Continental
The Future in Motion

Automotive Radar Systems

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Passive Safety & ADAS / Chassis & Safety
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Introduction

- Motivation: Radar drives future of automotive driving safety and comfort
- Company presentation: Continental (leading tier-one automotive supplier)
- ADAS: Continental roadmap towards ‘Vision Zero’, functions, sensors, product segments
- What is a radar?
- Radar systems overview
- Course overview
- Summary
- References

Introduction
Why & where am I at Continental?

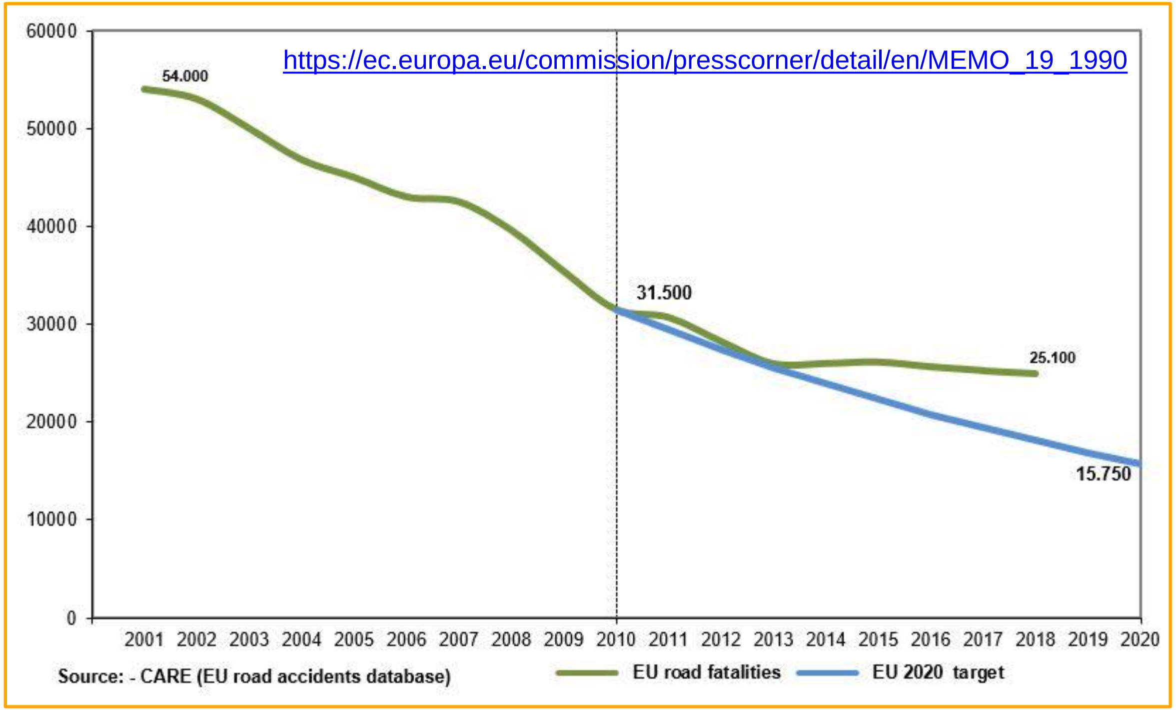
Born in Bangladesh
2000: B.Sc. in EEE at BUET, Bangladesh
2002: M.Sc. In CME at Hochschule Offenburg, Germany
2008: PhD in HFE at FBH-Berlin, Germany
Student job, thesis: Siemens München
2009: First entry at Magna Electronics, Ottobrunn, Germany
2011: radar group of Magna was bought by Continental

I started working for Continental in…	June 2011
My business unit / division is…	Autonomous Mobility & Safety (AMS)
My responsibilities are…	mmwave engineering, radar sensor technology for ADAS
I decided to work for Continental because…	Challenging professional opportunities
The different fields/ positions I got to know at Continental where…	State of the art professional competencies can be made

Motivation: Safer & more Convenient Driving

Save lives

- Every year, the equivalent of the entire population of a small city are killed in traffic accidents in the EU alone.
- ca. 1.35 million deaths per year due to road accidents [WHO]
- Road traffic crashes cost most countries 3% of their GDP.
- Obligation of new car generations
  - make driving safer and more convenient
  - reduce fatalities and severe injuries



Motivation: Safer & more Convenient Driving

Regulations

- United Nations General Assembly declares ‘Decade of Driving Safety’: 2011-2020
- European commission guidelines: reducing the traffic fatalities by a further 50%

"The Decade of Action for Road Safety can help all countries drive along the path to a more secure future... Today, partners around the world are releasing national or citywide plans for the Decade, hosting policy discussions and enabling people affected by road crashes to share their stories widely. Now we need to move this campaign into high gear and steer our world to safer roads ahead. Together, we can save millions of lives."

UN Secretary-General Ban Ki-moon
Message on the launch of the Decade of Action for Road Safety, 11 May 2011.

https://www.unece.org/united-nations-special-envoy-for-road-safety/decade-of-action.html

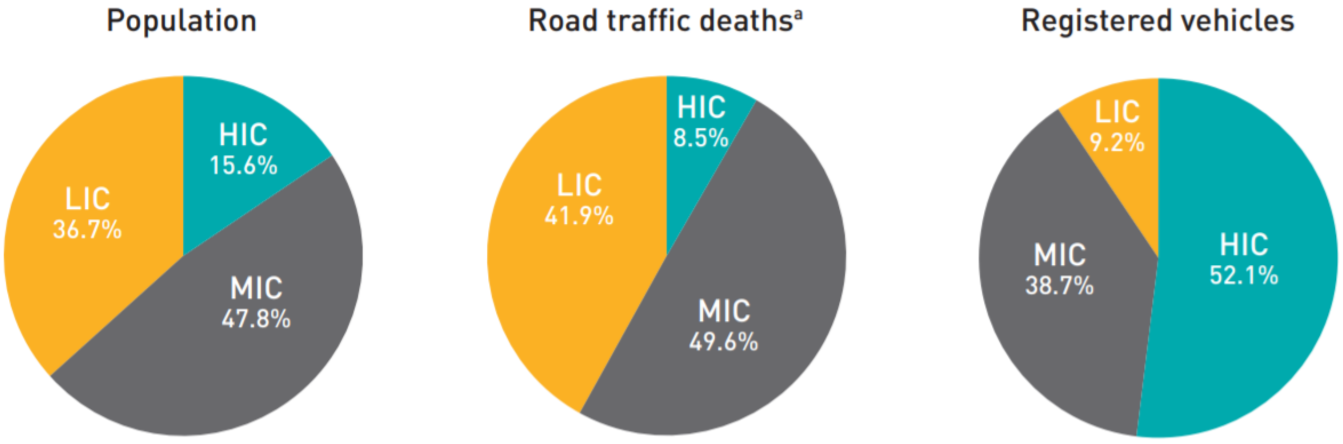
Motivation: Safer & more Convenient Driving

Safety for all

- safety in driving should be available to all and in all market

Save time

- More than 1.2 billion people spend more 50 min per day in driving vehicles.



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LIC: low income countries, MIC: middle income countries, HIC: high income countries

Motivation: Safer & more Convenient Driving

Engineering challenges

- Safety should be affordable to all and in all market
  - Go for added features, reduction in price, cheaper & matured technologies.
  - However, no compromise with quality issues and compliances.
- Increase in efficiency
  - Drive for solutions to ensure convenience and time saving.
- ADAS and networked safety systems, fusions
- Autonomous mobility and safety (AMS)

“70% of all serious accidents could potentially be avoided by driver assistance systems”

(BAST* Germany)

Increase safety & comfort is our mission!

ADAS Functions

"95% of all road accidents involve some human error, in 76% of the cases the human is solely to blame"

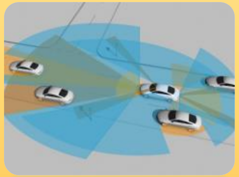
European Commission*

Traffic Sign Assist

Emergency Brake Assist

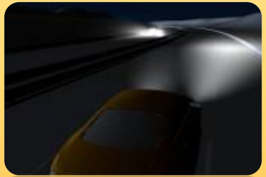
Lane Departure Warning

Adaptive Cruise Control



Surround View

Blind Spot Detection



Intelligent Headlamp Control

Rear Cross Traffic Alert

"70% of all serious accidents could potentially be avoided by driver assistance systems"

(BAST* Germany)

Increase safety & comfort is our mission!

* Bundesanstalt für Straßenwesen

Types of Driver Assistance Systems

Definitions

- **Safety:** car itself takes control of the car to avoid accidents or to reduce the severity of the injuries

  Active safety: technologies assisting in the prevention of a crash: Examples: AEB, ABS, ACC
  Passive safety: technologies to protect occupant during and after a crash: airbags, seat belts etc.

- **Comfort:** additional information to the car, relief from any type of discomfort (e.g. vibration), still full control belongs to the driver

  Passive comfort: only additional information to the driver, e.g. parking aid
  Active comfort: car takes some control to relief the driver from monotonous tasks, e.g. ACC

- **Performance** = Safety * Comfort

- **False positives** (real & imaginary ghost targets), **false negatives** (blindness) and complete failure

Mobility of the Future: Autonomous Driving

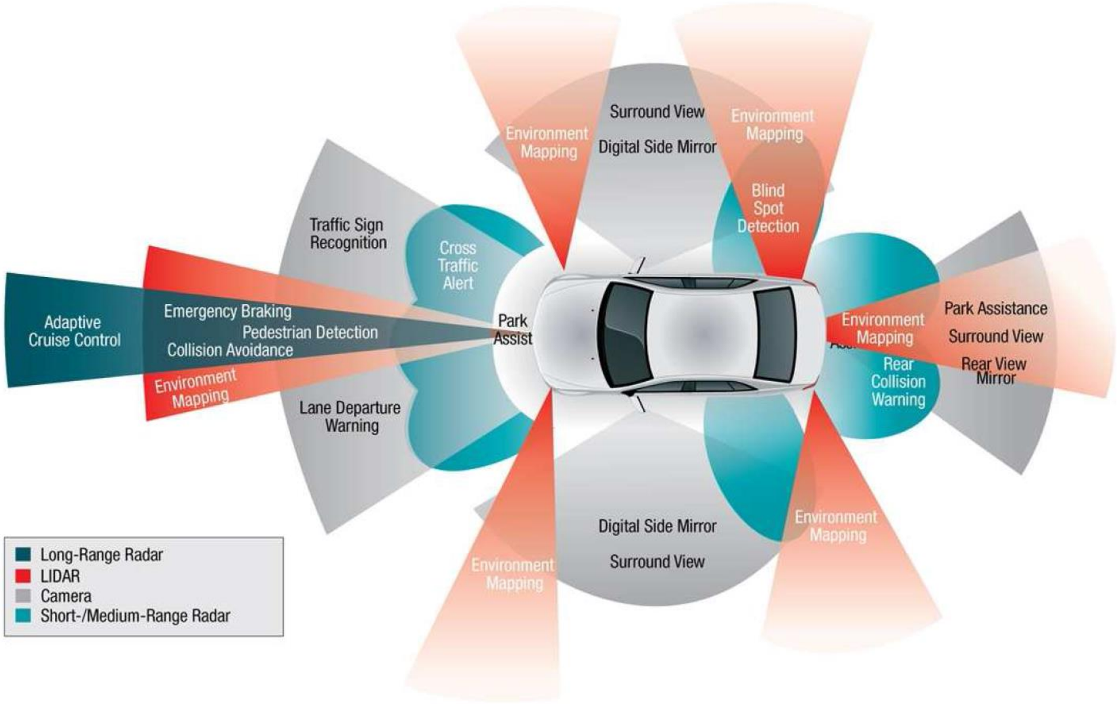
Continental's goals

- We are convinced that automated driving will be a key element of future mobility, as it will enhance the safety, efficiency and comfort of individual mobility even further.
- Automation will lead to a significant decrease in the number of road traffic casualties and it allows drivers to use their time in the car in other ways and therefore more efficiently.
- Our path to automated driving:
  - Partially automated driving by 2016. (Park assist) (Traffic jam assist)
  - Highly automated driving from 2020. (Highway chauffeur)
  - Fully automated driving from 2025. (Highway pilot) (Park pilot)
- In 2012, we became the first automotive supplier to be granted a test license for automated driving on public roads in the U.S. state of Nevada.

What is a Radar?

Ambient sensor

- In order to ensure the driving safety and avoid collisions, perception of the ambient is inevitable.
- Wrong perception & impacts
  - Blindness, ghost targets & complete failure
- Ambient sensors: radar, lidar, camera
- Sensor fusion



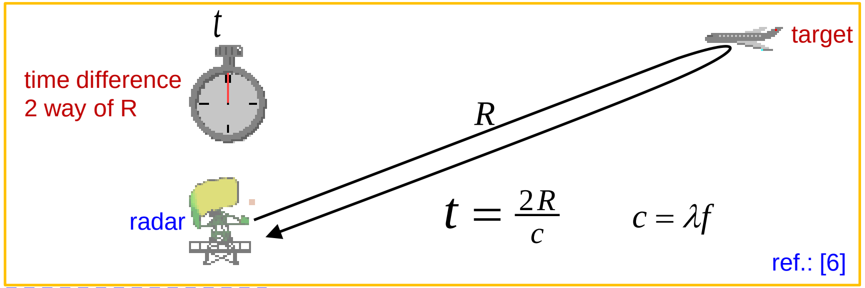
What is a Radar?

Embedded systems (ES)

- Application specific computer system - Information processing systems embedded into a larger product. ES are limited by the HW and SW functionalities, mostly with higher quality and reliability requirements.
- Reasons to buy ES are the dedicated applications, not the information processing
- Real time systems: react within the time specified interval. Right answer arriving after the specified time is considered as wrong.
- Electric/ electronic devices.

Source: http://www.electromsolution.com/embedded-system/

What is a Radar?

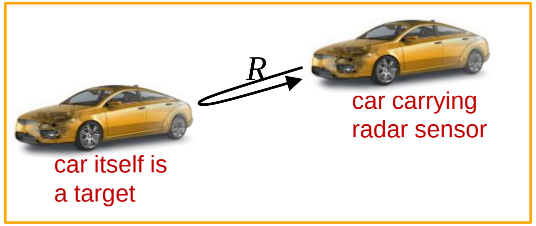


R(km)=0.15*t(μs)
R(nm)=0.018*t(μs)
1nM=1.825km

Detection of remote targets

› Radar: Radio Detection and Ranging

› Ambient sensor, embedded system



How radar works?

› Radar transmits through antenna EM waves towards region of interest

› Some energy of these EM waves is scattered by the distant target

› Radar receives a portion of the scattered energy – this is called echo of the target

› Time difference between 'when the EM energy is transmitted' and 'when the target echo is received' is measure of how far away the target is.

› c: 3e8 m/sec, R: distance bet. radar and target, λ: wavelength, f: frequency, t: round-trip time (**time of flight**)

automotive radar
R:0.5 to 250m
ΔR:~10cm,δR:~2cm
ΔV:~60cm/s,δV:~10cm/s
δΦ:~0.1°

R=250m → t~1.66μs

Why Radar? Pivotal technology for ADAS & AMS

Advantages of radar

- Radar can measure distance, velocity and angular positions of targets very precisely:

  long range (~1kmiles) detection and tracking, wide area search capability
- Operates in all weather, day & night: very much robust against environmental influences, e.g., extreme temperatures, bad light or weather conditions
- Simultaneous reliable target detection and rejection of unwanted clutter objects, target imaging (fixed/moving)
- Ability to adaptively shape antenna beam to mitigate interference and jamming
- Relatively loss less, straight line propagation

Challenges of radar

- Long range detection: large/heavy antennas, high power transmitter, significant power storage, high cost
- Radar beams not propagate well through the Earth, water, heavy foliage, around obstacles
- Vulnerable to jamming and anti-radiation missiles
- Target can detect that it is being illuminated
- Target can locate the radar in angle space
- Echo from some targets is becoming very small: low observable technology.

Why Radar? Camera? Lidar? Fusion??

Ambient sensor for ADAS & AMS

Radar: Very robust against environmental influences: extreme temperature, fog, rain, snow

- Not only distance and angle but also speed
- For near range targets radar needs high resolution, quite complex to achieve.
- Radar signals also return from non-moving objects like ground, fence posts, traffic signals or stalled car. It is not easy to separate them from moving cars.

Lidar and camera have troubles with fog, snow rain etc.

Lidar uses emitted light, so it works independent of ambient light. This is what camera can't. Lidar is robust against interference and has much higher resolution than radar.

Lidar sees only in grey scale, but **camera** sees colors like human eyes.

Lidar and camera do not see speed

Source: Automotive Radar and Lidar Systems for Next Generation Driver Assistance Functions - R. H. Rasshofer and K. Gresser

	Short Range Radar	Long Range Radar	Lidar	Ultrasound	Video Camera	3D-Camera	Far IR Camera
Range Measurement < 2m	o	o	o	++	-	++	-
Range Measurement 2..30m	+	++	++	-	-	o	-
Range Measurement 30..150m	n.a.	++	+	- -	-	-	-
Angle Measurement < 10 deg	+	+	++	-	++	+	++
Angle Measurement > 30 deg	o	-	++	o	++	+	++
Angular Resolution	o	o	++	-	++	+	++
Direct Velocity Information	++	++	- -	o	- -	- -	- -
Operation in Rain	++	+	o	o	o	o	o
Operation in Fog or Snow	++	++	-	+	-	-	o
Operation if Dirt on Sensor	++	++	o	++	- -	- -	- -
Night vision	n.a.	n.a.	n.a.	n.a.	-	o	++

++ : Ideally suited / + : Good performance / o : Possible, but drawbacks to be expected;

- : Only possible with large additional effort / - - : Impossible / n.a. : Not applicable

Sensor Fusion: inevitable for AMS

Challenges: resolving conflicts among the sensors

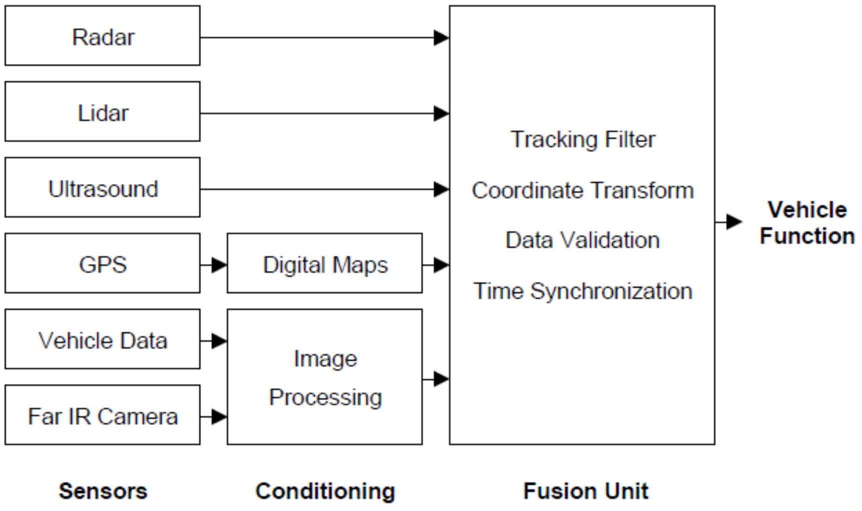
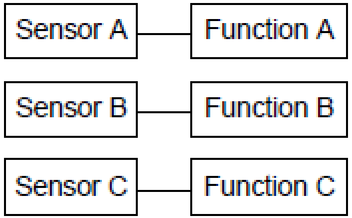


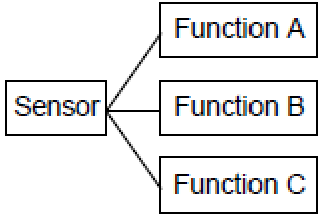
Fig. 7. Typical automotive sensor data fusion architecture.

Seperate systems ambient sensors

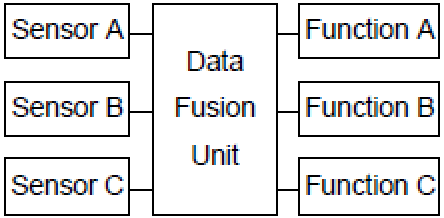


a)

Multiple use of sensors



b)

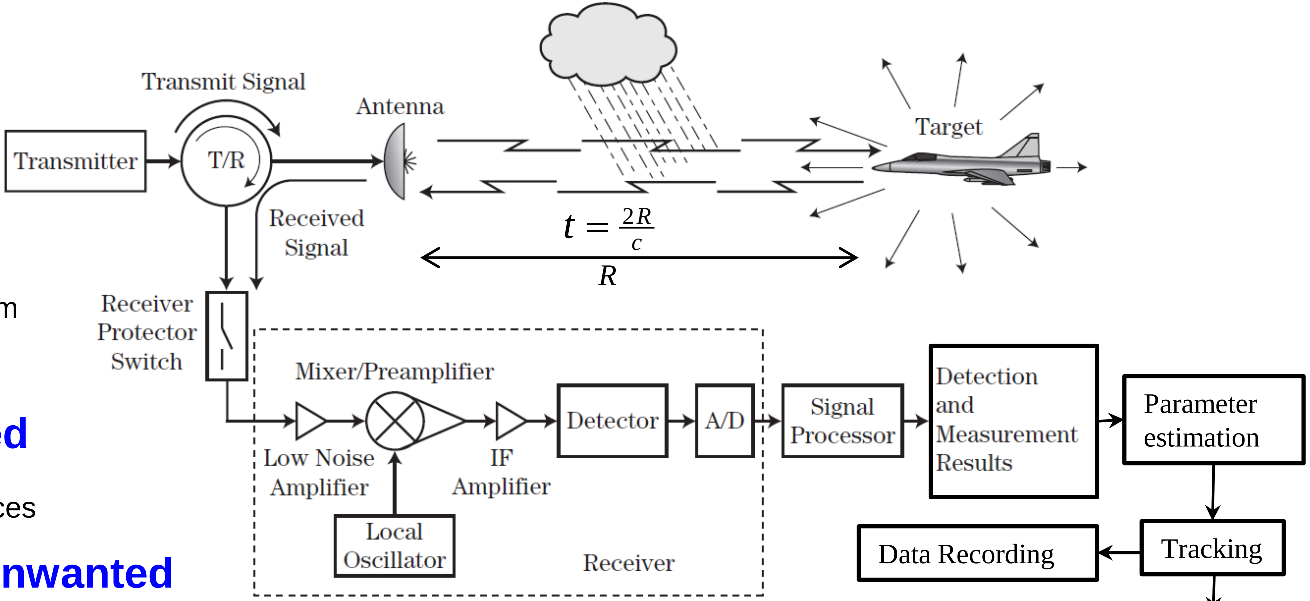


c)

Multi sensor data fusion

Source: Automotive Radar and Lidar Systems for Next Generation Driver Assistance Functions - R. H. Rasshofer and K. Gresser

Radar Systems



Modules

RF: Transmitter, antenna, receiver
LF: ADC, DAC, signal processor
Display, mechanical
Software: embedded, DSP, algorithm

Monostatic vs. bistatic

Targets: detection wanted

radar cross section (RCS)
Estimation of environmental influences

Interference: detection unwanted

Clutter: reflected EM waves from undesired objects (clutter)

EMI: unintentional EM waves, caused by man-made sources

Jamming (ECM) in the form of noise or false targets

Targets compete with noise (internal and external sources) to be detected

[Reference: 7,8]

Radar Systems

Modules

RF: Transmitter, antenna, receiver
LF: ADC, DAC, signal processor
Display, mechanical
Software: embedded, DSP, algorithm

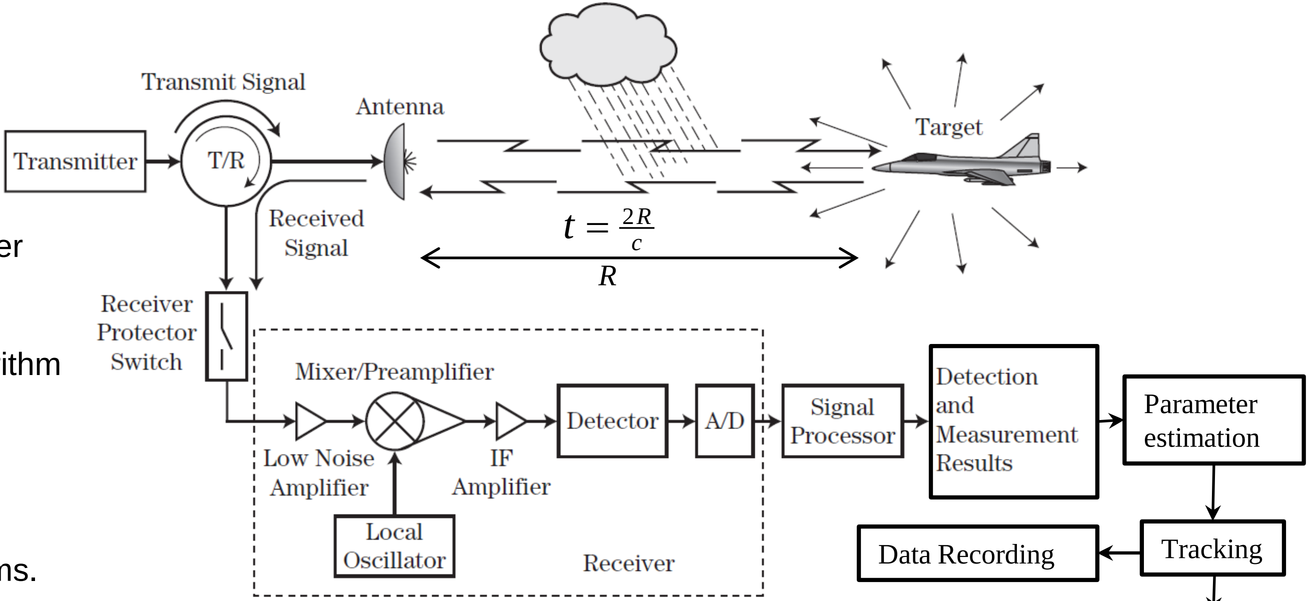
Monostatic vs. bistatic

Technology & domains

Advanced communication systems.

Multi domain modules: EE, ME

Driven mostly by the electrical engineering, information and communication theories.



Targets compete with noise (internal and external sources) to be detected

Course Overview

Lecture topics are divided into

- ‘Scopes’, ‘fundamentals’, ‘details’, ‘design issues’ and ‘real examples’, manufacturing
- Problem solving with MATLAB

Examination: written examination at the end of 13 weeks, each 4 hours,

- 5 ECTs, elective, catalogue ‘Automotive Electronics & Information Technology’
- Total 100 points, highest grade (1) needs at least 85 points, to pass (lowest grade of 4) 45 points

Goal: students will learn in depth practical knowledge of design parameters of radar as well as its different applications

- How radar drives the automotive driving safety, from engineering as well as managerial point of view
- Industrialization: from R&D to realization, from prototypes to volume production

Course Overview

Lecture topics are divided into

Scopes: possible application. Market overviews, advantages, disadvantages etc.

Fundamentals: application independent basic radar concepts

Details: different concepts, different modules (e.g. EE, HF, DSP, communication)

Design issues: combining different concepts into the design of a particular radar system

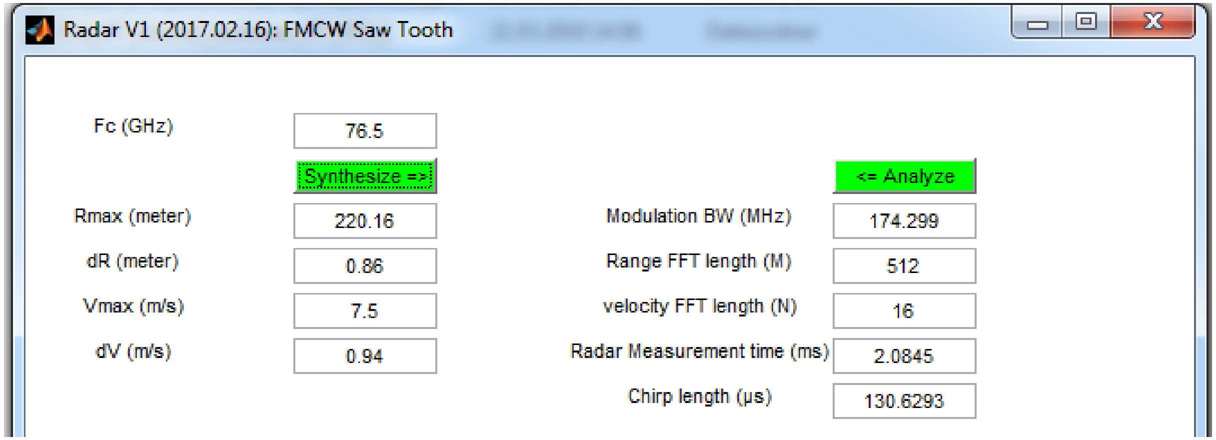
Real examples: Automotive radar systems: parts & parcels, technologies

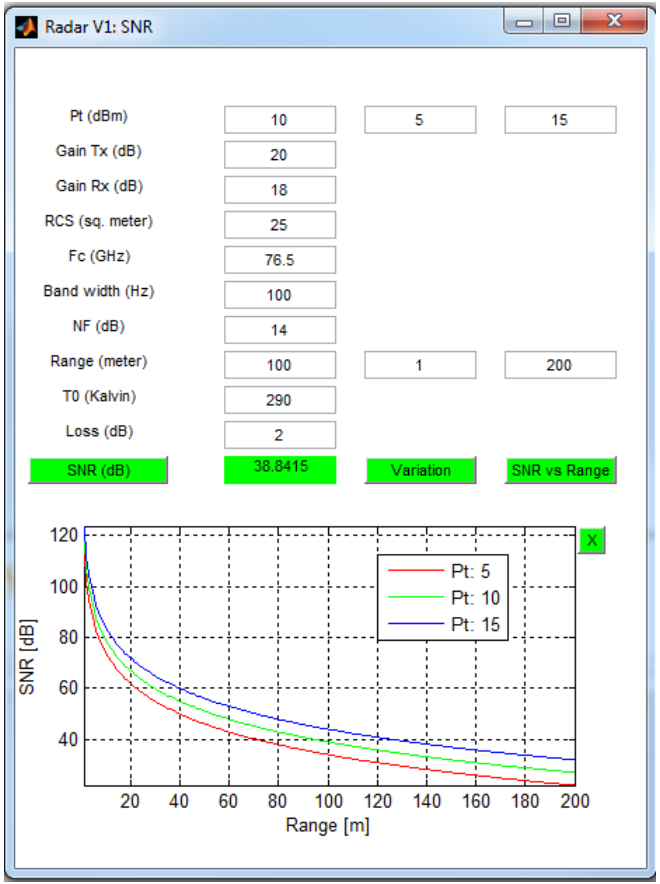
Manufacturing: production line issues

Course Overview

Radar related MATLAB Exercises

How to check basic radar design parameters?





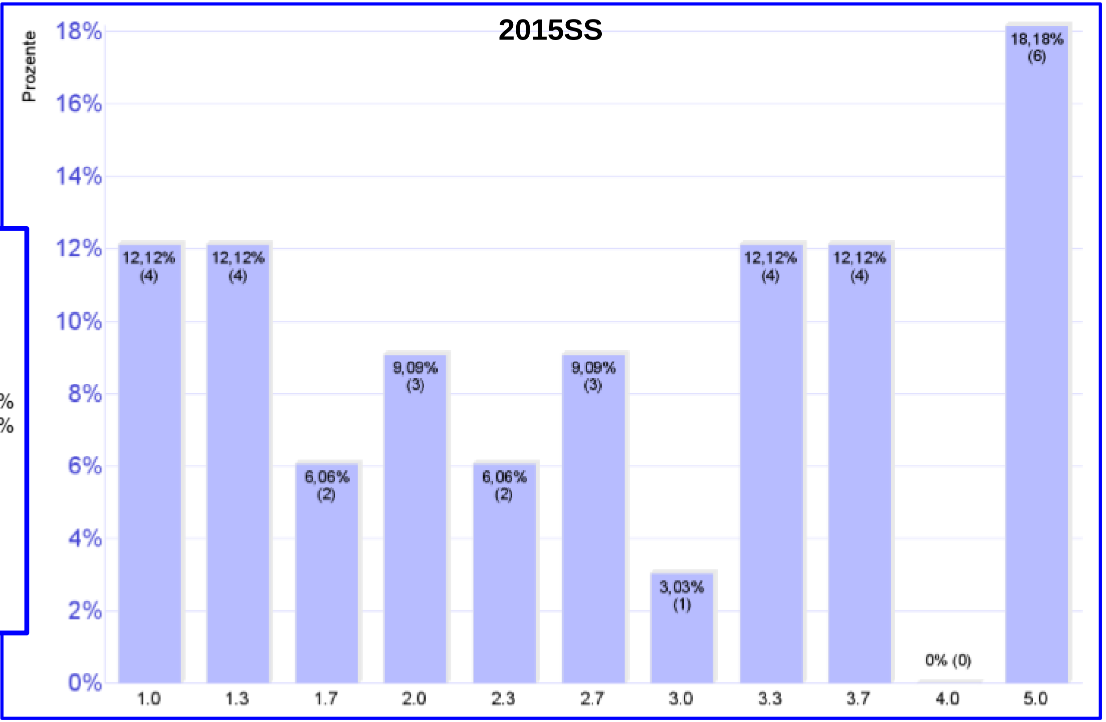
Course Overview

Examination of SS2015

2015SS+2015WS: total 44, fail 8

Semester	Sommersemester 2015
Studiengang	IA
Fach (AnC)	Automotive Radar Systems (011)
Prüfer(in)	Talukder
Prüfer(innen)liste	Talukder

1,0:	4	12,12%	**Angemeldet:**	53	
1,3:	4	12,12%	**Teilgenommen:**	33	62,26%
1,7:	2	6,06%	**Nicht teilgenommen:**	20	37,74%
2,0:	3	9,09%	**Mittelwert:**	2,80	
2,3:	2	6,06%	**Median:**	2,70	
2,7:	3	9,09%			
3,0:	1	3,03%			
3,3:	4	12,12%			
3,7:	4	12,12%			
4,0:	0	0%			
5,0:	6	18,18%			



Course Overview

Examination of SS2016/SS2017

Semester	Sommersemester 2016
Studiengang	IA
Fach (AnC)	Automotive Radar Systems (016)
Prüfer(in)	Talukder
Prüfer(innen)liste	Talukder

1,0:	12	54,55%	**Angemeldet:**	29	
1,3:	3	13,64%	**Teilgenommen:**	22	75,86%
1,7:	0	0%	**Nicht teilgenommen:**	7	24,14%
2,0:	1	4,55%	**Mittelwert:**	1,54	
2,3:	4	18,18%	**Median:**	1,00	
2,7:	0	0%			
3,0:	1	4,55%			
3,3:	0	0%			
3,7:	1	4,55%			
4,0:	0	0%			
5,0:	0	0%			

Semester	Sommersemester 2017
Studiengang	IA
Fach (AnC)	Automotive Radar Systems (009)
Prüfer(in)	Talukder
Prüfer(innen)liste	Talukder

1,0:	12	44,44%	**Angemeldet:**	42	
1,3:	7	25,93%	**Teilgenommen:**	27	64,29%
1,7:	1	3,70%	**Nicht teilgenommen:**	15	35,71%
2,0:	2	7,41%	**Mittelwert:**	1,56	
2,3:	1	3,70%	**Median:**	1,30	
2,7:	3	11,11%			
3,0:	0	0%			
3,3:	0	0%			
3,7:	0	0%			
4,0:	0	0%			
5,0:	1	3,70%			

Course Overview

Radar fundamentals

$$\frac{S}{N} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 k T_s B_n L}$$

- Radar modules
- Radar functions: what radars do
- Radar classification & applications
- Radar parameters: monostatic/bistatic, pulsed/continuous wave, coherent/non-coherent, Doppler shift, ambiguities
- Radar equation: calculates max. measurable range of a target, connects properties of radar, target and the medium, Radar losses
- Radar block diagrams: system and functional, different radars (pulsed, Doppler, pulsed Doppler, MTI, Tracking)
- Different communication systems

Radar Applications: Military

Search radars

Air defense systems : detects, tracks and identifies airborne threats

Over the horizon search radar

Ballistic Missile Defense Radars

Radar seekers and fire control radars

Instrumentation/Tracking Test Range Radars

Tracking, fire control and missile support radars

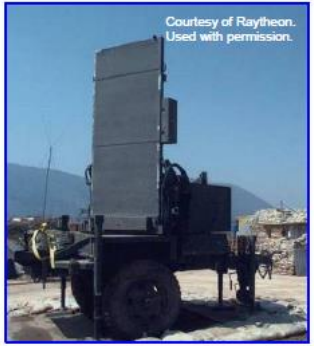
Multifunction radars

Artillery Location Radars

Target Identification radars


Courtesy of US Air Force.


Courtesy of Wikimedia


Courtesy of Raytheon. Used with permission.

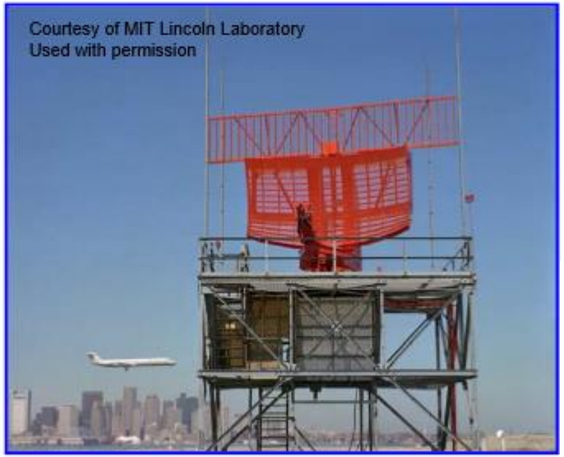

Courtesy of Northrop Grumman. Used with permission.


Courtesy of Raytheon. Used with permission.

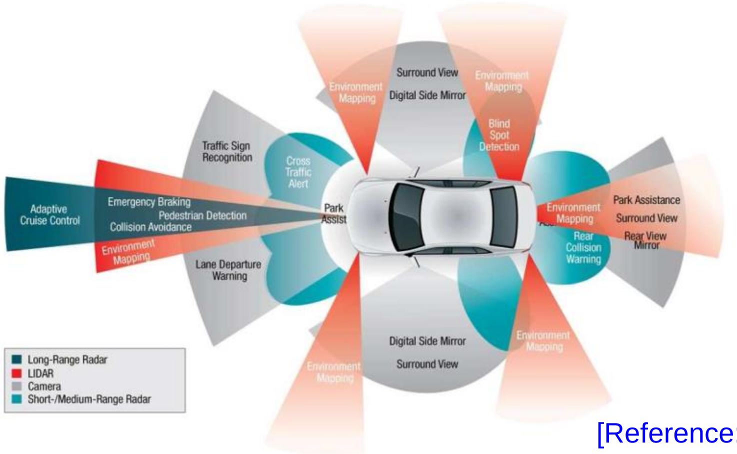

Courtesy of US Navy

[Reference: 8]

Radar Applications: Commercial



- Process control radars
- Airport surveillance radars
- Weather radars
- Wake vortex detection radars
- Marine navigation radars
- Satellite mapping radars
- Police speed measuring radars
- **Automotive collision avoidance radars**
- Ground penetration radars
- Radar altimeters



[Reference: 11]

Radar System Classification

By Function

Surveillance, Track
Fire Control – Guidance
Discrimination

By Mission

Air Traffic Control, Air Defense

Automotive safety

Ballistic Missile Defense
Space Surveillance
Airborne Early Warning (AEW)

Ground Moving Target Indication (GMTI)

By Platform

Ground
Ship
Airborne
Space

By Waveform Format

Low PRF
Medium PRF
High PRF
CW (Continuous Wave)

By Waveform

Pulsed CW
Frequency Modulated CW
Phase Coded, Pseudorandom Coded

By Antenna Type

Reflector
Phased Array (ESA)
Hybrid-Scan

By Range

Long, medium, short range

By Name

Pave Paws (FPS-115)
Cobra Dane(FPS-108)
Sentinel (MPQ-64)
Patriot (MPQ-53)
Improved Hawk (MPQ-48)
Aegis (SPY-1)
ALCOR
Fire-finder (TPQ-37)
Millstone
ARS3xx
ARS4xx
ARS5xx

By Frequency

VHF-Band, UHF-Band
L-Band, S-Band
C-Band, X-Band
KU-Band, KA-Band
W-Band

Other

Solid State
Synthetic aperture radar(SAR)
MTI
GMTI

Course Overview

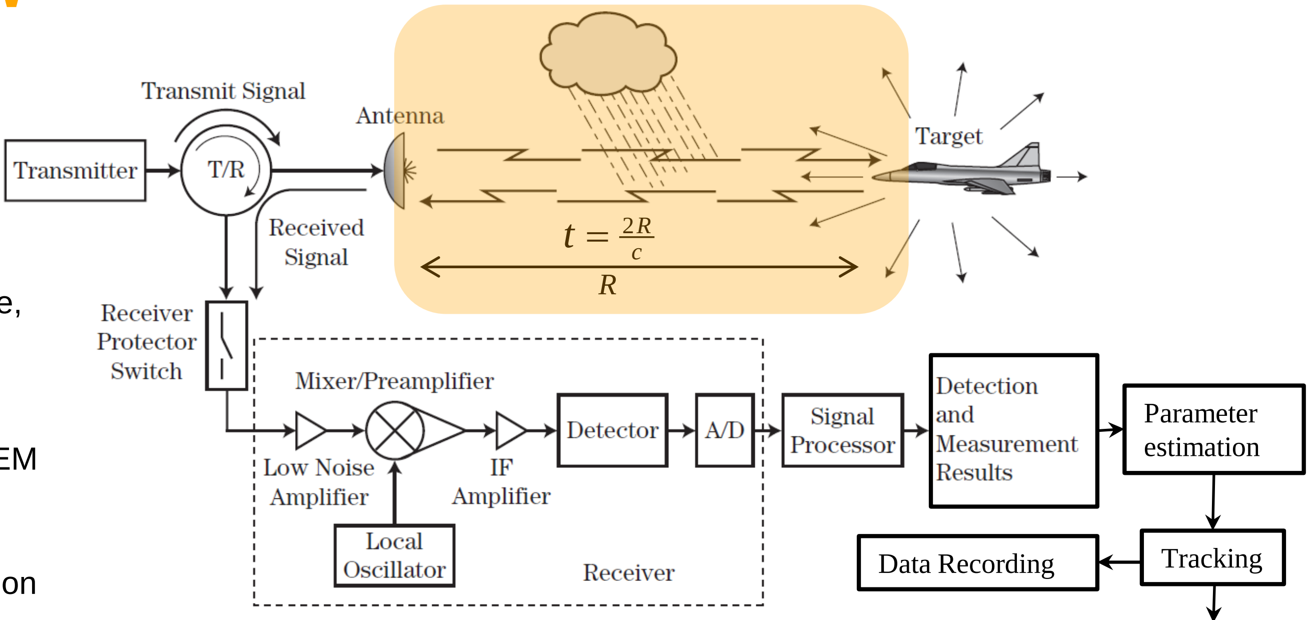
Radar (EM) wave propagations

Electromagnetic EM waves

- Maxwell's equations
- wavelength, frequency and phase, superposition (interference)
- Intensity, polarization

Atmospheric effects: interaction of EM waves with matter

- Diffraction, atmospheric attenuation, atmospheric refraction
- Reflection (scattering)



Electromagnetic Waves vs Mechanical Waves

Waves in general transport energy around us.

More waves (shorter wave lengths, higher frequency) means more energy transport.

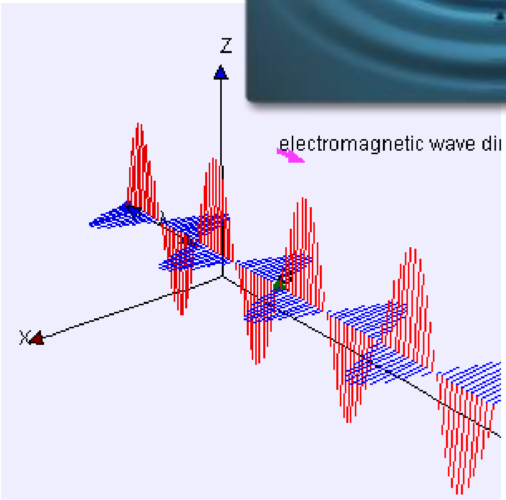
Mechanical waves are caused by disturbance or vibration in matter (medium: solid, gas, liquid or plasma).

Examples: water waves or sound waves

Sound waves cannot travel in vacuum, because there is no medium to transmit these mechanical waves.

EM waves are formed by the vibration of electric or magnetic fields.

Light, EM waves or radiation all refer to the same phenomenon of electromagnetic energy.



[Reference: 8]

Maxwell's Equations

Maxwell's equations form the foundation of classical electromagnetism, optics and electric circuits.

E: electric field (V/m)
H: Magnetic field (A/m)
B: magnetic flux density (tesla, T)
D: electric displacement (C/m^2)
J: electric current density (A/m^2)
ρ: electric charge density (C/m^3)
ε: permeability ($\varepsilon_0 = 8.854 \times 10^{-12}$ F/m in vacuum)
μ: permittivity ($\mu_0 = 4\pi \times 10^{-7}$ H/m in vacuum)

German physicist **Heinrich Herz** applied Maxwell's equations to the production and reception of radio waves. He proved that:

Velocity of radio waves is equal to the velocity of light.
E- and H-fields detach themselves from wire and go free.

Integral Form	Differential Form
$\oiint \vec{D} \cdot d\vec{S} = \iiint \rho \, dV$	$\nabla \cdot \vec{D} = 4\pi\rho$
$\oiint \vec{B} \cdot d\vec{S} = 0$	$\nabla \cdot \vec{B} = 0$
$\oint \vec{E} \cdot d\vec{s} = -\iint \frac{\partial \vec{B}}{\partial t} \cdot d\vec{S}$	$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$
$\oint \vec{H} \cdot d\vec{s} = \iint \left(\frac{\partial \vec{D}}{\partial t} + \vec{J} \right) \cdot d\vec{S}$	$\vec{\nabla} \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J}$

$$\vec{D} = \varepsilon \vec{E} \qquad \vec{B} = \mu \vec{H}$$

James Clerk Maxwell
(1831-79)

EM wave equations:

$$\left(\nabla^2 - \mu\varepsilon \frac{\partial^2}{\partial t^2} \right) \vec{E} = 0$$

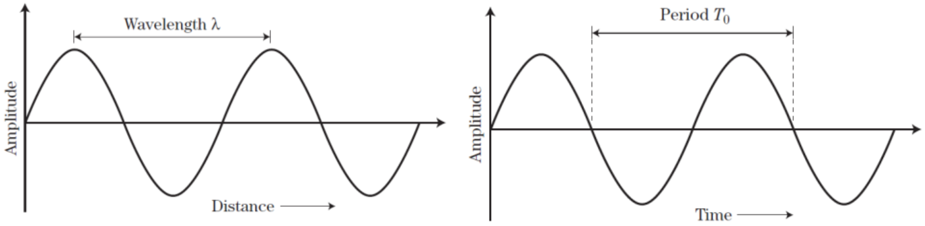
$$\left(\nabla^2 - \mu\varepsilon \frac{\partial^2}{\partial t^2} \right) \vec{B} = 0$$

Solutions of Maxwell's equations:
(no sources, vacuum, non-conducting medium)

$$\vec{E}(\vec{r}, t) = E_o e^{j(\vec{k} \cdot \vec{r} - jwt)}$$

$$\vec{B}(\vec{r}, t) = B_o e^{j(\vec{k} \cdot \vec{r} - jwt)}$$

Electromagnetic Waves: Properties



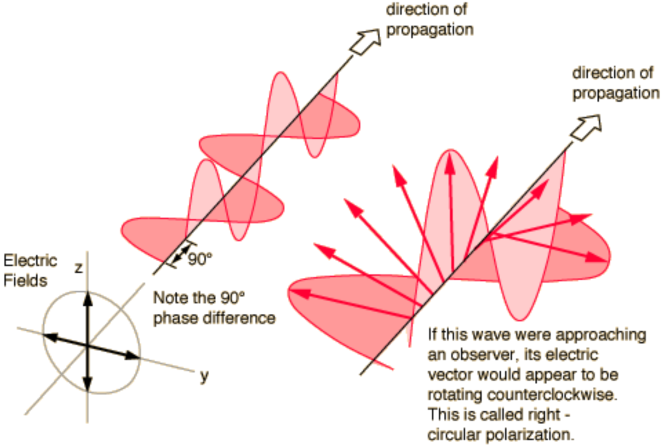
EM waves appear in space and time:

Simple solution of wave equation: $\mathbf{E}=\mathbf{x}E_0\cos(wt-kz+\Phi_0)$,
Wave number (spatial frequency): $k=2\pi/\lambda$ (radian/m) ,
Angular frequency: $w=2\pi f$ (radian/s)
temporal frequency, $f=1/T_0$

$c_0=\lambda f$, Phase: $wt-kz+\Phi_0$

Special frequency is used for angular measurements, whereas temporal frequency is used for range and velocity measurements.

Polarization: direction of E-fields (looking into the direction of propagation) which can be linear (horizontal or vertical), circular, elliptical. Radar sensors on the same car with different polarizations (e.g. horizontal & vertical) can be beneficial.



Impedance: $Z(\Omega)=E(V/m)/H(A/m)$: useful quantities are E and H rather than voltage (V)and currents(I). However they can not be measured directly.

Power density: ExH (W/m^2): Power can be measured directly, then E and H indirectly

[http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/polclas.html]

Electromagnetic Waves: Transmission and Reception

EM waves are generated at the generator.

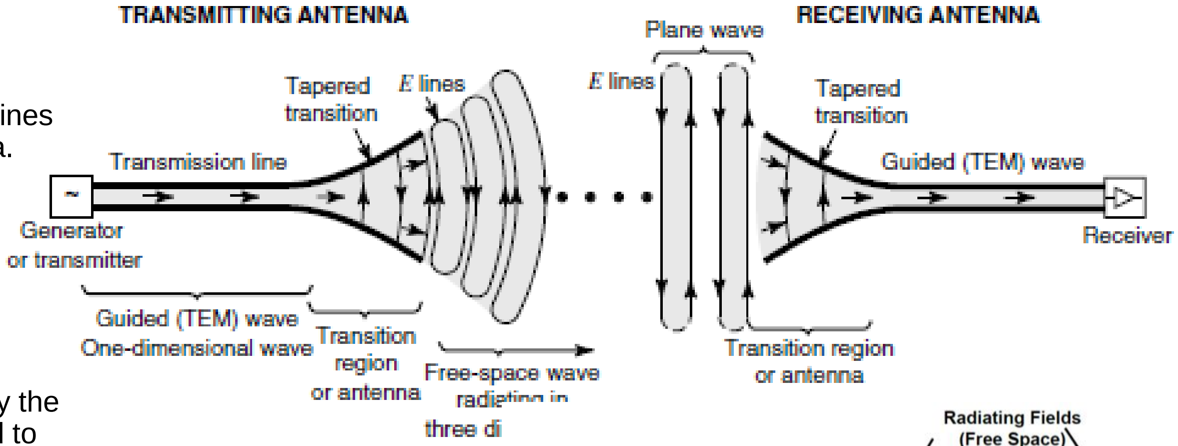
Then EM waves are guided by the transmission lines (waveguide, WG) and transmitted by the antenna.

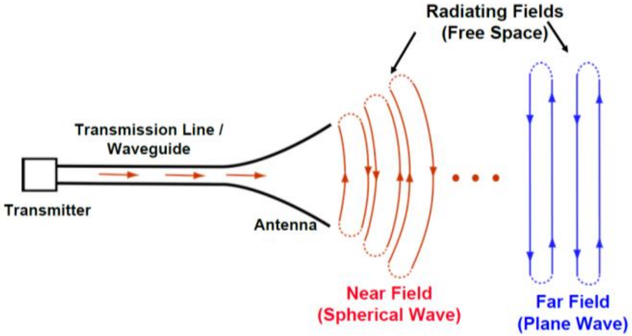
EM waves are attenuated in the free space.
  Path loss (mobile communication) ~ 1/ R^2
  Path loss (radar) ~ 1/ R^4

Plane waves are received by the antenna.

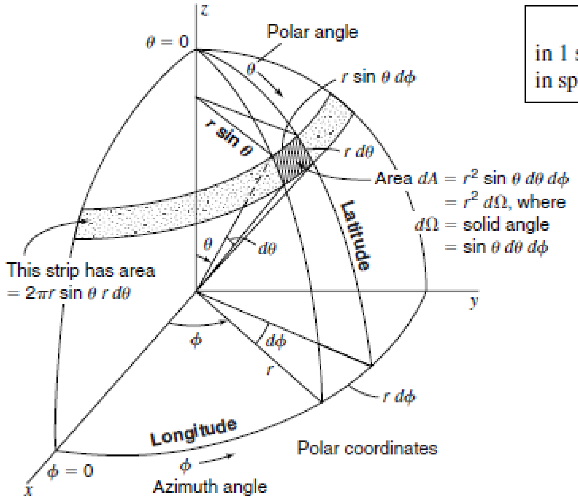
On the receiver end, the EM waves are guided by the transmission lines to the receiver, then converted to base band to collect information.

Antenna: matching network between WG and free space which allows transmission EM energy from the WG to free space, or reception of EM waves from the free space to WG. Same antenna can be used for transmission and reception, e.g. in case of monostatic radar.

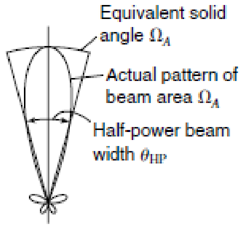


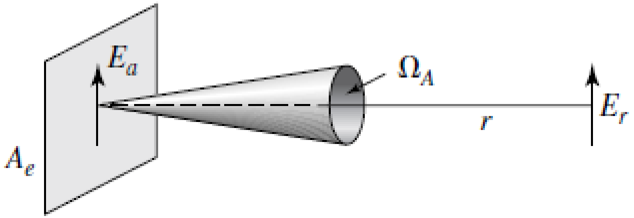


Antenna Beam Area (Beam Solid Angle)



Solid angle
in 1 steradian ≅ 3283□
in sphere ≅ 41,253□





Ae: effective antenna area

Radiation over beam area (ΩA) from aperture Ae

$$dA = (r\, d\theta)(r \sin\theta\, d\phi) = r^2\, d\Omega$$

$d\Omega$ = *solid angle* expressed in steradians (sr) or square degrees

$d\Omega$ = solid angle subtended by the area dA

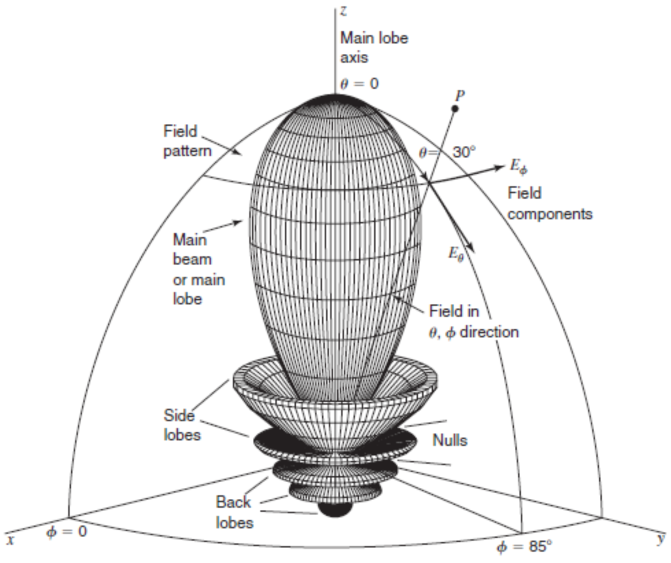
$$\Omega_A = \int_{\phi=0}^{\phi=2\pi} \int_{\theta=0}^{\theta=\pi} P_n(\theta, \phi) \sin\theta\, d\theta\, d\phi$$

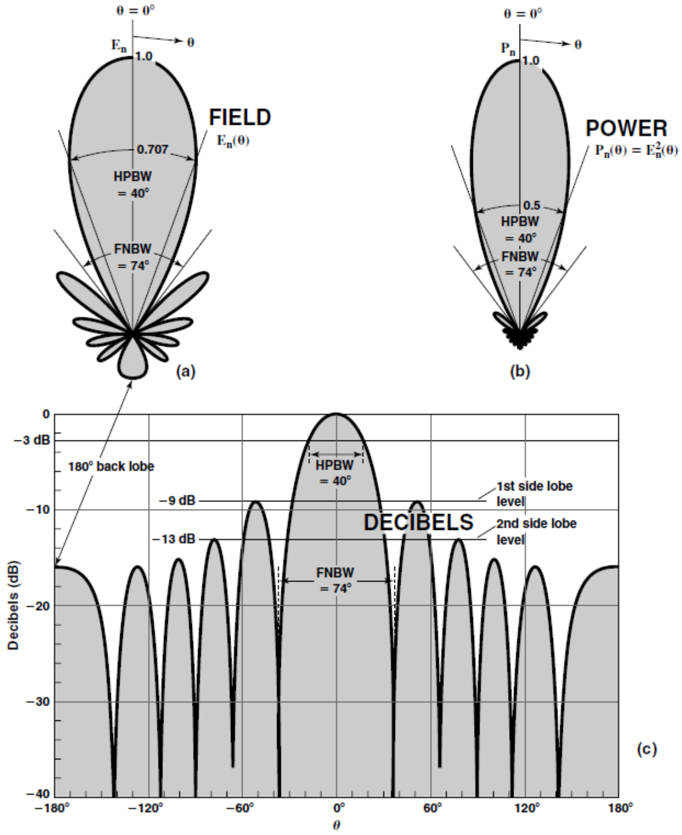
[Reference: .: 10]

[Reference: .: 10]

Antenna Beam Patterns

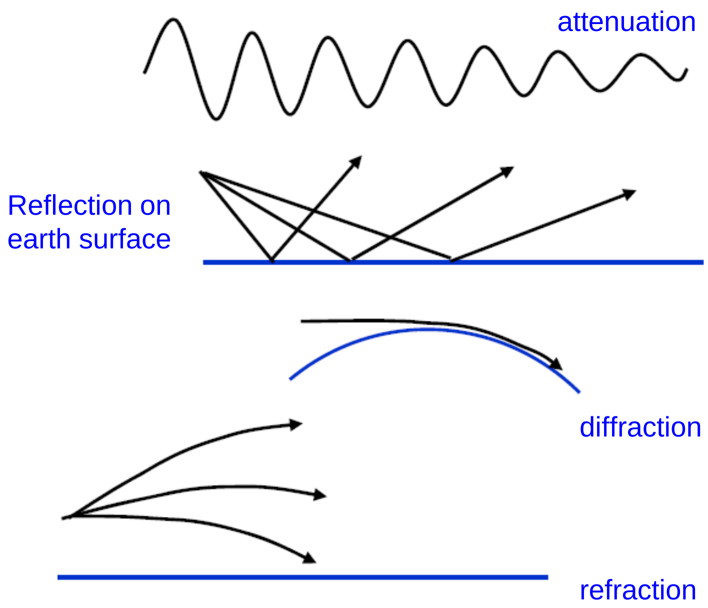
3D variation of E-fields or power as a function of spherical co-ordinates θ & Φ





Propagation Effects on Radar Performance

- Radar beams can be attenuated, reflected and bent by the environment
- In case of automotive application, attenuation and reflection are of most importance.
- Radar path loss ~ 1/ R^4



[Reference: 8]

[Reference: 7,8]

Course Overview

Radar cross section

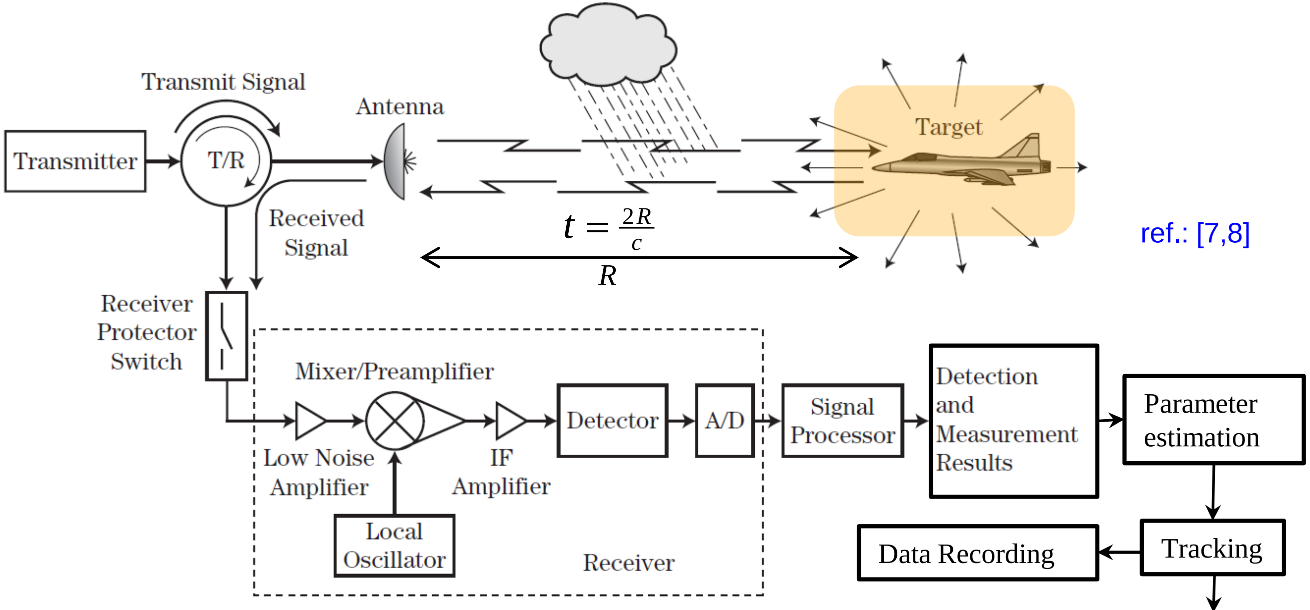
Effective area of the target depends on parameters of target and radar both.

Characteristics of radar targets are known mostly a priori.

Radar cross section of common targets: cars, trucks, bicycles, pedestrians etc.

Scattering mechanisms

Prediction of target's radar cross section

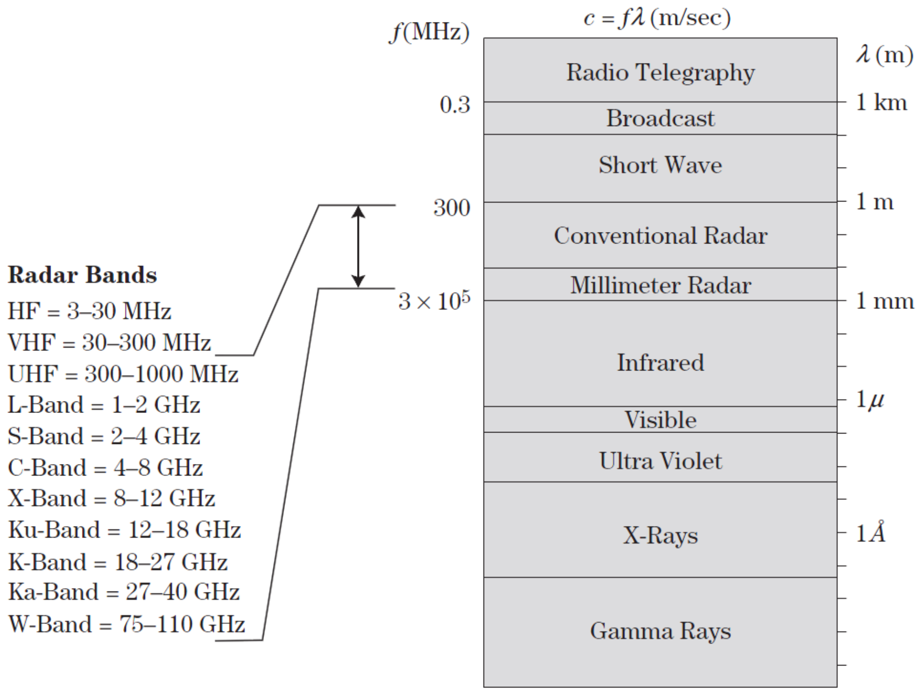


ref.: [7,8]

Radar Frequency Bands

Size of the radar sensors (antennas) are mostly determined by the operating frequencies.

D: antenna dimension, λ: wavelength, f: frequency
$D \propto \lambda$, $\lambda = c/f$

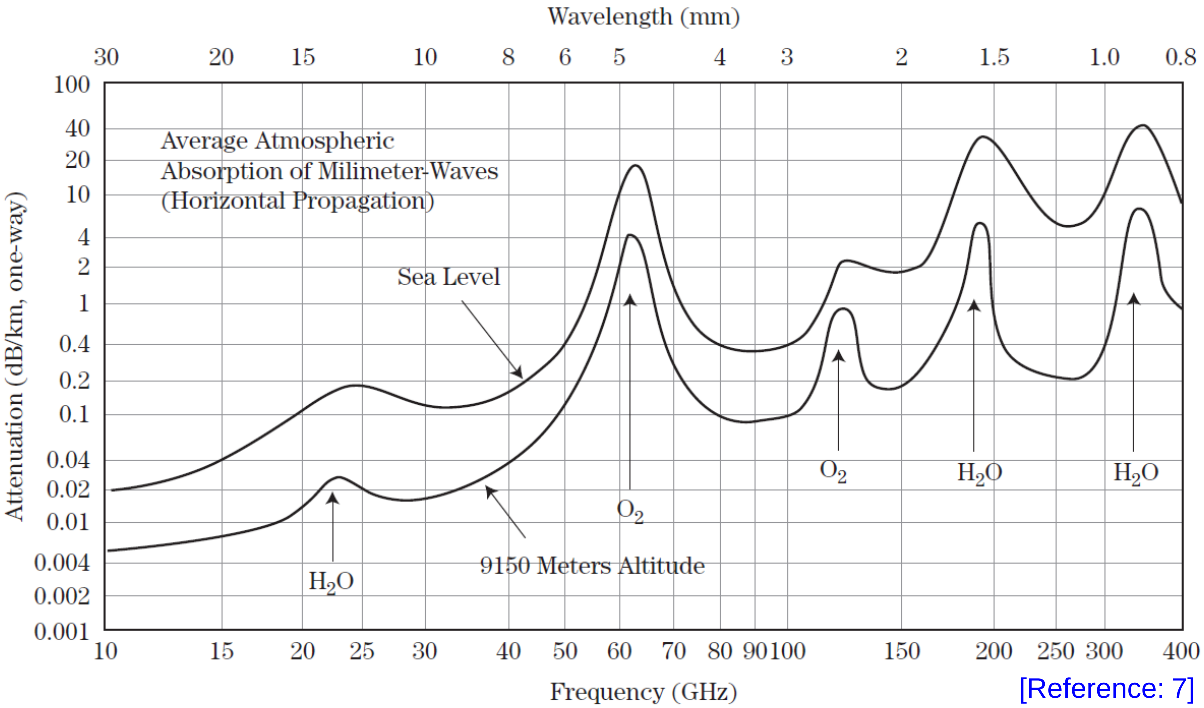


[Reference: 7]

Frequency bands	Radar types
HF. VHF, UHF. L	Search radars
C, X, Ku	Tracking radars
L, S, C, X	Search and tracking radars
C, X, Ku, K, Ka	Missile Seekers
VHF……..W band	Range Instrumentation radars
24 GHz, 76..81 GHz	**Automotive radars**

Electromagnetic Waves: Atmospheric Attenuation

- One-way atmospheric attenuation as a function of frequency at sea level and at 9150 meter altitude
- For radar: two-way attenuation
- Automotive radar bands:
  - 24GHz, 77GHz
- Rain, fog, clouds attenuate further EM waves. However, at radar frequencies rain and cloud attenuations are small, giving radar systems their famous 'all weather capability'



[Reference: 7]

dB Terminology

- At low frequencies, the strength of electrical signal is specified by voltage and current which can be easily measured.
- At microwave frequencies, electric and magnetic fields cannot be directly measured, only power can be measured. The electric and magnetic fields are calculated from the measured power.
- At microwave frequencies reference level of power is mW, not W
- dB: 10log(P1/P2), both P1 and P2 are of same unit
- dBm (absolute power): 10log(P1/1mW)
- Summation instead of multiplication
- 10log(2)=3dB, 10log(3)=5dB
- 80=2x2x2x10, 10log(80)=3+3+3+10=19dB
- 5=10/2, 10log(5)=10-3=7dB

power	dBm	comments
1 MWatt	90dBm	Transmitter level
1KW	60dBm	Transmitter level
1W	30dBm	
1mW	0dBm	Telecommunication, video display, computer, automotive radars
1µW	-30dBm	
1nW	-60dBm	
1pW	-90dBm	Receiver level
1fW	-120dBm	Detectable noise level

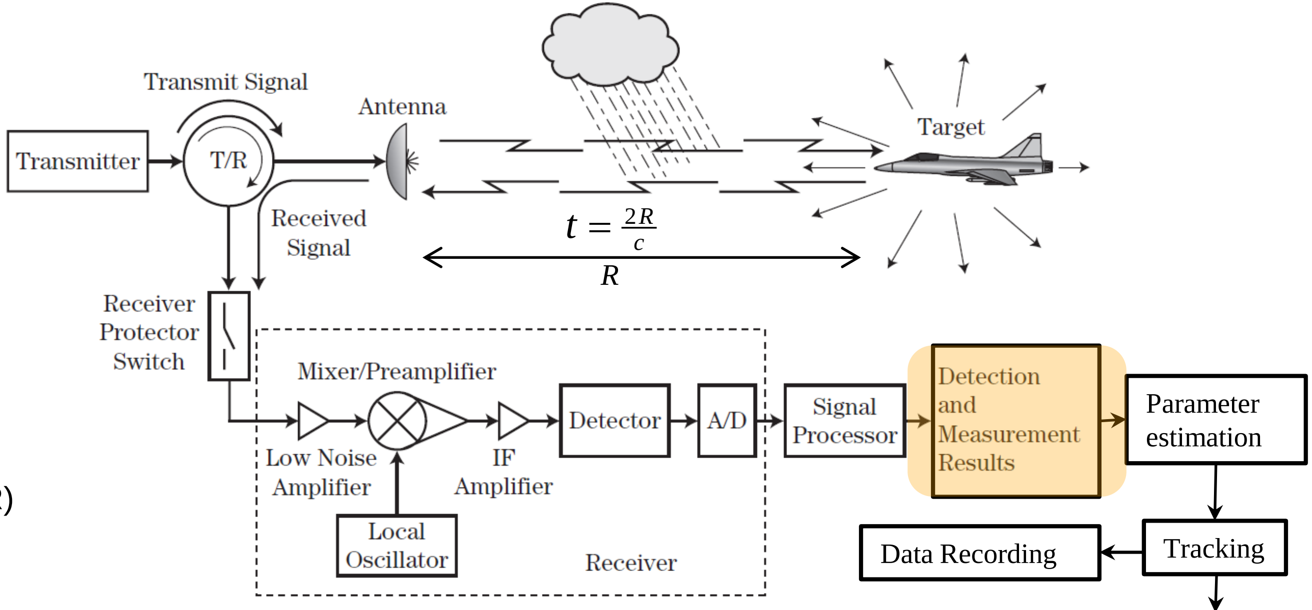
Electromagnetic Waves: Carrying Target Information

Designation	Frequency range	Wavelength range	Typical uses
L band	1 to 2 GHz	15 cm to 30 cm	military telemetry, GPS, mobile phones (GSM), amateur radio
S band	2 to 4 GHz	7.5 cm to 15 cm	weather radar, surface ship radar, and some communications satellites (microwave ovens, microwave devices/communications, radio astronomy, mobile phones, wireless LAN, Bluetooth, ZigBee, GPS, amateur radio)
C band	4 to 8 GHz	3.75 cm to 7.5 cm	long-distance radio telecommunications
X band	8 to 12 GHz	25 mm to 37.5 mm	satellite communications, radar, terrestrial broadband, space communications, amateur radio
K_u band	12 to 18 GHz	16.7 mm to 25 mm	satellite communications
K band	18 to 26.5 GHz	11.3 mm to 16.7 mm	radar, satellite communications, astronomical observations, automotive radar
K_a band	26.5 to 40 GHz	5.0 mm to 11.3 mm	satellite communications
Q band	33 to 50 GHz	6.0 mm to 9.0 mm	satellite communications, terrestrial microwave communications, radio astronomy, automotive radar
U band	40 to 60 GHz	5.0 mm to 7.5 mm	59-64 GHz: Broad band wireless communication systems (WPAN)
V band	50 to 75 GHz	4.0 mm to 6.0 mm	millimeter wave radar research and other kinds of scientific research
W band	75 to 110 GHz	2.7 mm to 4.0 mm	satellite communications, millimeter-wave radar research, military radar targeting and tracking applications, and some non-military applications, **automotive radar**
F band	90 to 140 GHz	2.1 mm to 3.3 mm	SHF transmissions: Radio astronomy, microwave devices/communications, wireless LAN, most modern radars, communications satellites, satellite television broadcasting, DBS, amateur radio

Course Overview

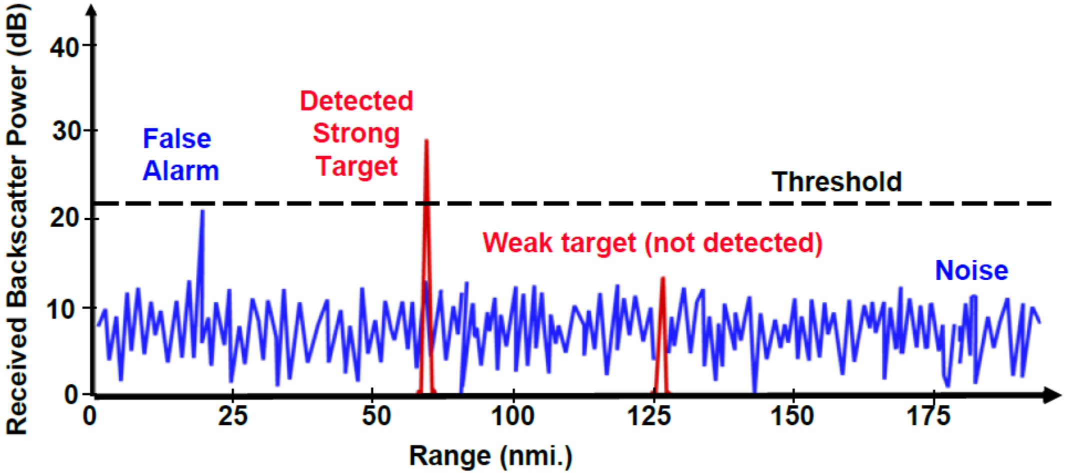
Detection of signals in noise

- Integration of radar pulses
  - coherent vs non-coherent
- Fluctuating targets: radar backscatter amplitude of the target vary from pulse to pulse
- Constant false alarm rate (CFAR) and thresholding
- Radar clutter: sea, land and weather clutter
  - Detection of targets in clutter



Detection of Target in Noise

- SNR are defined for specific applications
- Detection: target is higher than threshold
- False alarm: when a noise is higher than the threshold
- Missed target: when a target is below the threshold
- Only noise: no problem



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