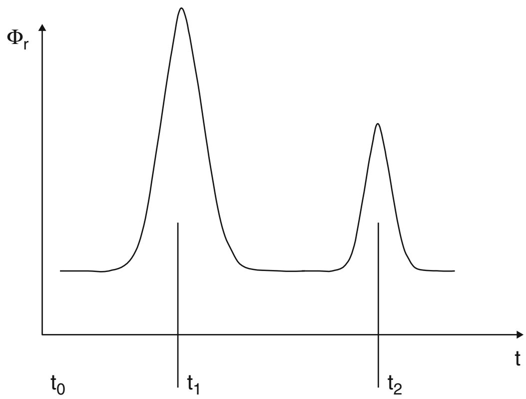
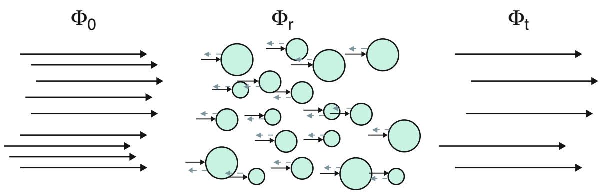


Fig. 5 "Soft" object (fog)



Thus, for example, the signal of mist or spray differs from the one of a vehicle (see Fig. 7). The shape of this signal contains information about the absorption degree of atmospheric disturbance. From the measurement of "signal length" x and analysis of the temporal decrease of $\Phi_r(t)$ (see Fig. 6), the prevailing visibility can be estimated.

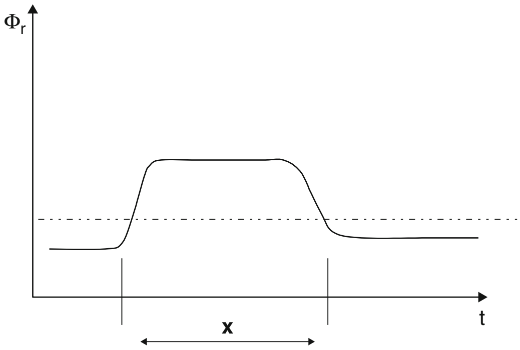


Fig. 6 Signal response "soft" object (fog)

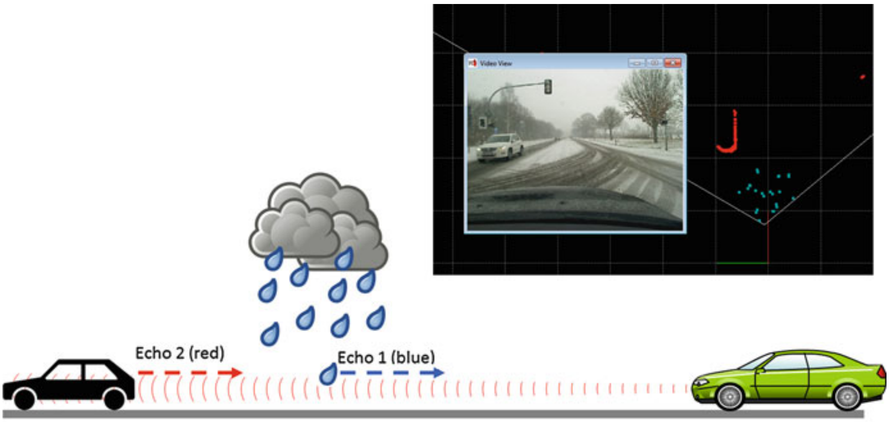


Fig. 7 Distinction rain – vehicle

The range performance is significantly influenced by the intensity of the emitted light pulse and the receiver sensitivity. The pulse power is limited by the eye safety requirements. Other parameters, such as transmission of the atmosphere and the size or reflectance of the object, however, are not influenced.

The received light intensity is described by the following equation (only valid if size of beam is smaller than size of object) (Eq. 2):

$$P_r = \frac{KK \cdot A_t \cdot H \cdot T^2 \cdot P_t}{\pi^2 \cdot R^3 \cdot (Q_v/4) \cdot (\Phi/2)^2} \tag{2}$$

In the case that the target (at a greater distance) is smaller than the beam surface, the following equation is valid:

$$P_r = \frac{KK \cdot A_t \cdot H \cdot T^2 \cdot P_t}{\pi^2 \cdot R^4 \cdot (Q_v \cdot Q_h/4) \cdot (\Phi/2)^2} \tag{3}$$

with:

P_r = intensity of the received signal (W)
KK: reflectivity of the measured object
Φ: angle of reflection object (rad)
H: object width (m)
A_r: target size (m^2)
T: transmission of the atmosphere
Q_v: vertical beam divergence (rad)
Q_h: horizontal beam divergence (rad)
A_t: receiving lens surface (m^2)
P_t: laser power (W)

1.3 Additional Functionality

Basically, LIDAR sensors can also be used for a limited visual detection of objects in addition to pure distance measurement. Here, the light intensity is then additionally evaluated accordingly. But due to the physical and technical principle, the performance is worse compared to a camera, as they have a higher resolution and are capable to detect a wide frequency. Furthermore, the performance depends largely on the contrast between objects to be detected and the environment (e.g., lines on roads).

1.4 Construction

In principle today's LIDAR distance measuring devices are constructed according to the same construction. There are differences in the way how to generate multiple measurement channels (beams) and the implementation of a beam deflection at "sweeping" (depending if, e.g., the curve radius is tracked) and scanning methods.

1.4.1 Transmit Path

LIDAR uses for active distance measurement a laser source, which typically emits in the range between 850 nm and 1 μm. In order to ensure an optimal target separation of multiple echoes, the measurement pulse should be kept as short as possible. During the design of LIDAR sensor, eye safety has to be guaranteed, since the integral of the pulse is emitted energy. The radiation peak power of the high-power diodes used may reach 75 W (OSRAM 2015; Laser Components 2015a) or even more. The pulse length is typically in a range of about 4–30 ns, with an active

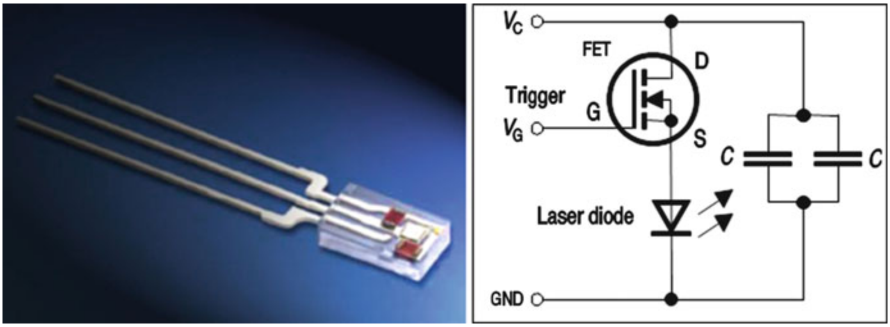


Fig. 8 OSRAM SPL LL90 – driver stage in the housing of the laser diode (OSRAM 2015)

surface on the semiconductor laser of about 200 × 10 μm^2. This corresponds to a laser power at the surface of about 35 GW/m^2.

In order to achieve the high electrical radiated power interference-free, the driver stage of the laser (see Fig. 8) has to be as close as possible and thus directly built to the housing of the semiconductor laser. Other challenges include the temperature of the boundary layers to the plastic housing and the power supply (operating voltage 12 V) to the whole component.

1.4.2 Receiving Path

The sensitivity of the receiver decisively impacts on the achievable performance of the sensor. Basically, the sensitivity of a sensor component can be reached via the size of the receiver surface. Limitation of this is the aperture and the quality of the optics. To achieve the required accuracy in the centimeter range, high measurement speed is required. In a measuring range from about 10 cm to about 150 m, the light travel time for different LIDAR systems is in a range from 0.1 ns to 1.0 μs. Another challenge is the "glare" by the ambient light. During the day several orders of magnitude causing the spread of the sunlight spectrum, which also includes a significant share in the infrared range, more light output than the LIDAR distance sensor. By suitable filter measures, the light component (caused by solar radiation) is suppressed. These measures are carried out mainly in hardware.

When receiving positive intrinsic negative (PIN) diodes or avalanche photodiodes (APD) used (Laser Components 2015b).

Avalanche diodes are used as a photodiode semiconductor detector for counting single photons. Typically they are operated with a large series resistance in the reverse direction. Due to the high field strength, a single photon is able to release an electron, which is accelerated by the field in the barrier layer, and triggers an avalanche effect. The resistance prevents that the diode remains broken through (passive quenching). The diode returns back to the locked state. This process is repeated periodically, and their measuring frequencies up to 100 MHz are possible.

The PIN diode is mainly used in optoelectronics for optical communications technology for optical waveguides such as photodiodes. PIN diodes are due to the

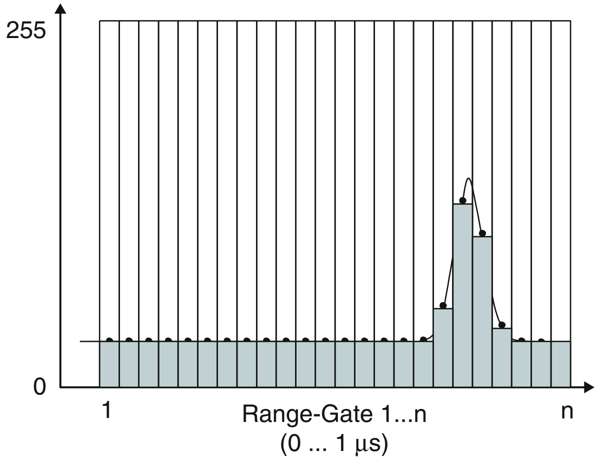


Fig. 9 Digitizing by means of parallel gating

thick i-layer (lightly doped, conductive-intrinsic conductivity) of thermally more stable and cheaper, but less sensitive, since in here more charge carriers can be stored. Peak values for sensitivity are between –40 and –55 dBm at a wavelength of 850 nm.

To improve performance, the APD is often implemented as an ASIC.

In order to achieve the spatial resolution of a few centimeters, the so-called "parallel-gating" process of the amplification of the signal among other things is applied. Here, the received signal is digitized via a time-controlled multiplexer and stored in individual "memory cells" (range gates) (see Fig. 9). Each memory cell corresponds to a "range gate" of, e.g., 1.5 m. The addition of multiple transmit pulses results in a Gaussian distribution of the range gates around the actual measurement point.

To increase the accuracy of time measurement in the processor unit of the sensor, the expected received pulse is reconstructed, and its apex is determined. Thus, from a still relatively coarse time (distance) and amplitude resolution, range resolution in the centimeter range can be achieved. A further increase in accuracy is possible by the temporal analysis of the calculated distances.

With the number of transmission pulses per measurement, the sensitivity of the sensor system can be increased or be controlled. With the described method, a dynamic range of more than 50 dB with respect of the optoelectronic current can be achieved. This is necessary to detect bad reflective objects in the target distance.

Figure 10 shows the basic structure of today's typical LIDAR distance sensor. Depending on the required numbers of individual sub-elements are integrated into an ASIC.

In addition to the hardware structure of a distance sensor, individual functions are realized by software. As mentioned above, a large part of the signal evaluation such as the determination of distance and relative speed detection is done by the software. Also on the block "signal processing," information on the visibility and

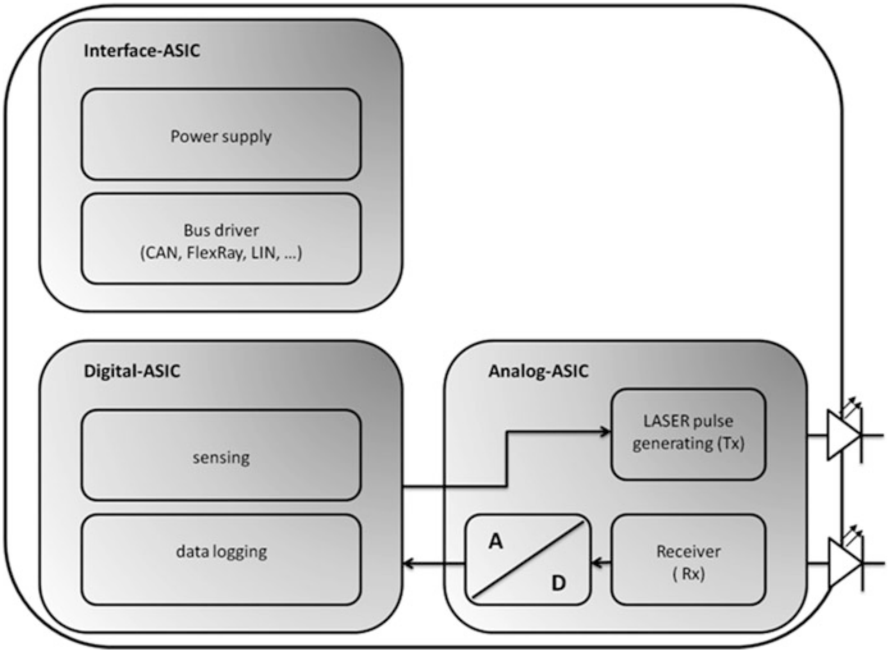


Fig. 10 Basic structure of a LIDAR distance sensor

system limitations are calculated. The single arrows represent the exchange of data between different software blocks (see Fig. 11).

The laser driver provides the timing of measurement and receiving channel.

1.5 Transmission and Reflection Properties

As with all the active and passive measurement methods, the transmission or the attenuation of the atmosphere plays an important role in the system design and the performance of the sensor system that can be achieved. While with passive methods, such as cameras, the distance from the object to the sensor has to be put back only once, with active technology, the distance from the object to the sensor has to be put back twice.

The transmission properties of the atmosphere are significantly affected by their constituents and their physical conditions (see Fig. 1).

Figure 12 shows a simplification of the test section in the atmosphere (l). It should be noted here that this represents only one way of the distance sensor relative to the object. The light must travel the same way again in the reverse direction back after reflection on the object (see Fig. 13).

The transmitter radiates the luminous power Φ_0. Through the atmosphere (containing water droplets, dust particles, etc.), parts of the light are reflected diffusely (Φ_r). In addition a part of the total energy is absorbed (converted into heat) until at the end of the track only a reduced optical power is available Φ_t:

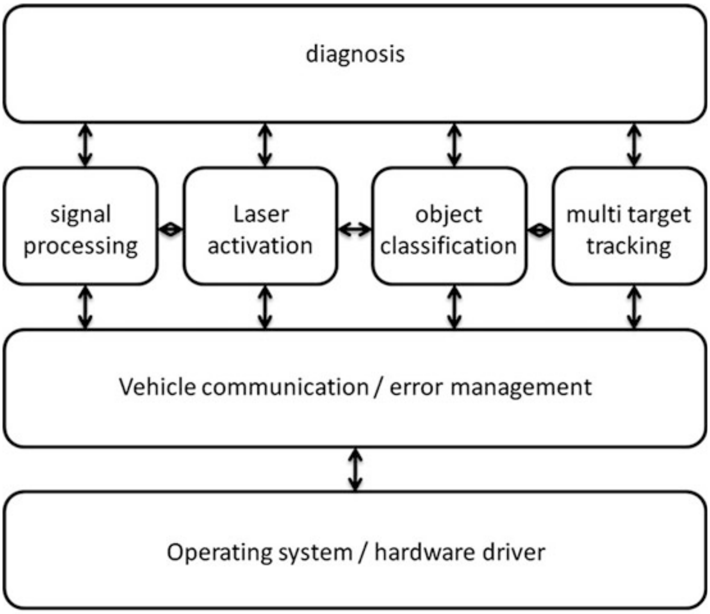
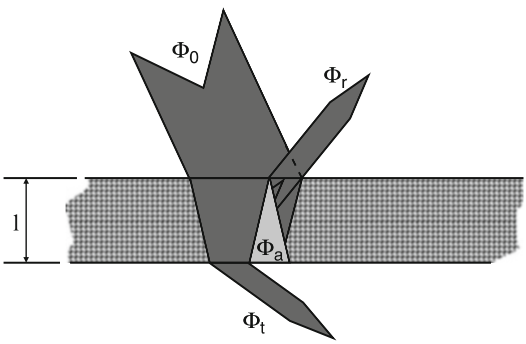


Fig. 11 Basic software functions

Fig. 12 Absorption, reflection, and transmission



$$\Phi_0 = \Phi_r + \Phi_a + \Phi_t \tag{4}$$

$$\text{Degree of reflection} \cdot \varrho_r = \Phi_r / \Phi_0 \tag{5}$$

$$\text{Degree of absorption} \cdot \varrho_a = \Phi_a / \Phi_0 \tag{6}$$

$$\text{Degree of transmission} \cdot \tau = \Phi_t / \Phi_0 \tag{7}$$

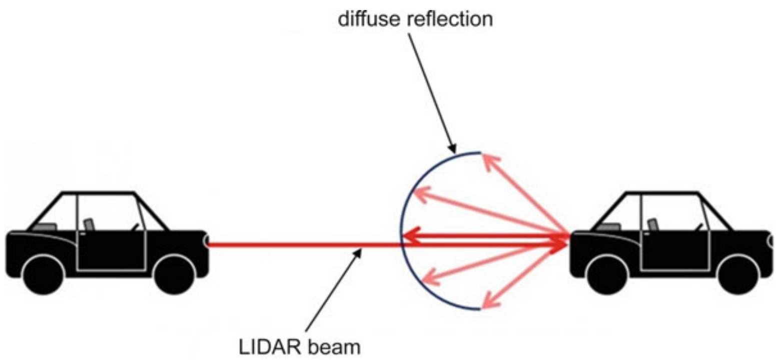


Fig. 13 Lambert reflector

where

Φ_0 – emitted luminous power
Φ_r – reflected luminous power
Φ_a – absorbed luminous power
Φ_t – received luminous power
l – path through the atmosphere

The proportion of the transmitted radiation is referred to as transmittance (τ) (see Eq. 7). The attenuation is generally composed of absorption, scattering, diffraction, and reflection and is wavelength dependent (see Eq. 4).

A major challenge in laser measurement is the requirement for eye safety which results in a very limited receiving energy after reflection from an object. It should be noted that usually the object (vehicle) is similar to a Lambertian reflector which radiates its energy diffusely in the half solid angle (180°) (see Fig. 12).

With the Lambert reflector the backscattered energy is not focused, but is distributed inhomogeneously in the solid angle (within a “ball”). Therefore, only the part of the backscattered energy that is radiated back directly into the sensor’s receiver can be used for detection. This is, in practice, at best, 20 % (usually much less) of the reflected energy to the object.

As mentioned, the average transmission power is limited, but as an improvement the beam can be bundled to increase the energy density or use a high gain receiver. The bundling has the disadvantage that at too small solid angles, the beam may, at a homogeneous surface on the vehicle (e.g., only the bumper) and thereby of the entire beam, be reflected away by total internal reflection.

Total reflection (see Fig. 14) occurs when narrow beams (see also “Lambert reflector” – Fig. 13) are used, which impinges on a sloping surface. This can be remedied by widened beam or several beams. The ideal situation is

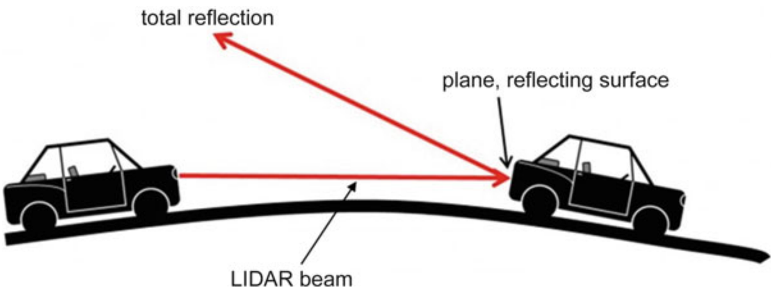


Fig. 14 Total reflection

to shed light on edges or directed perpendicular to the transmitter parts in the detection area.

These measures are sometimes counterproductive (see energy density problem); the problem of multiple receive beams is compensated by the use of scanning systems with multiple transmit/receive channels (several hundred) but sometimes also leads to higher costs.

1.6 Speed Motion Detection

Driver assistance systems require information about the own speed of the vehicle, the relative speed to objects, and the motion of objects in the relevant environment. The determination of the own speed (value and direction) is generally carried out by evaluating steering angle sensor and wheel rotation sensor. In principle, the Doppler effect to determine the relative speed of the detected objects is used by the LIDAR system. However, the increased demands and the associated costs in measuring the Doppler frequency in the spectrum of light prevent its implementation.

For this reason, one uses the differentiation of two one following ideally several successive distance measurements (see Eqs. 8 and 9).

$$\vec{v}_{rel} = \frac{\mathrm{d}\vec{R}}{\mathrm{d}t} = \lim_{\Delta t \to 0} \frac{\Delta \vec{R}}{\Delta t} \tag{8}$$

A prerequisite is that the distance information is definite, i.e., the same object/reflection point. Depending on the type of LIDAR, distance information R is either a purely radial distance value, or it contains additionally direction information. The horizontal angular resolution for scanning systems is typically in the range of $\leq 0.5°$. Neglecting vertical information, the relative velocity is given by

$$\vec{v}_{rel} = \frac{\vec{R}_2 - \vec{R}_1}{t_2 - t_1} \tag{9}$$

$\vec{v}_{rel}$: relative velocity in m/s
R: distance in m
t: time in s

This method is possible only when a very accurate distance measurement can be guaranteed. Accuracy increases can be achieved through suitable filter such as state observer or Kalman filter.

In order to achieve a better prediction of how the environment situation develops in the future, change in the movement of the relevant objects must be known. By analyzing the change of speed, the relative acceleration can be determined (see Eq. 10):

$$\vec{a}_{rel} = \frac{d^2\,\vec{R}}{dt^2} \tag{10}$$

$\vec{a}_{rel}$: relative acceleration in m/s^2

As a possible error in distance measurement, inaccuracy in calculation of relative acceleration increases. Thus, for a possible control task, the signal must be filtered accordingly.

1.7 Tracking Method and Selection of Relevant Objectives

The term tracking includes all processing steps that serve the tracking of objects. The aim of this tracking is, on the one hand, the extraction of information about the history of the movement and the position of an object and, on the other hand, the reduction of negative influences, mostly originating from random measurement errors (measurement noise). The accuracy of the determined position and motion information depends on the used tracking algorithm as well as on the accuracy of the measurements, the measurement error, and the sampling rate of the cyclic measurements.

In general, the target selection can be performed in two different ways. Either one covers the entire area and then selects a relevant target (see ▶ Chap. 45, “Adaptive Cruise Control”) with lane assignment and/or further selection features, or one is limiting the detecting of objects from the beginning on to the relevant range of expected travel trajectory. Both methods have advantages and disadvantages. Table 1 shows a comparison (Fig. 15).

The performance of the ACC sensor is determined not only by the sensitivity primarily by the quality of the determination of the relevant object. This requires a powerful calculation of the trajectory of the driving path (see ▶ Chap. 45,

Table 1 "Tracking" methods

	Option 1	Option 2
Figure	Figure 15a	Figure 15b
Description	Detection of objects in the entire detection area	Detection of objects in the entire detection area
	Discrimination of targets based on the determined driving path	Information about distance and direction of the measurement only in the relevant field
Advantage	Detection of all objects	Low computing power
Disadvantage	Computing and memory requirements also for nonrelevant objects	

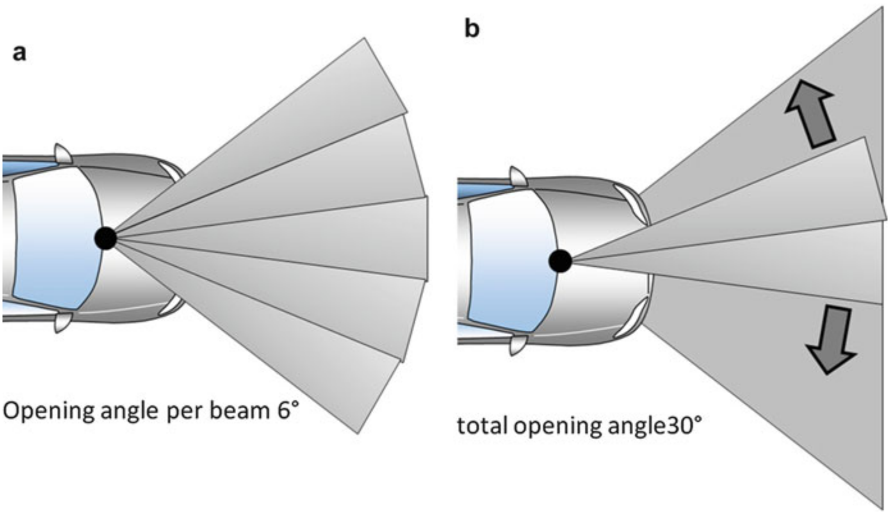


Fig. 15 Comparison of different tracking methods. (**a**) Multibeam rigid (number or value of the opening angle can vary). (**b**) Multibeam sweep (total open angle, number, and value of the single opening angle can vary)

"Adaptive Cruise Control"). The tracking can basically be divided into the following processing steps:

1.7.1 Prediction (Extrapolation/Estimation)

In this processing step, the (computational) prediction of the position and movement information on a basis of the known history as a function of physical properties of the relevant object (dynamic) and assumptions on how the objects will behave in the future. Of basic interest as well are other active road users (cars, people, etc.) and static objects (stationary vehicles, lane boundaries, etc.). For the prediction, it is important that the position and movement information with sufficient accuracy depending on the environment (highway, urban environment, etc.) and own vehicle velocity is precise enough to realize a corresponding application (e.g., avoidance assistant).

1.7.2 Association (Linkage of Objects)

In particular, when there are multiple objects observed in the detection area (multi-target tracking) and the system is able to clearly differentiate themselves through various measuring cycles, the component maintains a mapping of an observed object in previous measurement cycles at a current measured object. Errors in this processing step may have a very negative effect on the results of impact (v_{rel}, a_{rel}, etc.). Scanning systems offer significant improvements which have an angular resolution in the range of a few 0.1°.

1.7.3 Innovation (Linking Real Measurement and Prediction)

The determination of the current position and other relevant information takes place on the one hand by the prediction and the other by current measurements. The innovative step leads both results together, in which the individual results are weighted. This weighting can be done either dynamically or statically. If the prediction is weighted higher, then the result is smoother, while actual measurements yield results that adapt quickly to changes in the measured values. Depending on the function or situation (security system/emergency braking or comfort system/ ACC), the filters are then adjusted accordingly. The quality of the models or the degree of approximation to reality decisively determines the result of tracking. Usually for a LIDAR distance sensor, a Kalman filter is used.

1.7.4 The Kalman Filter: Function Principle

The Kalman filter (Wikipedia 2015a; Filos et al. 2015; Jiang et al. 2015) is used to estimate states and parameters of a system due to partly redundant distance and relative velocity measurements, which are superimposed by noise (Fig. 16).

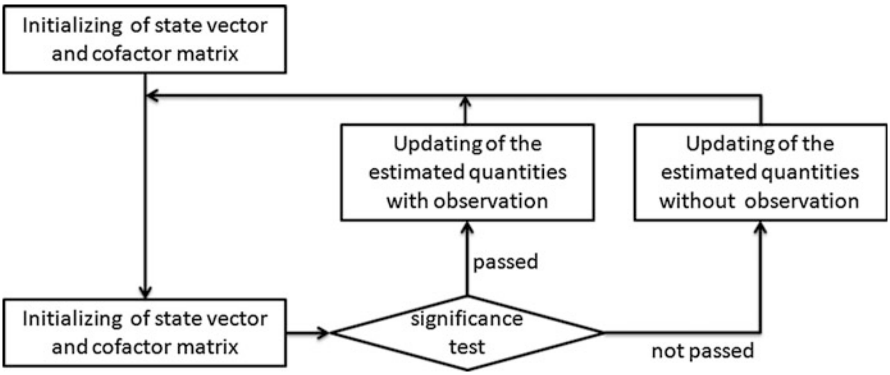


Fig. 16 Kalman filtering principle

Software Kalman filter tracking + classification

The filter has a so-called "predictor-corrector" structure. First it is predicted based on the system input data and the most likely new position and speed and then compared with the actual measurement data. The difference of the two values is weighted and used to correct the current state.

In simple terms, the distance measuring system is described linear and is based on a state space model with equation of state (Berges et al. 2002):

$$x(k) = Ax(k-1) + Bu(k) + Gv(k-1) \tag{11}$$

Prediction observation equation (Luo and Kay 1998):

$$z(k) = Hx(k) + w(k) \tag{12}$$

At a constant speed ($a_{rel} = 0$) can be described by the following state vector:

$$x = \begin{bmatrix} d \\ v_{rel} \\ a_{rel} \end{bmatrix}$$

and the system matrix:

$$A = \begin{bmatrix} 1 & T_k & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

When multiple objects are tracked simultaneously, the objects of a measurement step must be assigned to the correct object path. For this a Kalman filter has an association gate added. A common solution is the method of nearest neighbors. Taking into account the uncertainty of the measurements and deviations from the assumption of constant velocity results in a search area of the object in the new measurement. By estimating the new measured value with the Kalman filter, the measurement window can be specified. A track is assigned to the object with the least difference between prediction and measurement. The measured data are then used for the innovative step of the Kalman filter.

Readings outside the measuring range are discarded directly, as well as objects only once found to be excluded as a measurement error of tracking. On the other hand, a new path is initialized when the first time the detected object in the next measurement step, a measured value can be assigned. If no object is assigned to an existing track, the predication is done via additional measuring steps. The track will be finished if prospectively no further measurements can be assigned. Several closely spaced objects with similar relative velocity can be summarized (clustering). Misinterpretation can, however, only exclude retroactive, wherefore two measured values are initially kept separate.

2 Application in Vehicle

2.1 Laser Safety

Basically, it is only allowed to install in a vehicle LIDAR sensors which are certified according to laser protection class 1. Relevant for the determination of the laser class is the ICE 60 825-1, Amendment 2: 2001 (Wikipedia 2015b).

The explanation of details of the laser standard is certainly not the intention of this paper. The basic input is the emitted energy of the sensor and thus the energy balance on the retina of the human eye. As the frequency spectrum used for LIDAR is close to the visible range for humans, the eye acts as a focusing lens with his magnifying glass. However, since the laser light is not visible to humans, natural protection mechanisms of the eye such as closing of the pupil will not work. The energy transferred from the LIDAR laser into the eye heats the retina and leads in the worst case to a combustion of the visual cells (thermal retinal damage).

The calculation of the maximum radiated energy takes into account the ability of the energy to be forwarded into the tissue (heat dissipation). Thus, there are criteria that take into account the average heating, as well as the short term, caused by single pulse heating.

The following technical constraints are criteria that affect the eye safety:

- Wavelength (typical for automotive use is 850 nm to about 1 μm)
- Output pulse peak power (typically between 10 and 75 W)
- Output average power (typically between 2 and 5 mW)
- Duty cycle (pulse/pause ratio)
- Exit surface which can be refocused (fractions of mm^2 are typical when using optical fibers; the laser itself is just a few μm^2)

Details are strongly dependent on the particular design of the sensor. In particular, the duty cycles, output pulse power, and the exit surface which can be refocused are very different for the various established products on the market.

2.2 Integration for Forward-Oriented Sensors (e.g., ACC)

In general the integration into the vehicle with respect to the position is not that difficult. Basically, a LIDAR can be placed anywhere in the front. However, preferred positions are in the horizontal plane between the headlights and vertically between the upper edge of the roof and the bumper (see Fig. 17).

It does not matter whether the sensor is placed outside of or behind the windshield. Due to the detection of pollution, cleaning measures can be initiated, or if necessary the driver is informed. In contrast to a camera, however, “only” energy is transferred and thus a “clear” picture is not important. This reduces the requirements for a clean sensor surface considerably. Depending on the installation and

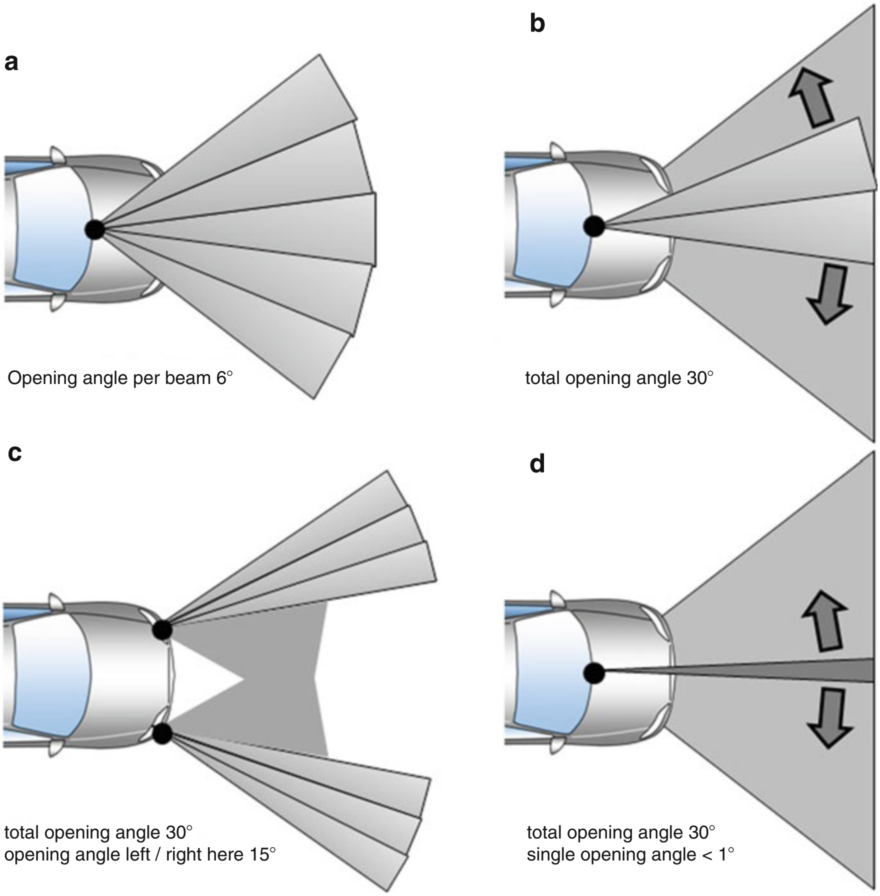


Fig. 17 Examples of different beam sensors: (**a**) multibeam rigid, (**b**) multibeam SWEEP, (**c**) multibeam spread, (**d**) single beam scan

integration considering aerodynamic requirements, a minimal negative impact on the sensor performance is caused by dark impurities (e.g., insects) on the sensor.

3 Additional Functions

With the LIDAR, it is possible to realize further very useful sensor functions.

3.1 Visibility Measurement

So with the abovementioned "soft target" detection, it is relatively easy to use it for computing the visibility by analyzing absorption. It can be used, e.g., for speed recommendation. Due to the wavelength which is close to the visible spectrum of human people, the measured reflection and absorption in the atmosphere is comparable to human visual obstruction.

3.2 Day/Night Detection

The measurable background illumination in the receiver changes significantly between day and night, when the sun gives off infrared beams many times higher than those emitted by the LIDAR.

This signal, adapted accordingly, can also be used as an additional control of driving lights (cf. the day/night or tunnel-dependent control of driving lights).

3.3 Pollution Detection

The basic functions of the self-diagnosis of a distance sensor include the detection of the degree of contamination of the sensor at the transmitter and receiver. This signal results in most of the cases not to a request to clean with the sensor, but the signal can easily be used to trigger an automatic cleaning of the headlight or windshield.

3.4 Speed Estimation

Today's LIDAR sensors have a sophisticated tracking and track up to 20 or more objects on and next to the road. The measurement of the distance and relative speed of objects next to the roadway such as delineator allow the determination of the intrinsic speed of the vehicle by means of distance sensor.

3.5 Driver Behavior/State

If the LIDAR is in passive mode, i.e., no active control system, the information on distance behavior, combined with the steering behavior, allows conclusions on driver condition and may then be communicated to the driver suitable (fatigue, inattention, etc.).

3.6 Object Expansion/Recognition

A scanning LIDAR system with high angular resolution can provide data which can be processed by further mathematical analysis, and as a result partly spatial extension of real obstacles as well as a recognition of the nature of the object can be obtained.

4 Current Series Examples

The sensors shown above satisfy all the required demands of modern ACC, FSRA, or even precrash systems. However, the realization of the optical properties is fundamentally different (Fig. 18, Table 2).

Hella relies on a multibeam principle. This is represented by multiple independent transmit and receive channels. In this case, an array of laser diodes is driven in multiplex procedure. Via the receiving optics, the information about a PIN diode array can be detected. The angular resolution corresponds more or less to the beam width of the individual transmit/receive channels. Up to 16 of these pairings are used to generate the corresponding lateral angle (see Fig. 19) (Höver et al. 2006).

Another method used in practice is the "sweeping" of "beams" as realized by **OMRON** in their second generation. Depending on the course of the road, five independent transmit/receive channels are pivoted laterally via a movable optic. The five transmit/receive channels are modeled by means of optical fibers. Different opening angle can be generated in the lateral and horizontal position depending on the channel. The "line of sight" of the beam light is tracked laterally as a function of the estimated road shape/curve radius. The advantage can be seen in less laser diodes and few moving parts. The disadvantage is that the detection depends on the quality of the estimation of the trajectory.

OMRON's third generation tries to improve the disadvantages of their second generation. The detection range is expanded to 30 × 10°. Instead of "sweep,"

Fig. 18 (**a**) AIS200 – Continental. (**b**) gen2 – Omron. (**c**) gen3 – Omron

Table 2 Examples from series production I

	AIS200 – Continental	gen2 – OMRON	gen3 – OMRON
Wavelength	905 mm	905 mm	905 mm
Eye safety	Class 1 (IEC825)	Class 1 (IEC825)	Class 1 (IEC825)
Radiated power	40 W (peak) 3.5 mW (average)	12 W (peak) 5 mW (average)	12 W (peak) 5 mW (average)
Detection area	±15° (azimuth/hor.)	±11° (azimuth/hor.)	±15° (azimuth/hor.)
	6.5° (elevation/vert.)	3° (elevation/vert.)	10° (elevation/vert.)
	Scan	Sweep	3D scan
Auto-alignment	Vertical		
Number of beams	15 . . . 30	5	1
Min. curve radius	100 m	300 m	100 m
Detection range	1 . . . 180 m	1 . . . 180 m	1 . . . 150 m
Size L × W × H	88 × 72 × 57 mm^3	180 × 89 × 60 mm^3	140 × 68 × 60 mm^3
Accuracy speed	1 kp/h	1 kp/h	1 kp/h
Specifics	Angular resolution 0.01°		

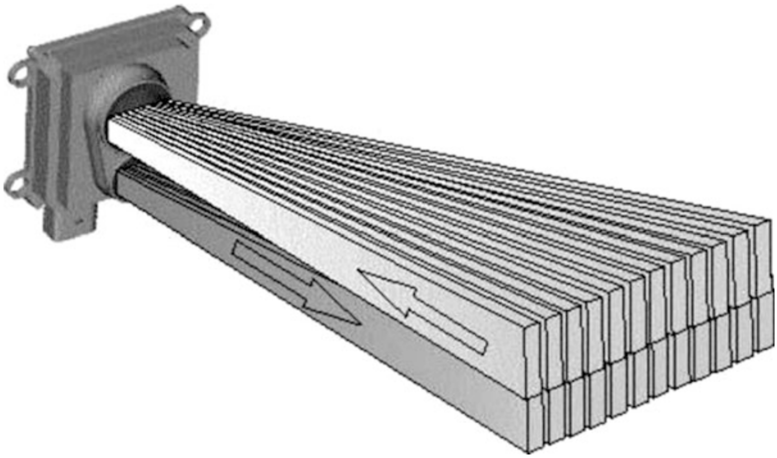


Fig. 19 Hella IDIS® – 12 Kanal laser

“scanning” is used. In doing so the entire lateral detection range is always detected and thus supposedly not captured interesting image sections. A unique feature is also the possibility to detect two other planes in the horizontal direction. This enables to use the sensor also in medium and compact class vehicles which do not have a level control. The mechanism is as robust as easy. Similarly, the swinging shaving head of a shaving apparatus thereby stimulates only the optics of the transmit and receive channels (Arita et al. 2007).

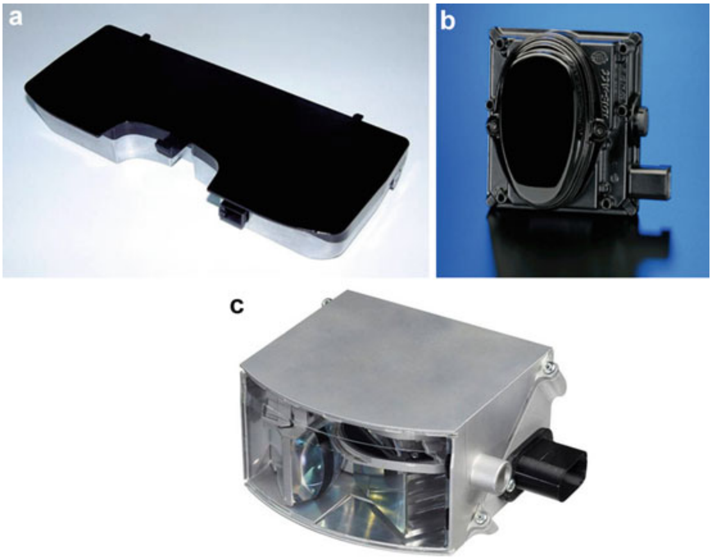


Fig. 20 (**a**) Siemens VDO. (**b**) Hella IDIS®. (**c**) ScaLa Valeo

Continental's latest series laser development, introduced by the takeover of the company **Siemens VDO**, also uses the already mentioned "sweeping" (see gen2 OMRON) of the total beam combination (five beams). Exceptional is the "sweep" field superimposed "Microscan," which makes an exact determination of the vehicle edges possible. Information of cut in of vehicles which can be earlier detected as "relevant" for the ACC system. Mirror optics allow the flat design of the sensor directly, like a rain sensor, mounted on the windshield. There is no unused optical free space, such as view funnel in front of the transmission range, and this can be integrated to save space in the rearview mirror area. This installation is located in the area of the windscreen wiper and is therefore always protected from contamination. In contrast, laser sensors mounted in the exterior have to deal with the strong salinity (winter) or during rainy conditions by the water droplets which causes significant attenuation. Different ranges, depending on weather conditions, are the result. The ACC system may work noticeably different (Mehr 2008).

Currently, a new sensor module is developed, which is provided for a series starting in 2015, "SRL-CAM400." Here, a CMOS camera with a LIDAR is integrated in a compact unit, which is housed in the mirror. The design is scalable provided, depending on vehicle class and performance requirements (Continental 2015) (Fig. 20, Table 3).

In 2010 **Valeo** has started a cooperation with company Ibeo. The aim is to develop Ibeo laser scanner technology (LUX 2010) in such a way so that it meets automotive mass market requirements. The Valeo LIDAR ScaLa takes into account the requirements for autonomous driving, i.e., broad coverage with a horizontal opening angle of 145°, an angular resolution of 0.25°, and a maximum distance of up to 150 m.

Table 3 Examples from series production II

	Siemens VDO	Hella IDIS®	ScaLa Valeo
Wavelength	905 mm	905 mm	905 mm
Eye safety	Class 1 (IEC825)	Class 1 (IEC825)	Class 1 (IEC825)
Radiated power		50 W (peak)	70 W
Total power consumption			<5.5 W (over the full range of temperature and the supply voltage)
Detection area	±15° (azimuth/hor.)	±11° (azimuth/hor.)	±15° (azimuth/hor.)
	6.5° (elevation/vert.)	3° (elevation/vert.)	10° (elevation/vert.)
	Scan	Sweep	3D scan
Auto-alignment	Vertical		
Number of beams	15 … 30	5	1
Min. curve radius	100 m	300 m	100 m
Detection range	1 … 180 m	1 … 180 m	1 … 150 m
Size L × W × H	88 × 72 × 57 mm^3	180 × 89 × 60 mm^3	140 × 68 × 60 mm^3
Accuracy speed	1 kp/h	1 kp/h	1 kp/h
Specifics	Angular resolution 0.01°		

TOYOTA Research has focused on the development of a new LIDAR sensor system and the performance shown by means of a proof-of-concepts prototype. It has a range of 100 m with 10 frames per second and a resolution of 340 × 96 pixels (IEEE 2013).

5 Outlook

In recent years the following tendencies regarding LIDAR technology can be seen:

(a) The number of companies which develop LIDAR sensors for the automotive sector has decreased.
(b) As common in the automotive industry, better performance for smaller, lighter, cheaper LIDAR is required and achieved, especially in the upper class. On the

other hand, cost-optimized sensors due to pending regulations as NCAP and EUR-NCAP are developed which optimize to these partly reduced requirements.

(c) While in the past driver assistance systems such as ACC, precrash, etc., are reserved for luxury vehicles, there is a clear trend that even middle and compact classes are equipped with such kind of features, finally accompanied by increased media interest in the relevant journals. This trend asks for the more cost-effective sensors for the realization of comfort and safety functions. Thus, interest in LIDAR sensors increases.

(d) For developments that deal with the topic of "autonomous driving" (Wikipedia 2015c) (see ▶ Chap. 62, "Autonomous Driving"), which became known through the "DARPA Urban Challenge," the main sensor was a laser scanner, for example, Velodyne LIDAR (Velodyne 2015). As autonomous driving can be found in almost any roadmap of vehicle manufacturers, the corresponding activities have been started to develop LIDAR sensors that meet the automotive requirements like cost and reliability and show a performance similar to the abovementioned laser scanner system.

(e) Sensors to record reference data known as "ground truth data" for system validation of series or pre-series development applications in the area of "part/fully autonomous driving" increasingly use laser scanner, for example, Velodyne LIDAR.

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