Range Sensor
용어

LASER: Light Amplification by Stimulated Emission of Radiation
LIDAR: Light Detection And Ranging
LADAR: Laser Detection And Ranging
RADAR: Radio Detection And Ranging
Sensor Comparison [15]
### Sensing Principles: Overview

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밀리파 레이더
Wavelengths at Various Frequencies [1]

The list below gives the wavelengths at various frequencies:
1 kHz = 300 kilometers
3 kHz = 100 kilometers
10 kHz = 30 kilometers
30 kHz = 10 kilometers
100 kHz = 3 kilometers
300 kHz = 1 kilometer
1 MHz = 300 meters
3 MHz = 100 meters
10 MHz = 30 meters
30 MHz = 10 meters
100 MHz = 3 meters
300 MHz = 1 meter
1 GHz = 300 millimeters = 30 centimeters
3 GHz = 100 millimeters = 10 centimeters
10 GHz = 30 millimeters = 3 centimeters
30 GHz = 10 millimeters = 1 centimeter
100 GHz = 3 millimeters
300 GHz = 1 millimeter

우리나라에서는 2001년 4월에 전파법 제9조의 규정에 의건, 지능형 교통 시스템과 관련하여 차량 레이더용 주파수를 특정 소출력 무선국으로 분류하여 분배하였다. 주파수 대역은 76~77GHz의 1GHz 대역폭이며, 용도는 차량 등의 충돌방지로 규정하고 있다 [2].
**Basic Principle of Operation [7]**

Radar (Radio Detection And Ranging) measurement of range, or distance, is made possible because of the properties of radiated electromagnetic energy.

**Reflection of electromagnetic waves:** The electromagnetic waves are reflected if they meet an electrically leading surface. If these reflected waves are received again at the place of their origin, then that means an obstacle is in the propagation direction.

Electromagnetic energy travels through air at a **constant speed**, at approximately the speed of light, (300,000 kilometers per second). This constant speed allows the determination of the distance between the reflecting objects (airplanes, ships or cars) and the radar site by measuring the running time of the transmitted pulses.

This energy normally travels through space **in a straight line**, and will vary only slightly because of atmospheric and weather conditions. By using of special radar antennas this energy can be focused into a desired direction. Thus the direction (in azimuth and elevation of the reflecting objects can be measured.)
Radar Equation [7]

First we assume, that electromagnetic waves propagate under ideal conditions, i.e. without dispersion.

Nondirectional Power Density $S_u$

\[
S_u = \frac{P_S}{4 \pi \cdot R_i^2} \quad \text{in m}^2
\]

$P_S = \text{transmitted power [W]}$

$S_u = \text{nondirectional power density}$

$R_i = \text{Range antenna - aim [m]}$

If the power radiated is redistributed to provide more radiation in one direction, then this results an increase of the **power density in direction of the radiation**. This effect is called **antenna gain**.

\[
S_g = S_u \cdot G
\]

$S_g = \text{directional power density}$

$S_u = \text{nondirectional power density}$

$G = \text{antenna gain}$

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Radar Equation [7]

Radar Cross Section
The size and ability of a target to reflect radar energy can be summarized into a single term, σ, known as the radar cross-section, which has units of m².

The target radar cross sectional area depends on:
- the airplane’s physical geometry and exterior features,
- the direction of the illuminating radar,
- the radar transmitters frequency,
- the used material types.

The reflected power Pr

\[
P_r = \frac{P_s}{4 \cdot \pi \cdot R_i^2} \cdot G \cdot \sigma \quad \text{in [W]} \]

- \( P_r \) = reflected power [W]
- σ = radar cross section [m²]
- \( R_i \) = range, distance antenna - aim [m]
Radar Equation [7]

Simplified a target can be regarded as a radiator in turn due to the reflected power. In this case the reflected power $P_r$ is the emitted power. Since the echoes encounter the same conditions as the transmitted power, the power density yielded at the receiver $S_e$ is given by:

$$S_e = \frac{P_r}{4 \cdot \pi \cdot R_2^2} \text{ in W}$$

$S_e$ = power density at receiving place
$P_r$ = reflected power [W]
$R_2$ = range aim - antenna [m]

At the radar antenna the received power $P_E$ is dependent on the power density at the receiving site $S_e$ and the effective antenna aperture $A_W$.

$$P_E = S_e \cdot A_W$$

$P_E$ = received power [W]
$S_e$ = power density [W/m$^2$]
$A_W$ = effective antenna aperture [m$^2$]

$$A_W = A \cdot K_a$$

$A_W$ = effective antenna aperture [m$^2$]
$A$ = geometric antenna area [m$^2$]
$K_a$ = efficiency
The power received, $P_E$ is then calculated:

\[
P_E = \frac{P_r}{4 \cdot \pi \cdot R_2^2} \cdot A \cdot K_a
\]  

(8)
Another equation, which will not be derived here, describes the antenna gain $G$ in terms of the wavelength $\lambda$.

$$G = \frac{4 \cdot \pi \cdot A \cdot K_a}{\lambda^2}$$

Solving for $A$, antenna area, and replacing $A$ into equation 9; after simplification it yields:

$$P_e = \frac{P_s \cdot G^2 \cdot \sigma \cdot \lambda^2}{(4 \cdot \pi)^3 \cdot R^4} \text{ in [W]}$$

Solving for range $R$, we obtain the classic radar equation:

$$R = \sqrt[4]{\frac{P_s \cdot G^2 \cdot \lambda^2 \cdot \sigma}{P_e \cdot (4\pi)^3}}$$
**Basic Principle of Operation [7]**

**Distance-determination**

\[
R = \frac{c_0 \cdot t}{2}
\]

where:
- \( c_0 \) = speed of light = \( 3 \cdot 10^8 \) m/s
- \( t \) = measured running time [s]
- \( R \) = slant range antenna - aim [m]

**Velocity-determination** [9]

\[
v = \frac{\lambda \cdot f_d}{\cos \theta}
\]

\( f_d \) 는 도플러 주파수 편이를, \( \lambda \) 는 발사된 전파의 파장을, 그 리고 각 \( \theta \) 는 레이더와 피측정체 사이의 각으로 레이더의 측정방향과 피측정체의 이동 방향이 이루는 각도

[Image: File:Doppler_effect_diagrammatic.png]

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Basic Principle of Operation [7]

Direction Estimation

1. Beam steering by mechanical rotation and encoder, Direction-determination by reflected power
2. Digital beam forming by transceiver array: electronic steering
3. DOA estimation by receiver array
4. Multi-lateration by sensor array
The rapid and accurate transmission of the bearing information between the turntable with the mounted antenna and the scopes can be carried out for servo systems and counting of azimuth change pulses.

Servo systems are used in older radar antennas and missile launchers and works with help of devices like synchro torque transmitters and synchro torque receivers. In newer radar units we find a system of Azimuth–Change–Pulses (ACP). In every rotation of the antenna a coder sends many pulses, these are then counted in the scopes.

Newer radar units work completely without or with a partial mechanical motion. These radars employ electronic phase scanning in bearing and/or in elevation (phased-array-antenna).
Basic Principle of Operation [7]

Direction Estimation

Digital Beam Forming (Electronic Steering)

A phased array antenna is composed of lots of radiating elements each with a phase shifter. Beams are formed by shifting the phase of the signal emitted from each radiating element, to provide constructive/destructive interference so as to steer the beams in the desired direction.

The main beam always points in the direction of the increasing phase shift. Well, if the signal to be radiated is delivered through an electronic phase shifter giving a continuous phase shift now, the beam direction will be electronically adjustable.

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Basic Principle of Operation [7]

Direction Estimation

DOA (Direction Of Arrival) Estimation

Since the phases are spatially distributed over the four receiving antennae the phase distribution over the four antennae is called a spatial snapshot or spatial sample, cf. figure 3.

This spatial frequency $f_s$ is dependent on the angle $\theta$ or direction of arrival (DOA) as the following formula states:

$$f_s = \frac{d \cdot \sin \theta}{\lambda}$$

where $\lambda$ is the wavelength of the impinging wave front and $d$ the distance between two neighboring antenna elements.

Figure 3: Wave front impinging on four antennae with corresponding spatial snapshot and time signals in a single target situation.

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Basic Principle of Operation [7]

Direction Estimation

Multi-lateration by Sensor Network

Fig. 4: Multilateration by least squares estimation
Dipole Antenna [1]

- The simplest form of antenna is the “dipole”.

A physical dipole consists of two equal and opposite point charges: in the literal sense, two poles [3].

Electric dipole field lines
**Dipole Antenna [4]**

A dipole antenna, created by Heinrich Rudolph Hertz around 1886, is an antenna that can be made by a simple wire, with a center-fed driven element for transmitting or receiving radio frequency energy.

Typically a dipole antenna is formed by two quarter wavelength conductors or elements placed back to back for a total length of $\lambda/2$. The quarter wave or unipole antenna is a single element antenna fed at one end, that behaves as a dipole antenna. It is formed by a conductor $\lambda/4$ in length. It is fed in the lower end, which is near a conductive surface which works as a reflector.
Parabolic Dish Antenna [5]

A typical parabolic antenna consists of a parabolic reflector with a small feed antenna at its focus. The reflector is a metallic surface formed into a paraboloid of revolution and (usually) truncated in a circular rim that forms the diameter of the antenna. This paraboloid possesses a distinct focal point by virtue of having the reflective property of parabolas in that a point light source at this focus produces a parallel light beam aligned with the axis of revolution.

Parabolic curve showing arbitrary line (L), focus (F), and vertex (V). L is an arbitrary line perpendicular to the axis of symmetry and opposite the focus of the parabola from the vertex (i.e. farther from V than from F.) The length of any line $F - P_n - Q_n$ is the same. This is similar to saying that a parabola is an ellipse, but with one focal point at infinity.
Parabolic Dish Antenna [5]

6. In a parabolic dish, the antenna is placed at the focal point. It may be a dipole and horn or any other type of antenna. The parabolic dish focuses the signal into a very narrow beam, representing a huge amount of gain. [Diagram] http://archive.electronicdesign.com/files/29/19463/fig_06.gif

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A Yagi-Uda antenna. From left to right, the elements mounted on the boom are called the **reflector**, **driven element (dipole)**, and **director**. The reflector is easily identified as being a bit (5%) longer than the driven element, and the director a bit (5%) shorter.
A patch antenna (also known as a Rectangular Microstrip Antenna) is a popular antenna type.

Its name is attributed to the fact that it consists of a single metal patch suspended over a ground plane. The assembly is usually contained inside a plastic radome, which protects the antenna structure from damage (as well as concealing its essential simplicity). Patch antennas are simple to fabricate and easy to modify and customize.

They are the original microstrip antenna as described by Howell, which are a length of microstrip transmission line of approximately one-half wavelength.
In telecommunication, there are several types of microstrip antennas (also known as printed antennas) the most common of which is the microstrip patch antenna or patch antenna. A patch antenna is a narrowband, wide-beam antenna fabricated by etching the antenna element pattern in metal trace bonded to an insulating dielectric substrate with a continuous metal layer bonded to the opposite side of the substrate which forms a groundplane. Common microstrip antenna radiator shapes are square, rectangular, circular and elliptical, but any continuous shape is possible.

- Microstrip antennas are also relatively inexpensive to manufacture and design because of the simple 2-dimensional physical geometry.

- Such an array of patch antennas is an easy way to make a phased array of antennas with dynamic beamforming ability.
Microstrip Antenna [10]

The most commonly employed microstrip antenna is a rectangular patch. The rectangular patch antenna is approximately a one-half wavelength long section of rectangular microstrip transmission line. When air is the antenna substrate, the length of the rectangular microstrip antenna is approximately one-half of a free-space wavelength.
4. A patch or microstrip antenna is made on a PCB. At microwave frequencies, it’s easy to make arrays of patches to form a phased array that will have gain, directivity, and the ability to incorporate beamforming and steering.

64-element vertically polarised X-band microstrip patch array. An antenna such as this shows exactly why the patch is such a popular choice for array design.

http://www.activefrance.com/Antennas/page2.html

http://archive.electronicdesign.com/files/29/19463/fig_04.gif
Phase and Interference [1]

• The phase of the two sets of waves could be matched up, with the peaks and valleys of both coinciding; or they could be completely out of phase, with the peaks of one coinciding with the valleys of the other and the reverse, a condition known as "antiphase"; or they could have a phase difference anywhere between those two extremes. If they are between those two extremes, the additive effect is intermediate. This phenomenon is known as "wave interference".

• Controlled interference effects can be used to deliberately shift the direction of a radio beam, a scheme known as “electronic steering”.

![Wave interference diagram](image)
Phased Array Antenna [7]

The **phase shifter** routes the microwave signal that is supplied to each radiating element through cables of varying length. The cables delay the wave, thereby shifting the relative phase of the output. The illustration shows the three basic delays each phase shifter can introduce.
A phased array antenna is composed of lots of radiating elements each with a phase shifter. Beams are formed by shifting the phase of the signal emitted from each radiating element, to provide constructive/destructive interference so as to steer the beams in the desired direction.

The main beam always points in the direction of the increasing phase shift. Well, if the signal to be radiated is delivered through an electronic phase shifter giving a continuous phase shift now, the beam direction will be electronically adjustable.
Phased Array Antenna [7]

**Linear Arrays**: These antennae consist of lines whose elements are fed about a common phase shifter.

**Planar Arrays**: These antenna arrays completely consist of singles radiating elements and each of it gets an own phase shifter. The elements are ordered in a matrix array. The planar arrangement of all elements forms the complete phased-array antenna.

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http://e-fab.com/space-fed-lens-antennas.htm
Antenna Propagation Pattern [1]

• Directional antennas don't always generate all their radio output in a nice neat directional beam. Interference between transmit signals may generate "sidelobes" that cause unwanted transmissions to the sides of the beam, or a "backlobe" in the reverse direction. The sidelobes and backlobe can rob the main lobe of energy and of course corrupt the directionality of the beam, generating and receiving signals in unwanted directions. Proper antenna design minimizes the power lost by sidelobes and backlobes.

• Sidelobes are a particular nuisance in radars, since they can produce false returns and can pick up radio interference, including deliberate interference produced by countermeasures systems. In radar systems, the ratio of sidelobe to main beam power is generally kept to less than $-40 \, \text{dB}$, or 1:10,000. This is done in arrays by carefully arranging the power levels of the array elements, with more power in the center elements than at the elements along the edge. There are a number of "aperture tapering" schemes to define the proper arrangements of power levels.
Waveform [16]

1. Pulse
2. FSK
3. FMCW

Fig. 1. Two CW waveform principles: (a) FSK modulation, (b) LFM modulation.

(그림 1) 펄스 레이다의 일반적 구조

(그림 2) 펄스 레이다의 신호파형

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Pulse Radar [7]

Maximum Unambiguous Range

The maximum measuring distance $R_{max}$ of a radar unit isn't orientated only at the value determined in the radar equation but also on the duration of the receiving time.

The maximum range at which a target can be located so as to guarantee that the leading edge of the received backscatter from that target is received before transmission begins for the next pulse. The pulse-repetition frequency (PRF) determines this maximum unambiguous range of a given radar before ambiguities start to occur. This range can be determined by using the following equations:

\[
PRT = \frac{1}{\text{PRF}}
\]

\[
R_{max} = \frac{c_0 \cdot (PRT - PW)}{2}
\]

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Pulse Radar [7]

Minimum Measuring Range

Monostatic pulse radar sets use the same antenna for transmitting and receiving. During the transmitting time the radar cannot receive: the radar receiver is switched off using an electronic switch, called duplexer.

The minimal measuring range $R_{\text{min}}$ (blind range) is the minimum distance which the target must have to be detect. Therein, it is necessary that the transmitting pulse leaves the antenna completely and the radar unit must switch on the receiver. The transmitting time $t_{PW}$ and the recovery time $t_{\text{recovery}}$ should are as short as possible, if targets shall be detected in the local area.

$$R_{\text{min}} = \frac{c_0(t_{PW} + t_{\text{recovery}})}{2} \text{ in } [m]$$
Pulse Radar [7]

Range Resolution

The target resolution of a radar is its ability to distinguish between targets that are very close in either range or bearing.

Range resolution is the ability of a radar system to distinguish between two or more targets on the same bearing but at different ranges. The degree of range resolution depends on the width of the transmitted pulse, the types and sizes of targets, and the efficiency of the receiver and indicator. **Pulse width** is the primary factor in range resolution. A well-designed radar system, with all other factors at maximum efficiency, should be able to distinguish targets separated by one-half the pulse width time $\tau$. Therefore, the theoretical range resolution cell of a radar system can be calculated from the following equation:

$$S_r \geq \frac{c_0 \cdot \tau}{2}$$
Two discrete frequencies $f_A$ and $f_B$

The frequency step $f_{\text{Step}} = f_B - f_A$ is small and will be chosen in dependence of the maximum unambiguous target range.

Due to the small frequency step in the transmit signal a single target will be detected at the same Doppler frequency position in the adjacent CPI (coherent processing interval)’s but with different phase information on the two spectral peaks.

$$R = -\frac{c \cdot \Delta \varphi}{4\pi \cdot f_{\text{Step}}}$$

Phase difference $\Delta \varphi = \varphi_B - \varphi_A$ in the complex spectra
FMCW [17]

Radars which apply pure linear frequency modulation technique (LFM) modulate the transmit frequency with a triangular waveform.

Δf+ and Δf− represent the difference frequency of emitted signal and received signal in the rising part and declining part of a triangular modulated cycle, respectively.
FMCW [17]

frequency $f$

transmitted frequency ramps 1 and 2

received frequency

$df_1$ $df_2$

$dt = 2s/c$ time $t$

s = const.

frequency $f$

$df_1$ $df_2$

$s = const.$

$v_{rel} < 0$

$f_D = -2v_{rel} * f_0 / c$

$f_0 =$ center transmitter frequency

$c =$ speed of light

spectrum of ramp 1

spectrum of ramp 2

$df$

$-df$

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FMCW

With Multiple Target

If a spectral peak is detected in the Fourier spectrum at index $\kappa$ (normalized integer frequency) the ambiguities in target range and velocity can be described in a $R-\nu$ diagram by the following equation [7]

$$\kappa = \frac{\nu}{\Delta \nu} - \frac{R}{\Delta R} \quad \Leftrightarrow \quad \frac{\nu}{\Delta \nu} = \frac{R}{\Delta R} + \kappa$$

![Diagram of $R-\nu$ diagram for two targets measured with up chirp.]

Fig. 2: Example $R-\nu$-diagram for two targets measured with up chirp.

![Diagram of Multi-target detection by FMCW.]

Fig. 2 Multi-target detection by FMCW
FMCW [7]

For reason of resulting range–velocity ambiguities further measurements with different chirp gradients in the waveform are necessary to achieve an unambiguous range–velocity measurement even in multi–target situations.

In multi target situations a waveform as shown in Fig. 3 (a) is used which consists of 4 different chirp signals. The detected spectral lines from all 4 chirp signals can be drawn in a single $R$–$\nu$ diagram (Fig 3 (b)) where the gradient of a single line is dependent on the chirp sweep rate.

![Diagram](image.png)

Fig. 3: (a) waveform for use in multi target situations and (b) corresponding example $R$-$\nu$-diagram for a two target situation and the related intersection points.
FMCW [19]

CFAR (Constant False Alarm Rate): a common form of adaptive algorithm used in radar systems to detect target returns against a background of noise, clutter and interference.

http://en.wikipedia.org/wiki/Constant_false_alarm_rate

A more exact frequency value has to be estimated.
FMCW [19]

Freq. Estimation and Extraction

(range, velocity) Intersection Analysis

Tracking

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TUHH

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FMCW [19]

Detected frequencies vs time for chirps = 1, 2, 3, 4
Detected frequencies are then passed through the intersection algorithm. It resolves occurring ambiguities in multiple target situations, a single measurement consisting of 4 chirp signals with slightly different signal parameters. The target range and target radial velocity is calculated by this algorithm. There is a high false alarm rate (isolated points in the plane $(Range, Speed)$) and targets are not yet associated to tracks (represented by a single color).
These detected range/speed couples are then used to feed the advanced tracking algorithm.
Which is target? [21]

Figure 2. Radar image 1

Figure 3. Indirect transmission path from target

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Which is target? [21]

Figure 4. Radar image 2

Figure 5. Indirect transmission path from crash barrier

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What is UltraWideBand?

- Communication that occupies more than 500 MHz of spectrum
- Communication with fractional bandwidth of more than 0.2
Short Range Radar [12]

Fig. 1 Short range radar sensor and mounting behind bumper

Fig. 5 a) M/A-COM SRR sensor, b) block diagram

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Short Range Radar [12]

Fig. 3 Schematic diagram of a 24 GHz SRR front-end

Fig. 4 SRR specification

- Radar Principle: Pulse Radar
- Frequency: 24.125 GHz
- Tx Power: <17dBm EIRP
- Bandwidth: 5 GHz
- Pulse width: 1.0–1.5 ns
- Pulse Repetition Frequency: ~3 MHz
- Detection Cycle Time: 40 ms
- Antenna Detection Characteristic: ± 8° Elevation 3dB limit
  ± 65° Azimuth 3dB limit

Object Parameters
- Number of Objects: 10
- Parameters Types: Range, Bearing, Velocity, Quality, Track ID

Range Parameters
- Detection Range: 20 ... 30 m
- Range (Object) Resolution: 15 cm
- Range Accuracy: 5 cm
Siemens VDO Blind Spot Detection Sensor – View on Radar Antenna
Long Range Radar [13]
The modulation control and the signal preprocessing (pre-amplification, A/D conversion, filtering) is integrated in an ASIC (Radar-ASIC).
Long Range Radar [13]

MMIC (Monolithic Microwave Integrated Circuits)

Fig.5: Block diagram and photograph of 77 GHz transceiver

Fig.6: Block diagram and photograph of reference oscillator

Fig.7: RF-module with SiGe-MMICs and Radar-ASIC on backside

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### Long Range Radar [13]

#### Tab. 1: Global sensor parameters

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<th>Value</th>
<th>Unit</th>
<th>Remarks</th>
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<td>Operating Frequency</td>
<td>76-77</td>
<td>GHz</td>
<td>Global type approval</td>
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<td>Modulation</td>
<td>FMCW</td>
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<tr>
<td>Transmitted power</td>
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<td>dBm</td>
<td>EIRP peak</td>
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<tr>
<td>Antenna principle</td>
<td>4 fixed beams simultaneously</td>
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#### Tab. 2: Field of view performance

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<td>Horizontal FoV</td>
<td>30 deg, 20 deg, 12 deg</td>
<td>deg</td>
<td>Short range, Mid range, Long range</td>
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#### Tab. 3: Measurement performance

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<td>0.5</td>
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<tr>
<td>Relative velocity</td>
<td>m/s</td>
<td>-80...+30 m/s</td>
<td>0.12</td>
<td>0.6</td>
</tr>
<tr>
<td>Angle</td>
<td>deg</td>
<td>-15...+15 deg</td>
<td>≥ 0.1</td>
<td></td>
</tr>
</tbody>
</table>

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**Long Range Radar [13]**

Fig. 7: Polarimetric 76 GHz radar frontend mounted on a van for road testing

DCX 1997

Raytheon 1997

Fig. 8. Experimental car of the Technical University Hamburg-Harburg equipped with a 77GHz far range radar sensor.

[16] 2001

Volvo, Autocruise, 2009

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Applications

Curve prediction

Figure 3: Azimuth angle and relative velocity.
Applications

Advanced Path Prediction

Fig. 3. Input and intermediate images from the algorithm (U.K. urban environment). (a) Radar sensor output. (b) Thresholding applied to (a) with a variable threshold index number of 3.7. (c) Peak detection applied to (b) with a window size of 22 pixels. (d) Hough transformation applied to (c) with a 12-histogram bin for curve fitting.

Example of real radar and optical images of a highway

Figure 4. APM’s output
Applications

Target classification

Fig. 5: Doppler spectrum of a walking person

Fig. 6: Doppler spectrum of a slowly driving car

Parking assit

Figure 1: Car parking scenario

Figure 4: Detected (blue dots) and tracked (red dots) target positions for a simulated parking lot

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References

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References

레이저 레이더
Fig. 2  Construction of Laser Radar System
Fig. 3  Construction of Optical Transmitter
< Transmitting lens (Convex lens) >
Fig. 6 Construction of Optical Receiver
<Receiving lens (Fresnel lens)>
LIDAR [1]

APD (avalanche photo diode)

광다이오드에 빛을 입사시켜 역 바이어스 전압을 증가시켜 가면, 발생된 전자가 높은 전계에서 가속되어 원자와 충돌하여 새로운 전자와 정공이 발생하는 눈사태 현상(avalanche phenomenon)이 생기는데, 이 현상을 이용하여 광신호를 전기 신호로 변환하는 것. 광통신용의 수광 소자로 이용되고 있다. 재료로는 Ge, Si, Pt–GaAs 등이 사용된다. 특징으로는 다이오드 자신의 눈사태 효과에 의한 전류 증폭 작용으로 신호 대 잡음비(S/N)가 높고, 고속 디지털 회선에 적합하지만 바이어스 전압이 높으며, 온도 의존성이 크다는 등의 결점이 있다. 광통신의 검출기로는 그 밖에 PIN 다이오드(PD) 등이 사용되고 있다.
Scanning Laser Radar [1]

Motor with Angle Encoder

Rotating Mirror

IR-Transmitter Diode

Outgoing Beam

Photo Diode Receiver

Reflected Echo

ALASCA design

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Scanning Laser Radar [1]

A basic LIDAR system involves a laser range finder reflected by a rotating mirror (top). The laser is scanned around the scene being digitised, in one or two dimensions (middle), gathering distance measurements at specified angle intervals (bottom).
Scanning Laser Radar [1]

Ibeo Automotive Systems LUX

Range 0.3m to 200m (50m @ 10% remission)
Horizontal beam width
   with 4 layers: 85°
   with 2 layers: 100°
Vertical opening angle: 3.2°
Angular resolution: 0.125°
Scan frequency: 12.5 Hz / 25.0 Hz / 50.0 Hz

Figure 1: Sensor integration in the INTERSAFE demonstrator.
Scanning Laser Radar [2]

Figure 1: Laserscanner mounted at the front of the car. It is rotated so that the first layer hits the road 10 meters in front of the car.

Fig. 4 Two-dimensional scanning structure (Provided by NHK Spring Co., Ltd.)

Fig. 6 Scanning procedure
References